

Technology and You Singapore Infocomm Foresight 2015



Singapore Infocomm Foresight 2015

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Preface

Dear readers,

Welcome to the fifth instalment of our Infocomm Technology Roadmap (ITR5) report series. ITR5 is our inaugural technology planning report that focuses on long-term strategic planning (10 years) in contrast to our previous four technology planning reports that are more short-term (5 years). It is launched in conjunction with the ITR public symposium held this time in March 2005.

The ITR initiative constitutes the key effort by IDA for long range technology planning. Complementary to and together with our past short-term roadmaps, ITR5 is intended to provide comprehensive inputs and guidance to organisations and corporations in Singapore on infocomm technology trends to 2015.

For IDA, this ITR5 will act as the technology roadmap input for crafting our next national infocomm blueprint that goes beyond the present Connected Singapore Master Plan. We are extremely excited by the prospects arising from the confluence of the computing and communications waves supplemented by innovations from nano and bio technologies. Together these technologies will herald the arrival of the Sentient Wave by 2015.

- **Computing Wave.** The computing wave that brought us the mainframe, mini and personal computer is far from over. Computers are everywhere and have become ever more indispensable for modern living but they are about to disappear into the background. They will be embedded into the very fabric of our lives. We will move from the era of "power of a mainframe on every desktop" to "power of a mainframe on every person!"
- **Communications Wave.** Communications is a basic human need. Communication technologies have already given us the mobile phone, broadband connectivity and the internet; these technologies have transformed our lives. But this is just the beginning, the future is even more exciting, we see mass deployments of all IP optical transmission backbones bringing communities together in cyberspace where there is no restriction of distance or time. We see seamless integration of fixed and mobile communications; of communication and entertainment content being delivered over smart self-configuring (cognitive) radios that adapt themselves to deliver compelling services to the end-user.



- **Sentient Wave.** Roget's thesaurus defines "sentient" as being "marked by comprehension, cognizance, and perception". When you combine developments in computing, communications with embedded sensors and intelligence, you start to create a world of things that think. This will be the era of people-centric technologies, proactive computing, sensor technologies and Small Software. Besides bringing in new levels of ease and convenience for end-users, a new eco-system of hardware, software, systems-level players that exploit sentient smart spaces will be created. There will bring tremendous opportunities for those in our infocomm industry who are prepared to rise up to the challenge.

The full ITR5 report will delve into the background and describe in more detail the opportunities mentioned above. We hope you will find it an interesting read.

Last but not least, I would like to thank our readers for their continued support and interest in ITR reports. ITR5 is a combined effort by the industry, academia, research and government agencies. We would like to thank all participating individuals and organisations for their contributions.



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Executive Summary

Introduction

The computer, the mobile phone and the Internet have transformed our lives, dramatically changing the way we live, work, and play. The pace of technological advancements has continued unabated, relentlessly eroding organisational and geographical boundaries. It leaves in its wake a highly distributed, yet closely interconnected global network of resources, and in the process, enriching people's lives through applications and services.

Several trends are discernible and have been put forth as "so called laws," these include;

- Moore's Law where computing power doubles every 18 - 24 months;
- Disk Law where storage doubles every 12 months;
- Fibre Law where communication doubles every 9 months;
- Metcalfe's Law where the value of a network increases by the square of the number of devices connected to it;
- Community Law where content increases by $2^{(\text{number of people})}$

In recent years, through the use of powerful computers and information sharing made available by the Internet, our understanding of the basic sciences has improved tremendously. We are now entering the era of nano and bio technologies; these will, in their own way, have their impact on how infocomm technologies develop.

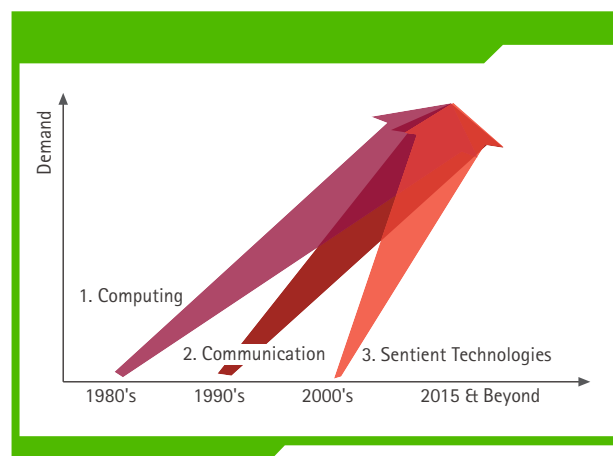
How will the myriad accelerating technological forces, driven by the confluence of infocomm, nano and bio technologies transform Singapore's landscape in 2015?

The IDA Technology Roadmap team undertook an in-depth study into this question; to understand the strategic significance to Singapore and how the country could capitalise

on it for a sustained competitive edge. Opportunities, challenges and key growth areas over the next ten years will be highlighted, so as to better prepare the industry, research community and academia. Our findings arise from extensive literature research and intensive interviews with thought leaders, visionaries, industry players, researchers, academia and government.

Waves of Change in Technologies

To understand the strategic technology evolutions and revolutions that will come to bear on the Singapore Infocomm landscape in the next decade, we drew insights from macro observations of technology innovation cycles in the past. The graph below shows the waves of change we have witnessed and are seeing towards the future.



First Wave of Change – Computing revolutions infused with nano and bio technologies

The Personal Computer (PC) offered a disruptive alternative to room-sized mainframe computers. It made computing affordable to the general public. The introduction of productivity enhancing software applications such as word processors, spreadsheets and databases, together with a user-friendly graphical user interfaces made computing accessible to the masses. With these innovations, you no longer need to be a computer engineer to be able to exploit the power of the computer. Indeed, the PC and Internet have become indispensable in our offices and homes.

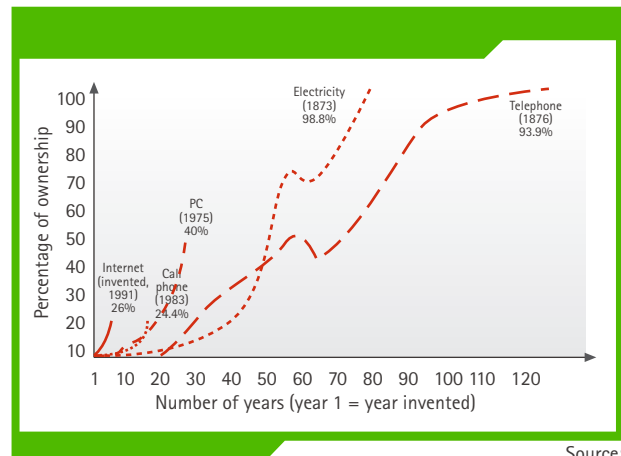
While the PC and the Internet have reached the masses, there are other computing innovations arising from the research community that will similarly make that leap in the next 10 years. These include Grid Computing, Peer-to-Peer technology, Service-Oriented Architecture like Web Services, Semantic Web and software agent technologies. In the much longer term, beyond 2015, novel software programming paradigms arising from biology-inspired models, such as amorphous or swarm computing and neuro-computing may make their mark.

On the device front, computing hardware which had faithfully followed Moore's law in the last twenty years will be further revolutionised by infusions from nanotechnology. While the rallying call for the computer industry for the late nineties was "mainframe computing power on every desktop", we expect to see "mainframe computing power on every person" by the time we reach 2015.

In fact, FISTERA¹ predicted the disappearance of the PC in the timeframe 2008–2010, where the PC 'disappears' and becomes miniaturised and embedded in everyday objects. It is not commonly known, but for every PC sold today, there are over 100 microprocessors sold embedded in everyday objects and IT appliances. But these embedded devices have very limited computing and storage capabilities and perform only a narrow range of specific functions. However, by 2015 thanks to Moore's law and nano-technology, we expect these embedded devices to have more computing power and storage capacity than the best desktop PCs of today. This transformation means that we will have at our fingertips a walking office, databank, software and entertainment centre available wherever we are and at anytime we want them.

Second Wave of Change – Communications in the future

It is a basic human need to stay in touch, to communicate. Thus, society has embraced communication technologies such as the telephone, mobile phone, and the Internet with open arms. And, the rate of adoption for each new technology is faster than the one before. It took approximately 35, 15 and only 5 years for the telephone, cell phone and the Internet to cross the 25% adoption mark respectively.



Source:
International Engineering Consortium

While we may seem pretty well served by our communication systems today, the situation "under the hood" is far from pretty. Our present systems such as the Public Switch Telecommunication Network (PSTN), GSM cellular phones, public WiFi hotspots and broadband DSL were designed to serve specific needs. Being developed independently from each other, seamless inter-working across these networks is almost impossible. As a result, the poor user has to carry many devices (POTs, cell phones, DSM modems, WiFi access cards) and carry different log-in identities as he transverse across these networks to access the services he needs.

As we move towards 2015, the situation will improve significantly. In the interim, we see technologies such as Software Defined Radio (SDR) reaching maturity. With SDR, the device adapts itself to accommodate any wireless standards or protocols necessary for communications to take place. The user no longer needs to carry multiple devices for communications, nor does he need to remember multiple user identities and passwords; his overall user experience will be much enhanced. In the longer term, the communication infrastructure itself will undergo a transformation. The disparate communication systems of today will be unified by a common backbone infrastructure based on fibre and DWDM multiplexing. They will carry multiple wavelengths of light (also called lambdas), each pulsing at rates of over 40 Gbps. The light pulse will transport data using Internet Protocol (IP) and this infrastructure will link all major population centres of the world. This transport technology is much more efficient and cheaper to maintain. As a result, the cost of transmitting data will drop to a fraction of what it costs today. Even EDGE devices, such as mobile phones and set top boxes, and applications will converge to use IP natively. In fact, the trend is already very clear, future versions of the wireless 3G standard (R5 and beyond) already calls for an all-IP transport core and on-going research into 4G radio technologies seeks to exploit the use of IP at the radio access side as well.

¹ FISTERA (Foresight on Information Society Technologies in the European Research Area) in an article by Telecom Italia in IEEE Communications Magazine

Hence, by 2015, we can imagine a world covered by an extensive network of optical fibre. They will provide an almost unlimited capacity to transport data anywhere around the world over a wide geographical location which will result in unlimited bandwidth subscription rather than time-based charging being the norm. These highways behave like the arteries and veins in our body. To reach out to the last mile, and the last inch, the fibre network will be complemented by low cost wireless access nodes that permeates everywhere connectivity. It is much like how blood capillaries bring nutrients to every cell in our bodies, irrespective of where the cell is. Users will no longer need to worry about different devices and logins for different systems. IP will be the unifying platform, providing high levels of end-to-end quality of service and security. By 2015, we will truly have an always-on, broadband, anywhere, anytime connectivity.

Next Wave of Change – Sentient Technologies

The computing wave brought affordable computers to the masses. The communication wave will bring a fabric of network connectivity that is broadband and everywhere where service is needed. When we interleave into this fabric powerful computing nodes and devices that can sense and interact with one another, we enter into the era of sentient technologies. Sentience is the capacity for basic consciousness: the ability to feel or perceive. Taking the analogy of the human body one step further, sentient computing is the equivalent of giving our communication network and systems a nervous system and a brain. The goal of sentient computing is to make machines and applications perform better by giving it an ability to collect information about its surroundings, its context and for it to make judgements based on this information.

In the past, the Internet (Net) acted more like a repository of information; we go to the Net to look for information. The amount of information accumulated on the Net is tremendous and growing at a fast pace. Within a decade from the Net's invention, we have moved from a world of "not enough information" to a world of "too much information and information overload". Presently, all the Net does is throw information at the user and the user has to exercise his intelligence to sort the information based on his needs or context. By 2015, we believe that through the use of sentient technologies, intelligent agents residing on the Net can automate, analyse, synthesise and present information that is personalised to us.

The transformation of the Internet from one that is passive to an Internet that delivers personalised information requires development of technologies such as sensors and distributed sensing networks to capture physical, behavioural or mental context. Also needed are software agent technologies deployed at sensor nodes, inside computing and communication devices, crawling and mining information over the network. They collaborate to sense and deduce context awareness and work collaboratively to deliver information to us. These wonderful capabilities are made possible from the innovations from the computing and communication waves from the past two decades.

Singapore Infocomm Landscape in 2015

The Singapore Infocomm Landscape in 2015 will be strongly shaped by the convergence of computing, communications, and sentient technologies in line with global trends. Besides technologies, the Singapore landscape will also be strongly influenced by the country's social-political environment. A scenario planning exercise, facilitated by the Strategic Policy Office, Public Service Division in the Prime Minister's Office (PSD PMO), was conducted as part of this roadmap initiative to identify the challenges facing Singapore in 2015. The challenges identified for Singapore are:

- **Economic Growth.** How can Singapore sustain its competitiveness and develop new pillars of growth where it can excel?
- **National Security.** Singapore, like any other country, will continue to face security threats from terrorism, chemical and biological attacks, natural disasters, health epidemics, and cyber-attacks.
- **Population Demographics.** Like many advanced economies, our population is greying and the country is experiencing a decline in birth rates.

Meeting these challenges. Singapore positioned itself well to ride the computing and communication waves of the past two decades. Many of the over 6,000 MNCs that invested in Singapore are from the Infocomm space and Singapore has won many international accolades for its adoption of advanced infocomm technologies. With our well developed infocomm infrastructure and strong focus on infocomm-related research and development in our research institutes and universities, we are well positioned to exploit the next wave of sentient computing to tackle our national challenges for 2015. Specifically, the ITR5 roadmap attempts to show how computing, communications and sentient computing can be put to good use:

- **Addressing Economic Challenges.** Singapore is already one of the world's earliest players in the sentient computing space with its nationwide Electronic Road Pricing system and the use of RFID in its public libraries. These systems contain elements of computing, communications and sensors all tied together to an intelligent control infrastructure, albeit used only for billing at present. Our Research Institutes and universities are building on this lead and are very active in research into nanotechnology and bio-inspired computing, advanced communications networking, and embedded sensors. Nanotechnology will enable lower cost manufacturing, give more extensive sensing capabilities to our microelectronics and generate new materials useful in data storage and fuel cells. Sentient computing will increase our work productivity and provide efficient automation for various industries. Together these technologies, as building blocks for Sentient Singapore, could become sweet spots for the infocomm industry and lead us into another new phase of economic growth by 2015.

- **Addressing Security Challenges.** To meet our security challenges, the three waves of technologies can work together to build nationwide sensor networks that operate around the clock, seven days a week, capable of detecting and responding to a wide range of threats. There are opportunities for chemical and biosensors to detect chemical and biological threats. These are connected to the infrastructure by low power and low cost wireless links that plug into the nationwide IP backbone and could use ad-hoc networking capabilities to enhance their tolerance of individual node failures. In terms of cyber security, we have also identified advanced network security technologies such as quantum cryptography, biometrics, RFIDs and contactless smart cards as areas where infocomm technologies can be brought to bear on the problem.
- **Addressing Population Challenges.** Sentient and people technologies in this report will continue to enhance the quality of life for both young and old, and even those physically challenged. Smart systems can be deployed to advance eldercare, such as to sense and remind elderly patients at home to take their medication or multiple pills at different times, especially when dementia sets in. Preventive healthcare systems help to reduce costs too. For instance, monitoring of elderly at home, detection of abnormal behavioural changes can be achieved through telematic systems enabled by communication technologies, sensor networks, tracking systems, biosensors and wearables. These technologies are equally appropriate for the care of young pre-school and school going children. By reducing the burden on these young home-makers, there is the possibility that these stressed individuals will consider having more babies to reverse the country's declining population. Lastly, sentient technologies can also create more exciting lifestyles in smart homes and entertainment applications for the masses.

To provide a more vivid description of the Singapore Infocomm landscape in 2015, we describe how individuals and the infocomm industry may be impacted by the confluence of infocomm, nano and bio technologies.

Impact on Individuals in Singapore in 2015

Individuals in 2015 will be able to enjoy seamless mobility of broadband services, regardless of wireline or wireless technologies because everything will converge to a common IP platform. Their mobile computing devices will be faster in processing, smaller, lighter, and denser in storage, with longer-lasting power. Future non-volatile high density magneto-resistive RAMs can allow devices to power up instantly, offering more satisfactory user experiences.

Miniaturised sensors and computing devices, realised through nanotechnology, will be abundantly deployed in ad hoc networks, embedded into our surroundings or smart materials can be painted on our walls, providing ergonomic and intelligent interfaces. Smart sentient objects could be your wall mirror animated with multimedia virtual secretaries or edutainment avatars, with hyperlinks to shopping or

entertainment services. Working environments can be enhanced with mixed reality applications.

Walking down the streets and shopping malls, we will experience efficient time saving and personalised shopping experience with mass customisation systems that we can identify with and set preferences for. Push and pull services will be more personalised with efficient automated data mining by intelligent networks and software agents, such that only useful information will come to us and be presented in an attractive manner via aesthetic human computer interfaces.

Our lives will also be safer with smart security networks that are integrated with multiple technologies to anticipate potential threats. Healthcare costs can be reduced by promoting preventive healthcare systems enabled by smart technologies, nano-biosensors and networks. The environment we live in will be better maintained with sensor monitoring systems.

In 2015, the Semantic Web will break out of the virtual realm and extend into our physical world. URLs can even point to physical entities. The first concrete steps have already been taken in this area, with work on developing a standard for describing functional capabilities of devices (such as screen sizes) and user preferences. This standard by W3C is called Composite Capability/Preference Profile. In other words, we can use semantic technologies to describe devices such as cell phones and TVs. Such devices can advertise their functionalities, what they can do and how they are controlled, much like software agents.

Impact on Industry in Singapore in 2015

To the industry, the development of the technologies in this report can create new innovative leadership products and services, enhance business efficiency and processes, and provide real time intimate customer experiences.

We have identified various promising areas of growth such as:

1. Sentient Technologies

Many sentient and security applications we envisage in the future will require sensor technologies. Two key areas in sensors are (1) physical networks and (2) distributed & small software.

- **Physical Network Domain:** Wireless sensor networks for distributed sensing – i.e. networking technologies, middleware architectures and new algorithms that provide efficient wireless sensing. Innovations are needed to meet technical challenges in
 - security, trust models and reliability,
 - models of computation for sensor networks,
 - self-reconfigurability and adaptability, autonomic cognitive systems,
 - safety versus usability.
 Examples of developmental programmes are Intel's Proactive Computing, Xerox's embedded collaborative computing and sensing, US EmNet, SensorNet.

- **Software Intelligence Domain:** Distributed Intelligence & Small Software – i.e. software technologies for sensors & networks for distributed data inference, management, query, processing, storage and retrieval, as well as small software optimised for embedded networked devices like tiny open source computing. Mobile agents and agent collaboration for proactive computing are also important. Distributed intelligence can be enabled by localised algorithms. Personal peer-to-peer applications will grow within dense pockets of computing devices. New programming languages are also important for sensor development (hardware programming example like Stargate, software examples like Emstar and NesC), and so is the building of an inventory of customisable & parameterised libraries and development kits that people can use to build applications and programmes.

There are also other technologies that enable end-to-end system building and integration like:

- **Enabling Technologies:** Web Services, system clustering, Semantic Web, location based technologies, tiny efficient sensor-on-chip with power efficient designs. There are technologies that can contribute to affective and useful computing like intuitive human computer interfaces, mixed reality and smart wearables – smart fabrics, embedded data technologies, social software. There are also privacy enhancing technologies, network security technologies like quantum cryptography and common authentication infrastructure using biometrics or contactless smart cards.

2. Computing infused with Nano and Bio-technologies

Developments in the computing space with strong inputs from nano and bio-technologies will bring about new infocomm products in the key areas of:

- **Electronics** – Moore's Law marches onwards unabated. Presently, microelectronic fabrication line widths for cutting edge products have already transcended into the nano-range. By 2015, they will be the norm rather than the exception. Devices that exploit nano-phenomena such as the carbon nanotube and nanowires will bring in new capabilities in signal processing and sensing capabilities. In parallel, developments in new architecture for processors, such as cell-based computers and re-configurable computer cores will take centre stage.
- **Storage** – The entire storage space is on the cusp of a revolution. Soon we will see mobile phones with magnetic hard disk drives and by 2015, technologies such as magnetic random access memory (MRAM) and 3-D holographic storage may overshadow the storage technologies we are so familiar with today such as magnetic hard disks, flash and optical disks. With the projected reduction in cost per bit and increasing storage capacity offered by these technologies, it is not inconceivable for a person to carry

with him terabytes of storage. This is more than sufficient to store all the information he normally needs for daily interactions. Just as the PC and Internet transformed our lives, when this threshold is crossed, our lives will never be the same again.

- **Display technologies** – The opportunities range from wall-size displays, along the lines of the 102" plasma display showcased at CES2005, to low cost flexible displays based on plastic electronics (OLEDs). These flexible displays may be used for making foldable paper-like displays to overcome space limitations on mobile phones and PDAs. Another promising front for the development of display and display technologies is in the area of augmented and virtual reality systems.
- **Power** – One of the key technologies necessary for the 2015 vision to come to fruition is the availability of high density portable power supplies to power the devices and sensors that make up the sentient space. Opportunities here include polymer Lithium-ion batteries, micro fuel cells, nanocones and nanowalls for increasing capacities of batteries and fuel cells. Another interesting call of energy storage is that of ultra-capacitors which offer very high energy densities and yet do not suffer degradation from repeated charge and discharge cycles. Organic or printable solar cells represent another opportunity where very high charge rates are not needed, when coupled with efficient light emitters such as white light LEDs, and could play an important role for lighting of public spaces for convenience and safety.

Furthermore, in the very long term, bio-inspired computing like swarm or amorphous computing, organic computing, neuro-computing, neuro-silicon chips, brain-computer interfaces, will yield disruptive capabilities to software programming, smart manufacturing, robust control and analysis systems. Lab-on-a-chip systems will continue to grow strongly, as already witnessed today.

3. Communications Technologies

Over the next ten years, as operators and service providers move towards a converged IP platform, communications will see healthy growth in the following areas:

- **Broadband Wireless Internet.** This refers to the cluster of technologies that are capable of delivering high speed internet access to mobile individuals wirelessly. According to Nokia, there will be around 2 billion mobile subscribers in 2008 and this figure is expected to reach 4 billion by 2015. This projection is driven by user preference of mobility over fixed line as seen from the higher number of global mobile subscribers compared to fixed-line subscribers today. Telecommunication operators will evolve from selling fixed-line broadband to the home to promoting wireless broadband to the individual.

- **Short Range Wireless.** Short range wireless technologies are expected to move beyond its existing personal area network application to the new wireless sensor networking application. Ultra-Wideband (UWB), Radio Frequency Identification (RFID), ZigBee and other similar standards are expected to evolve over the next ten years to create highly scalable sensor networks that will collectively monitor and process vast amount of data to help run factories, optimise supply chain management, and for environmental monitoring.
- **Fixed-Line Broadband.** Fixed-line access is still expected to complement wireless access in 2015 because of its inherent advantages like higher access speed and better security. Fibre-To-The-Home (FTTH) will be the next phase of growth in this space beyond the existing DSL and cable broadband access technologies.

In Closing

We have painted a picture of how the computing wave, the communications wave and developments from nano and bio-technologies will come together to form the sentient wave in the next ten years. We have also attempted to envision how Singapore may be able to exploit these developments to address its national challenges and thus create new opportunities for its infocomm industry.

We would now like to invite you to read this report in detail, to explore for yourself what these trends mean to you and your business and how you may be able to position your company to best take advantage of these developments. We have also included in the report details some of the potential barriers which that must be overcome for the vision to come to fruition. Finally, we have also summarised the roadmap technology milestones into a poster chart which will be distributed in conjunction with this report.

Track 1

Sentient Technologies

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Sentient Technologies Landscape 2015

1.1 Introduction

Introduction to key domain areas in sentient¹ spaces.

Around the world, our analysis found common concepts or related variants in actual research, national technology roadmaps, military roadmaps, product development programmes by private and public organisations (mostly IT related). The commonality lies in themes alluding to living seamlessly and working productively in a smart or sentient space where key enabling technologies come from domains in **computing, communications, distributed sensing and embedded systems**.

In these technology domains, we see in 2015 and beyond the following strategic developments:

In computing, hardware performance revolutions will come mainly from the advent of nanotechnology and advanced chip designs, organic or molecular engineering, whereas software computing revolutions will come mainly from bio-inspired computing. Other computing applications on the Internet will continue to evolve and remain important, like grid, peer-to-peer and service-oriented computing paradigm (Web Services). These will deliver ubiquitous computing and storage utility with personalised services to the individual and enterprises. Furthermore, we will see the evolution towards computing technologies that are people centric and intuitive. These computing evolutions for better personal or enterprise applications will have to become more "brain-width" friendly as the amount of data on the Internet has swelled to 8 billion web pages today. To make the Internet friendlier for machine and application automation, Semantic Web and network-based agents will continue to evolve. Internet usage will also become more transactional requiring higher reliability and trust.

In communications, network bandwidth provision will continue to evolve towards higher and higher bits per second as applications become more multimedia in nature, and as more and more people are being connected. While bandwidth are expected to evolve to Mbps and Gbps for the user depending on the type of communication technology, there are also disruptions in enabling communication technologies like advanced cognitive software defined radios, all IP optical networking and switching, wireless sensor or ad hoc networks, converged 4G mobile broadband internet platform, IPv6 and beyond, end-to-end QoS and security. These will all converge into an IP based platform with seamless and secure end-to-end connectivity over heterogeneous networks. Broadband will be pervasive with high connectivity everywhere and anytime.

In distributed sensing, we will see new revolutions for sensor networking, information retrieval and processing, sensor data fusion and reasoning, power efficient algorithms and architectures. With advanced sensing capabilities, IT devices and networks can now not only compute, communicate, but also reason and sense with dynamic knowledge of physical environmental parameters and context. This makes computing in a smart space more affective and cognitive. In fact, the applications residing on the Internet today is not so cognitive to user needs as they are unable to understand the 'last mile or last inch' physical context of operating environments without 'feelers' into these physical spaces. Sensors and human computer interfaces incorporating various sensing features are automated input and output 'feelers' to create more user and context awareness data. With this data, the Internet will become a Sentient Internet that can be more autonomous to act and reason on its own without too much user inputs, and be able to deliver end to end service integration.

¹ 'Sentient': [adj] consciously perceiving. (Wikipedia definition): Sentience is the capacity for basic consciousness: the ability to feel or perceive, not necessarily including the faculty of self-awareness. The word sentient is often confused with the word sapient, which can connote knowledge, higher consciousness, or appreciation which would mean a very sophisticated level of artificial intelligence comparable to humans, unlikely to be achieved by 2015. The Sentient Web is coined by Michael N. Huhns from the University of South Carolina. In the movie 'i-robot', we can find the term 'Sentient Machines', while in 'Matrix' we hear the term 'Sentient Programmes'.

In embedded systems, we see the miniaturisation evolution towards embedded hardware via the convergence of computing, communications, sensing into one system-on-chip device or lab-on-a-chip. According to In-Stat, revenues for lab-on-a-chip devices are predicted to grow at a Compound Annual Growth Rate of 31.2% through 2008. Multi-functional miniaturised yet more powerful components can then be embedded conveniently into our smart environments or devices. Many computing and communication devices are getting smaller, and at the same time, wearable computers, internet appliances are also emerging. For many of these miniaturised devices, sensors and computing objects, we will need small embedded software like tiny open source operating system/database/security that can be run on these systems efficiently. Embedding into systems cognitive and collaborative functionalities with simple software agent codes can further enhance such embedded environments with sentient or proactive capabilities and also facilitate task automation. Agents deployed at sensor nodes, running in computing and communication devices, and multi-agent collaboration for distributed intelligence allow us to develop software applications that are responsive and intuitive to our needs at any moment, mining and presenting data that we want.

To describe these key strategic trends we see above, we have structured ITR5 in the following format:

"Sentient Technologies". This covers the system overview of ITR5, where our focus is on how computing, communication, distributed sensing and embedded technologies converge to create sentient spaces. It describes system programmes, application trends around the world in sentient spaces but also covers technology developments that are people-centric, offer smart automation and context awareness like sensors, and many others that can be used to build a smart sentient space system. These system and application technologies rely heavily on advancement in foundation infrastructures like communication networks and computing systems which are further described in the two tracks below.

"Communications for the Future". This covers the developments in communication and networking technologies that enable smart connectivity in sentient spaces. The technologies here form the physical medium for data transport and communication, upon which we build sentient space software applications.

"Computing Revolutions with Nano and Bio". This covers basic infocomm foundations in processing, storage, power, display transformed by nanotechnology that make embedded systems used in sentient spaces faster, better, cheaper and smaller. It also covers developments in the longer term towards the convergence of bio-nano-info whereby bio-inspired computing offers even more disruptions in performance to embedded systems in sentient spaces. Sentient space software applications operate on and across these computing systems.

1.2 Vision For Sentient Technologies

The goal is to create smart sentient working & entertainment spaces, networked embedded spaces with sensory & distributed intelligence, characterised by human-friendly computing, as well as business-efficient automation.

Many technologies are involved to achieve the creation of smart sentient spaces. There can be advances in man-machine, machine-machine, machine-environment hardware and software interfaces, emerging sensor computing paradigms like tiny open source computing, tiny DB (database), robust security with quantum encryption and key exchange, smart hardware like nanotechnology, new materials and molecular engineering, learning agents, amorphous or swarm computing, social software, semantic web, mixed reality (augmented reality, augmented virtuality), etc. The future is towards an Internet (the Network of networks) and cyberspace that are more entwined with the real world, thanks to its connectivity to millions of smart sensory devices existing in the real world that act as its feeder inputs and outputs.

To understand this in simple terms today, we can look at how RFID tags have brought about increased efficiency and cost savings for supply chain and inventory management. Today's RFID sensors may only tell the object identity to the network, while more advanced UWB (ultra-wideband) tags can also inform the network system on the carrier location in an indoor environment. But sensors have even more potential than to simply authenticate or locate an object, they can be ubiquitously deployed or embedded in everyday spaces to tell the mood of the person by the voice signature, alert through networked homecare service a live-alone elderly who is in danger, do environmental protection, be used in fire fighting to predict fire paths, monitor the structural safety of buildings, warn of possible emergence of health epidemics by identifying viral zones and be networked to hospital records, school absentee lists and clinic alerts, or enable intelligent transport and traffic management IT systems. The range of possibilities comes with more than 50 000 known types of sensor products today in the world, and emerging ones based on new embedded technologies that are coupled with wireless and online capabilities.

Also, human computer interfaces (HCI) have seen a relatively much slower pace of evolution than IT networks and other computer technologies. It is increasingly being recognised as the bottleneck to how much our brains can absorb and interact with data. Impoverished interface technologies limit our ability to fully exploit and digest the vast amount of virtualised data on the Internet and distributed databases. The way humans interact is via our senses. Hence, improving sensors or sensing interfaces can be critical for augmenting our interaction capacity with data. By doing so, we are moving towards the new Sensory Internet.

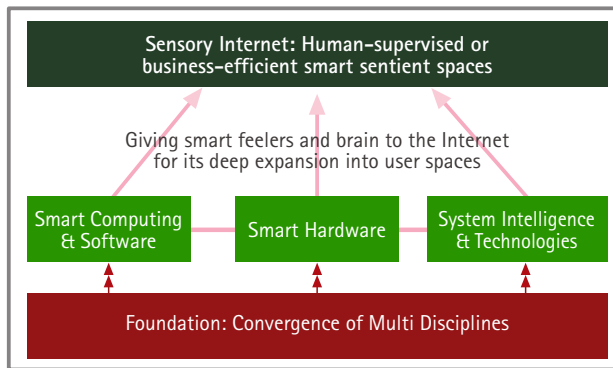


Figure 1. The Sensory Internet and Sentient Spaces

By the description 'deep expansion into user spaces', we mean embedded connectivity and computing intelligence into our environment in objects that are part of our lives. For example, an embedded car air-pressure sensor can relate wirelessly via its integrated communication interface the information on the condition of car tyres to the central display console for the car driver or his wireless phone for personal convenience; this can prevent accidents and possibly also save on fuel, it is probably more accurate and timely than us having to manually check on tyres.

There is also an inference to 'integrated wireless (primarily) connectivity' to networks for system software to coordinate,

direct and ensure macro-efficiency by making sense of different streams of data and context from distributed input nodes, in order to achieve designed outcomes.

To be deep into user spaces, the experience should be intuitive via 'affective user interfaces' between both real and virtual worlds. This can be made possible via smart and designed-for-humans hardware, or via smart learning software and especially via collaborative software agents. The experience can be made smooth by enabling the system to be proactive, as in Intel's proactive computing concept. Hence, Intel sees that we will move from a human-centered model where computing is tedious requiring frequent human intervention towards a human-supervised model where we can be more relaxed as there will be a lot more task automation by computing.

To conclude, we see vision as a movement from today's impoverished web systems to tomorrow's affective, smart, proactive and sentient web systems. The intelligence in the latter has to be built-in stages, from physical connectivity – e.g. sensor networks (intelligence at physical level), to virtual artificial intelligence (e.g. proactive and cooperative agents, learning system software, virtual reality), and finally to the possibility of a mixed model of both physical and virtual intelligence.

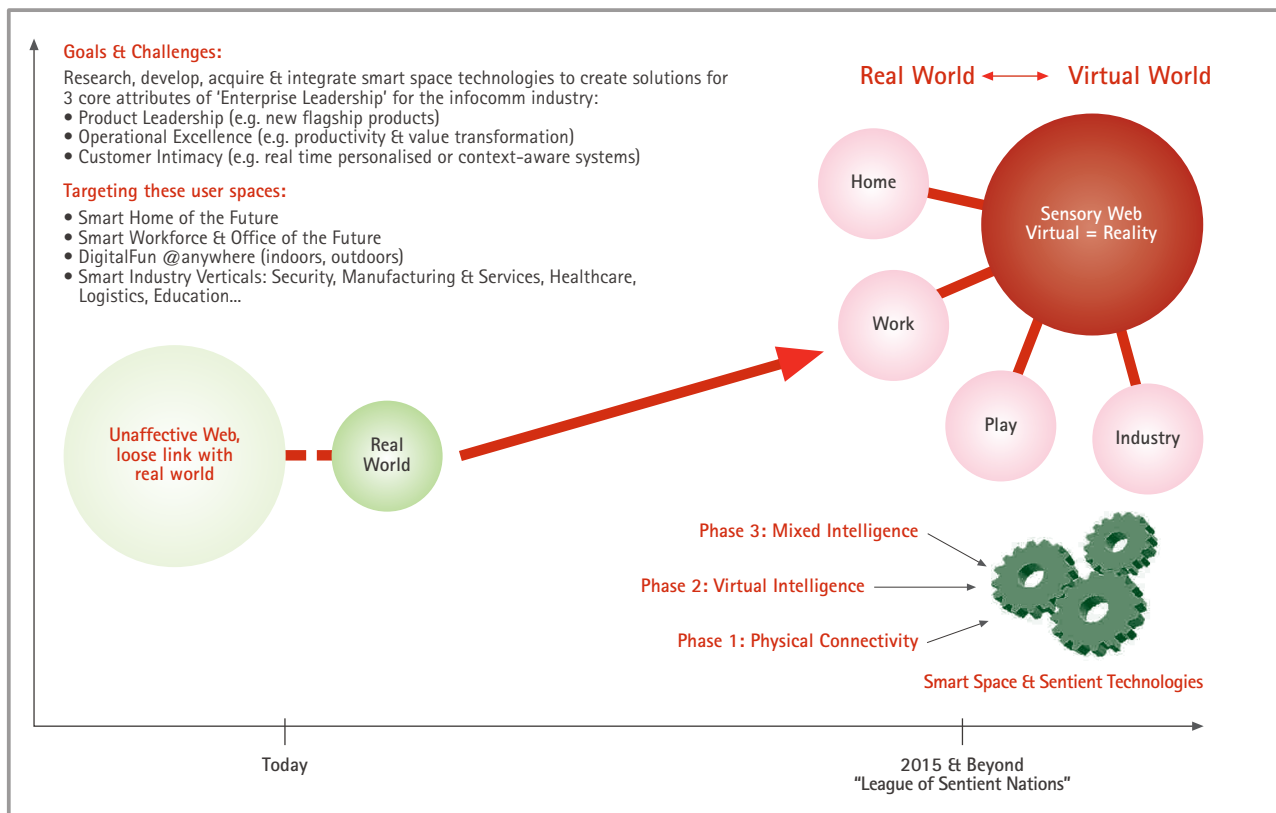


Figure 2. Roadmap Vision for Smart Sentient Spaces

In moving towards this vision, there are also many challenges that are described in this ITR5 report. Research or developmental efforts should result in tangible outputs that meet different enterprise challenges, in particular different growth strategies geared towards either new product innovation (i.e. market dominance via product leadership), or operational excellence (i.e. doing better, cheaper, faster than others), or customer intimacy (e.g. real time personalised or context-aware systems).

1.3 Global Outlook

All winds blow to the same future. Sentient space related technologies and iconic programmes are found around the world from different protagonists below:

- **From R&D:** EU-funded European programmes for IT Society like Ambient Intelligence, Disappearing Computer (e.g. Global Smart Space GLOSS in UK), EU's Bio-inspired Intelligent Information Systems (Bio-I³), MIT's Project Oxygen, Affective Computing, Internet of Things. Technical journals and papers in Omnipresent Computing, Pervasive Computing, Ubiquitous Computing, Super Senses, the Sentient Web, Embedded Smart Spaces and Invisible Computing, many laboratories named or linked to 'Smart Spaces'...

- **From Infocomm Industry:** Intel's Proactive Computing/Deep Networking, HP's Cooltown vision, Motorola's sensor programmes for Intelligence Everywhere, Philip's Connected Planet, Xerox's Calm Computing, Embedded Collaborative Computing, Collaborative Sensing, Distributed Diagnostics, Nokia's future mobile vision for Calm Computing and specialty companies on modern wireless micro-sensor products like Ember, Crossbow Technology, Sensoria, Dust Inc...

- **From Associations:** ITU's vision report on Portable Internet, IEEE's Sensor Nations and its development of sensor related standards...

- **From Governments:** Distributed Sensor Network (DSN) and Sensor Information Technology (SensIT) programmes at DARPA (Defense Advanced Research Projects Agency) in USA, SensorNet in USA, Ubiquitous Sensor Network (USN) in Korea, IPv6 Sensor Networking Consortium in Japan, and Smart Space Laboratory (by NIST, USA) and many others.

The concept of 'sentient', 'seamless', 'smart', 'invisible', 'vanishing', or 'disappearing' comes from the following trends:

- **Towards seamless Internet connectivity and configuration.** The Internet known today being just a stack of protocols may in future evolve into more efficient or alternate protocols, alongside other protocols like ad hoc sensor networking, and will be 'absorbed' into software defined cognitive wireline and wireless systems, which in turn will be embedded (hidden) in highly efficient hardware processing chips or in smart computing interfaces;

- **Disappearing PC, towards effortless and proactive man-machine-Internet interfaces.** In an article by Telecom Italia in IEEE Communications Magazine, it quoted the work of FISTERA (Foresight on Information Society Technologies in the European Research Area) which predicted the disappearance of the PC in the timeframe 2008-2010. In fact, for every PC sold, there are over 100 microprocessors sold embedded in everyday objects and IT appliances. About 7.5 billion embedded controllers were sold in 2001. Everyday objects are becoming a 'PC'. The Adidas 1 running shoe selling at US\$250 when it was first launched in Dec 2004, contains a hall-effect sensor that communicates with a 20 MHz micro CPU to measure shoe cushion compression to within 100 micrometers and to adjust the shoe's firmness at a rate of 10 000 times per second. Nokia envisions temperature sensors in phones to deduce context awareness of whether the phone holder is indoors or outdoors, and promotes calm computing as the next step from ubiquitous computing. Calm computing is a term invented by Xerox, in which humans live to live, not to compute. It is very much the same concept as Intel's vision of proactive computing.

The world in 2015 and beyond. Ericsson's Dr Frank Reichert's vision paints the year 2015 as the year of the societies of devices, or what others called the Internet of Things. These mass devices collaborate to create smart sentient spaces. IBM's Zurich Research Laboratory commented that the number of sensors and actuators connected to the Internet in just a few years will outnumber PCs, PDAs and mobile phones, and the majority of computer transactions will be due to sensors and actuators. In this era, there will be a dramatic increase in Internet value to the economy when millions or billions of computing devices are interconnected to it. This is in accordance to Metcalfe's law which symbolises the increase in a network's value by the square of number of devices connected to it. When the value of the Internet of Things increases by leaps and bounds, the infocomm industry would probably benefit most from it by the increase in demand for IT services to manage the data churned out by sensors and devices.

The rise of the Internet of Things may lead to social impacts and privacy concerns to address, but also opens up a new economic space and can change the way we live and work in the future. In ITU's Sep 2004 report on "The Portable Internet", the vision of the Internet of Things was repeated, and ITU saw the biggest opportunities in the future to lie in the convergence of wireless technologies with smart materials equipped with sensors and actuators.

Interestingly, in its next step, the Semantic Internet will break out of the virtual realm and extend into our physical world. URLs can point to anything, including physical entities. This means we can use the RDF language (resource description framework, a semantic web technology) to describe devices such as cell phones and TVs. Such devices can advertise their functionality, what they can do and how they are controlled, much like software agents. Being much more flexible than low-level schemes such as Universal Plug and Play, such a semantic approach opens up a world of exciting possibilities.

For instance, what today is called home automation requires careful configuration for appliances to work together. Semantic descriptions of device capabilities and functionality will let us achieve such automation with minimal human intervention. The first concrete steps have already been taken in this area, with work on developing a standard for describing functional capabilities of devices (such as screen sizes) and user preferences. Built on RDF, this standard by W3C is called Composite Capability/Preference Profile. The Web can in future reach out into a physical space and interacts with it autonomously, creating productive sentient spaces.

From old to new applications for 2015. From defence applications where intense R&D was carried out in the 1980's and 1990's, today's modern sensor technologies have prospered due to progress made in computing, wireless communication and sensing technologies like MEMS that were much a constraint back in the early days of R&D. We can also better find off-the-shelf products today to integrate into sensor networks that were not available back in the early days. The applications have spilled over from defence to mainstream applications in the commercial realms for building and infrastructure security, anti-terrorism, drug interdiction, smart traffic control and surveillance, air traffic control, industrial and manufacturing automation, distributed robotics, environment and habitat protection, etc. Today IT systems, products, wireless phones, biometric applications, gaming gadgets, cars, libraries, modern home living, factories, security systems, chemical and biomedical industries, as well as many other daily and industrial spaces around us are already pervaded by sensor technologies, sometimes mandated.

Imagine 2015 with smart sentient objects all around us. It could be your home mirror connected to an online wardrobe shopping service, a garden glass table with online gaming for entertainment, an animated cartoon as 'live' guide on your toilet mirror to make brushing teeth an enjoyable task for kids, or a living room wall that acts as smart ambient screen display or 'alive' with painted temperature sensors. Imagine saving millions of dollars for equipment downtime by early prevention and warning system via wireless online embedded sensors. Imagine saving lives and enhancing homeland security via sensors. Imagine monitoring and protecting the environment with sensors. Imagine automating supply chains and processes with sensors. The applications and potential opportunities are virtually unlimited for sentient spaces, and only limited by our own imagination.

The search for new business models and applications.

In Japan, the Japanese government has mandated the transition to IPv6 by 2005. Eight Japanese companies formed a consortium called the IPv6 Sensor Networking Consortium

in Jun 2003 that will promote and propose standards for sensor networks in smart homes and intelligent buildings. Their aim is to examine the possibility of creating a business out of networking electric equipment and embedded sensors in buildings, factories, home or local communities, as well as to solve relevant problems. The USA also has their national research report (EmNet) that highlighted the need to find new business and computational models for sensor networking.

What would make an impact towards 2015? In Business Week, networked micro-sensors are said to be one of the most important technologies for the 21st century. In a Forbes article, MEMS experts like Professor Clark Nguyen from the University of Michigan proclaimed, "I like to be conservative about things, but in a way, [sensor networks] could be bigger than the Internet". In Business 2.0 (May 2003), one of the six technologies² that will change the world is entitled "A Swarm of Sensors" led by the visionary Kris Pister, CEO at Dust Inc and Professor at the University of California at Berkeley (of 'Smart Dust' fame), and in his quote, "My dream is to make silicon walk." Can it really walk in future? If we draw inspiration from nature's extreme examples, the gecko can climb on any surface without the need to secrete any sticky chemicals via ridges found underneath its limbs. The ridges consist of nano-scale hair-like structure that intertwines with any surface at the molecular level, such that the gecko can hold on even to a vertical glass pane. Nanotechnology may in future allow any tiny sensor, artificial objects or robots or even humans to scale any surface. Sentient robotics can then also roam anywhere on any surface.

Many like IEEE believe that future societies will be inundated by smart wearables, disposable wearables, sensors and embedded computing devices transacting with one another, creating smart Internet spaces. Some IEEE members believe that the last step in the revolutions of communication networks lies in achieving ubiquity and sensor networks. In a 2004 IEEE Technology Survey comprising of 1038 Fellows, sensor technology, wireless and pervasive networking were also cited as technologies that will have a major societal impact over the next ten years. IEEE Jul 2004 issue described Sensor Nations, of how such technologies will transform our future living landscape, and an article on privacy issues intriguingly called "Sensors & Sensibility".

Also in Nov 2004, IEEE Spectrum magazine³ celebrated its 40th anniversary by interviewing the world's top 40 thinkers, personalities and technology movers on their insights in past and future technology innovations. In summary, the most important technology invented in the last 40 years is the integrated circuit, which gives birth to computers and enables the Internet. Technology surprises were not on

² The others being: "God's Ink-Jet" – printing human organs on demand; "Robots you can relate to" – affective computing; "The Plane that does Hong Kong and back in a day" – supersonic jet; "All Day Portable Power" – fuel cell in size of a marble; and "Electronic Paper" – computer screens as thin and flexible as paper.

³ See Nov 2004 Issue of IEEE Spectrum. The article and full transcripts are accessible to public. URL at <http://www.spectrum.ieee.org/WEBONLY/publicfeature/nov04/1104lumi.html>

specific technologies but rather at the pace of change of technologies in the past 40 years. In moving forward to the next decade, the confluences of different technologies, in particular Infocomm, Nanotechnology and Biotechnology will be important and life changing. Specific important areas of impact to society and economy include broadband wireless Internet (communication and computing applications), sensors and distributed sensing, smart embedded systems. The Internet will still be important in the next decade and IP technologies in particular will make further inroads into smart spaces, body area networks and even into our body with non invasive biological and nanotechnology-based computing. Many sentient space applications rely on the advent of wireless communication technologies, and much of future sensor hardware are based the advent of nanotechnology and MEMS for instance.

Certain luminaries in the IEEE interview transcripts also brought up related interesting topics for next decade technologies that can enhance our insights:

- **Phaedon Avouris (IBM):** "It'll be interesting to see what computing has to offer the life sciences...We'll also see more of the effect of biology, new gene therapy. But these are small, evolutionary changes. The real revolutionary changes will be in protein engineering..."
- **Gordon Bell (Microsoft):** "Wireless – whether it's low-power wireless sensor nets or ubiquitous Web Services... We've got IP in space, it'll come into the body, it goes in and around your home..."
- **Francine Berman (San Diego Supercomputer Centre):** "Data software and hardware technologies,... all of those sensors out there are giving you data..."
- **Mark Bregman (VERITAS Software Corp):** "I think it's software: embedded systems in lots of stuff. I think the biggest impact will be from small software (not big software like SAP, Oracle databases, or big operating systems). Small software – putting intelligence in your phone or your door knob – will have a big impact, and for much further than a decade out." Coincidentally, this ITR5 report talks about tiny computing based on open source, sweet spot for sensor software currently pursued by the industry.
- **Federico Capasso (Harvard University):** "quantum technology...My statement is that in the next 10 to 30 years, quantum mechanics will have an even more pervasive impact on technology, not only on communications and computing, but also on sensors... a new frontier is opening up [MEMS with quantum technology like Casimir effect]... interface between bio [neurons] and chips..."
- **Vinton Cerf (MCI):** "Nanotech...neuroelectronics... robotic devices... non invasive medical...Another thing I'm pretty convinced will happen, though it is not a difficult prediction, ... appliances will all be able to interact and connect... smart ambient environment... IPv6..."
- **John Chambers (Cisco Systems):** "... affordable broadband access... to every home and across the globe."
- **Donald Christiansen (Editor of IEEE Spectrum):** "... Technology and techniques that enable interfacing between the physical world and computers (sensors and transducers)... man-machine interface,...nanotechnology,...self diagnosing systems (IBM's autonomic computing)..."
- **Herve Galliere (Xerox):** "Nanotech in combination with MEMS [as sensor and actuator to impact the environment]..."
- **Wendy Hall (University of Southampton):** "...wireless embedded computing...the mixture of wireless and sensors, small devices...nature inspired computing, or biologically inspired computing. I do not mean bioinformatics, using computers to analyse biological data..."
- **Colin Hill (Gene Network Sciences):** "... systems biology...convergence of mathematical, computing and biological data..."
- **Herwig Kogelnik (Lucent Technologies Bell Laboratories):** "...bio/info is the future."
- **Raymond Kurzweil (Kurzweil Technologies):** "...molecular nanotechnology,... nanobots... virtual reality from within the neurological system..."
- **David Liddle (Venture Partners):** "Wireless broadband and wireless data..."
- **Tsuneo Nakahara (Sumitomo Electric):** "Technology fusion among IT, biotechnology and nanotechnology..."
- **Priscilla Nelson (National Science Foundation):** "...distributed sensing at all scales... Sensing Revolution..."
- **Sanjay Parekh (Digital Envoy):** "...nanotechnology, especially as related to energy..."
- **Rick Rashid (Microsoft Research):** "...confluence [bio/nano/IT]... natural language processing,...quantum computing..."
- **Mathukumalli Vidyasagar (Tata Consultancy Services):** "...life sciences... nanotechnology..."
- **Lotfi Zadeh (UC Berkeley, Soft Computing):** "development of question answering systems..."

Beyond 2015. By 2020, the European research report on foresight for information society technologies predicts that ambient mediated interfacing will be the norm, with first impact by the end of this decade and profound impact in the next decade. Smart space technologies include human-computer interfaces, intelligent ambient and cooperating objects, autonomous avatars (or virtual secretaries), cognitive science, real time translation, expert to layperson prototypes, etc.

Impact of Sentient Technologies

2.1 Introduction

In this chapter, we investigate the impact of moving towards sentient technologies. We would analyse the impact vis-à-vis businesses and the infocomm industry, government, society and individuals.

When Business 2.0 mentioned "Robots You Can Relate To" as one of the technologies that will change or impact the world, they are referring to machines that interact with people the way people do. This effort led by MIT's Media Lab requires breakthroughs in advanced sensors and actuators, natural language & gesture processing. Sponsors include IT companies like IBM, Intel, Nokia and Sony. The advent of robotics will enhance the smartness of sentient spaces, for instance in industrial spaces or smart toys that can relate to kids.

2.2 Impact on Businesses

Different companies are doing different programmes for sentient space technologies either as part of their key business R&D activities or are actually already selling products and solutions in smart sentient spaces.

Intel Research's vision of Proactive Computing⁴.

Non affective ubiquitous, pervasive and interactive computing are passé. According to Intel, proactive computing is a new era that will see billions of computing devices, which are tiny sensors and actuators, deeply embedded within our physical environment to manage a multitude of data.

Limitations today. Today's interactive computing still requires individuals to interact on a one-to-one basis with computers, inputting commands and waiting for responses. This mode of behaviour is not scalable, brain-bandwidth unfriendly, requires our constant intervention and is limited to a few services at any one time. Instead of extracting value out of

services, we are bogged down by interacting in the intermediate processes with the computer and network. Intel sees limitations in such an interactive computing model today, as we contend with multiple computers, from desktops and laptops to cell phones, PDAs, and a growing variety of consumer electronic devices. Infocomm advancement will be hampered by our inability to interact simultaneously with multiple embedded computing services.

The Future: from pervasive/interactive to proactive computing.

Being pervasive and interactive is not enough, computing needs to be service oriented instead of product oriented. The goal is to bring out the service value of the "Internet of Things", and is not to churn out sensors that can connect between themselves, but rather how they can talk to each other in a meaningful way and bring about useful services and optimise our brain capacity to tap on knowledge present in a networked economy. Proactive computing is one means to achieve this goal, by anticipating our needs and taking action on our behalf, so that humans will be freed to focus on higher-level functions. This is achievable via sensory devices and interfaces that detect our preferences and mood, automated agent negotiation technologies, speculative execution and machine learning. Intel Research has a roadmap on proactive computing on its website.

In this Intel Research's roadmap, smart sensors and sensor networking play a key role in Deep Networking, where sensor networks permeate our environment. It is what uniquely differentiates tomorrow from today. Sentient related technologies figure at each step of Intel Research's proactive computing programmes such as Nouvel Sensors, Deep Networking, Planetary Scale Systems, Bayesian Networks & Computational Nanovision, Machine Learning, Complex Adaptive Systems & Supply Chain Modelling. There is also a social engineering programme dedicated to empowering individuals and addressing their concerns over security and privacy.

⁴ For more information, see <http://www.intel.com/research>.

Smart Dust. The Smart Dust⁵ project, linked to University of California at Berkeley and funded by various organisations such as DARPA and Intel was started in 1997 and completed in 2001. It was led by visionary Kris Pister, CEO at Dust Inc and Professor at the University of California at Berkeley. It was about building a distributed network of tiny sensors, with computing power, wireless networking ability, independent power supply, and intended to be scattered in mass.

New computing like open source tiny operating system (TinyOS) was invented in this project. Wireless sensors can replace wired sensors, saving hundreds of thousands of dollars in downtime for many applications for example in monitoring oil or gas pipelines, or in ensuring the structural safety of buildings.

A sensor node, or Intel's mote, is a small circuitry device that consists of a sensor, micro-controller and a wireless communication unit. By 2006, the project expects 150 million motes to be shipped and ubiquitously deployed from art museums to aircraft carriers. These motes create ad hoc networks amongst themselves, transmitting data to a central server. In a typical scenario like Intel's wafer fabs, there can be up to 4000 sensors in each facility to monitor the equipment vibration for early prevention of wear and tear. This can help to avoid costly breakdowns and saving millions of dollars in downtime.

Xerox Parc. Xerox promotes calm computing concepts, whereby our computing environment and the man-machine interfaces are so intelligent that humans can now live to enjoy and not to compute. Xerox's Smart Matter Integrated Systems⁶ looks at paper-like displays, embedded reasoning, large area electronics (organic electronics), modular robotics (for robust self-configurable sensors), sensor networks and smart sensing systems.

Amongst the several sentient related programmes, the Embedded Collaborative Computing sub programme focuses on addressing fundamental problems in designing, programming, and deploying distributed sensing and diagnostic systems, both in the environment and inside machines. Xerox's work is based on the convergence of several technologies including MEMS, wireless networking, and embedded processing. Advances in these technologies have enabled the deployment of large numbers of inexpensive micro-scale sensors.

Their research is focused on two problem spaces – collaborative sensing, which deals with networks distributed across large geographical distances, and distributed diagnostics, which focuses on networks of sensors located inside machines.

Collaborative Sensing. Large-scale, distributed, sensor-rich wireless networks are designed to track physical phenomenon, including multiple moving objects such as vehicles or animals. Potential applications include traffic control, battlefield target tracking, security, and monitoring of wildlife, environmental pollutants, and infrastructures such as power and telecom grids. Scientists are exploring the problems of information processing, communication, storage, and routing in such networks, which are constrained by energy and bandwidth limitations.

Distributed Diagnostics. Sensor-rich networks that track the performance of components inside electro-mechanical machines are leading to a new generation of machines that can diagnose and repair themselves. Distributed sensors monitor multi-modal data, measuring physical attributes such as vibration, noise and electrical current. Xerox researchers are developing scalable, model-based techniques for processing the information from these distributed sensors to achieve highly distributed sense making, diagnosis, and rapid device reconfiguration and repair.

Nokia. In Nokia's Connection 2004 presentations at Helsinki, they presented their visions for research for mobile devices and applications. Amongst the technologies, most of which are essentially the same as in this report, are advanced human-computer interfaces (3D displays, flexible bistable displays, embedded temperature sensors), buddy networking, calm computing, for which sentient technologies can play a key role. Hence, many concepts we paint here for Internet applications are also applicable to the mobile space.

MIT's Internet of Things, Affective Computing⁷ and Project Oxygen⁸. As a leading research institute, Massachusetts Institute of Technology looks at massively distributed sensors in an Internet of things made up of 'Mate': virtual machine of tiny OS motes. Project Oxygen summarises aptly its intent, *"Bringing abundant computation and communication, as pervasive and free as air, naturally into people's lives."* Life in such a sentient era will be more seamlessly integrated with technologies.

MIT is a strong advocate of human-centred computation for the future, as outlined by its affective computing programme. Guardian Angel, which is MIT's service concept, paints the picture of an automated home sensory system for parents and kids. Other than embedded computing, sensors, other technologies like semantic web and metadata are also used to create smart sentient household applications.

Hewlett Packard's Cooltown. HP Labs has been working at the intersection of nomadicity, appliances, networking, and the web. In their vision of the Cooltown, HP sees a technology future where people, places, and things are first class citizens

⁵ <http://robotics.eecs.berkeley.edu/~pister/SmartDust/>

⁶ <http://www.parc.xerox.com/research/subtheme.php?subtheme=Smart+Matter+Integrated+Systems>

⁷ <http://affect.media.mit.edu/>

⁸ <http://oxygen.lcs.mit.edu/Overview.html>

of the connected world, wired and wireless – a place where e-services meet the physical world, where humans are mobile, devices and services are federated and context-aware, and everything has a web presence. Different technologies from computing, communications to sensing and embedded web systems will need to be integrated to fulfil this sentient vision of Cooltown.

ITU's "The Portable Internet". The International Telecommunications Union (ITU) has published a report on "The Portable Internet" to coincide with the Sep 2004 ITU TELECOM Asia 2004 exhibition and forum. A recurring theme found also in the report is the Internet of Things, and specific mention for technologies like sensors/actuators, smart materials, human computer interfaces, wearables, biometric sensors, RFIDs, much similar to what is advocated in this report. The next generation of portable technologies on mobile phones will carry healthcare and lifestyle sensor technologies. The Internet in future will not only be sensory, sentient in stationary installations but also portable and on-the-move.

Motorola's "Intelligence Everywhere". Motorola fuses biology, physics, music/art, semiconductor, virtual reality, affective computing into its Intelligence Everywhere vision. The e-field sensor⁹ was a collaborative development between MIT Media Lab and Motorola. The Motorola's e-field sensor detects and maps hand movements when within vicinity of the e-field. This can give rise to virtual reality applications or as a high-tech virtual desk keyboard with the chip embedded underneath the desk. It can also be used for remote control when embedded into an armchair in the living room or in a driver's seat inside a car. The imaging chip from Motorola is now enabling contactless sensing and imaging of low-level electric fields for a variety of systems and products, from automobile air bag controllers to wheelchairs.

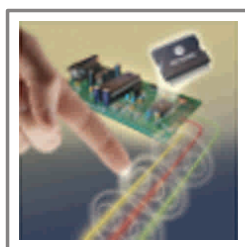


Figure 3. Motorola's e-field Sensor
Source: Motorola

European Union's Vision on Ambient Intelligence¹⁰ European research activities in IT are structured around consecutive four-year programmes, or so-called Framework Programmes (FP), and master-planned for the European Union by the

Information Society Technologies management Committee (ISTC) and its Advisory Group (ISTAG). Readers can refer to numerous technology, scenario and policy reports and presentations that can be found on the ISTAG website (in footnote). The focus of IST in its latest FP6 supported by a $\text{€}3.6$ billion funding scheme is on the future generation of technologies in which computers and networks will be integrated into the everyday environment, rendering accessible a multitude of services and applications through easy-to-use human interfaces. Conceptualised in the late 1990's, this vision of 'ambient intelligence' places the user, the individual, at the centre of future developments for an inclusive knowledge-based society for all. In essence, this again confirms our conviction that the world is moving towards sentient spaces.

EmNet in USA. The USA has a similar vision via its 'Embedded Everywhere' report for R&D directions focused on building sensor-based EmNets (Networked Systems of Embedded Computers). The report is envisioned by prestigious authorities from the National Research Council, whose elite members come from the councils of the National Academy of Sciences, the National Academy of Engineering and the Institute of Medicine. The report was also supported by DARPA and NIST, and industry experts from companies like HP, Intel, Lucent Technologies, Sensoria Corporation, Sun Microsystems and others. The report painted the R&D challenges, desired system features for these smart networked embedded systems, and identified the gaps between today's technology and tomorrow's needs, and proposed areas of focus for future development work, as well as recommendations to various government agencies.

The general direction towards Sentient Spaces or Invisible (seamless) Internet can also be found in the literature like Peter J. Denning's book entitled "The Invisible Future: The Seamless Integration of Technology into Everyday Life", summarising a roundtable dialogue of thought leaders in technology.

Philips¹¹. Like potentially other European companies participating in the EU vision of Ambient Intelligence, Philips has dedicated research resources into this area. For Philips Research, Ambient Intelligence refers to a world in which people are surrounded with electronic environments that are sensitive to their presence and responsive to their needs (via sensors, context aware agents for instance). More specifically, this means that stand-alone electronic devices will increasingly be networked and at the same time disappear into the background by being integrated into the environment.

⁹ <http://www.motorola.com/content/0,,1708,00.html>

¹⁰ <http://www.cordis.lu/ist/istag.htm>

¹¹ <http://www.research.philips.com/InfomationCenter/Global/FNewPressRelease.asp?/1ArticleId=2841&1NodeId=13>

In the following figure by Philips, it shows a living room scene, where a large holographic screen on the wall shows a lot of information, particularly on electronic commerce. At the same moment a virtual person is present taking part in the discussion.



Figure 4. Ambient Intelligence

Source: Philips

In fact, one of Philips' Ambient Intelligence programmes called Connected Planet imagines a world where our office, our car, and even our clothing could all become extensions of our digital home. Another Philips' office example is a smart design studio, allowing designers to work together on their design using a wall-size interactive display and natural interaction such as speech, gestures and tangible objects to activate steps in the design process.

Accenture's Reality Online. Sensory interfaces provide what Accenture termed as Reality Online. Using RFID tags, we can create digital identity copies of real objects into the virtual world. Using sensor capture, we can further create digital image, sound, video copies of real objects in the virtual world with multi-dimensional characteristics like temperature, pressure, velocity, colour and texture. We can even output these characteristics, like feeling the texture of goods you buy by touching a special sensor-enabled screen. Data capture and output will be coded digitally and produced instantaneously with advancement in processing power and communication technologies. New business models may emerge from this mixed virtual and real world, and services could then be made more intuitive, responsive and immersive.

Specialty Sensor Companies. There are also spin-offs from sensor R&D that resulted in commercial specialty companies like Ember, Crossbow Technology, Sensoria and Dust Inc. Crossbow Technology was voted by IEEE to be one of the ten companies to watch out for in the next ten years. Ember is another start-up that is backed by networking pioneer Bob Metcalfe and is building chips for smart dust systems. These companies produce smaller nodes from card to particle size much smaller and lighter than early generations of sensor nodes. Also while sizing down to embedded chip form,

the sensing, communication and computing functionalities are also integrated into a single entity. The power duration of such products has also advanced from hours and days to weeks and months, and eventually with new technologies, to years in the future sentient space.

Sensor Network Consortium¹². Boston University started in late 2004 the Sensor Network Consortium. Such initiatives follow the success of similar industry-academia efforts such as MIT's Auto ID Center for the promotion of RFID. The consortium initiative fosters research in sensor networks and facilitates the interaction among academia and industry as well as between industry participants. It provides an interesting mix of companies: start-ups, system integrators, users and various small and large corporations. Current members include BP International Ltd, Ember Corporation, Honeywell International, INETCO Systems Limited, Intel Corporation, Invensys Inc., L-3 Communications/Henschel, Millennial Net, Inc., Radianse Inc., Sensicast Systems, and Textron Systems.

Its mission is to promote sensor network industry growth through industry-academic collaborations. Its goals are to:

- Create a collaborative forum to drive research, development, commercialisation and adoption of sensor network technology;
- Develop strategic partnerships to access federal funding in related technology areas;
- Facilitate interactions among the academic community, industry and other selected participants who support the sensor network industry;
- Collectively enhance the visibility of all consortium participants, focusing attention on the 'intellectual and commercial capital' within the Boston area and East coast in the burgeoning space of sensor networks;
- Facilitate the development and transition of well-trained graduates to industry positions.

Conclusion – downstream impacts for infocomm businesses. Should sentient spaces packed with sensors, computing and communication devices one day be widely deployed and embedded into our environments, this will lead to a massive demand for internet traffic of higher orders of magnitudes, providing possibly the impetus for metropolitan networks to migrate to higher capacity networks. In the last mile, fibre to the home may then become a necessity than luxury.

¹² <http://www.bu.edu/systems/consortium/index.html>

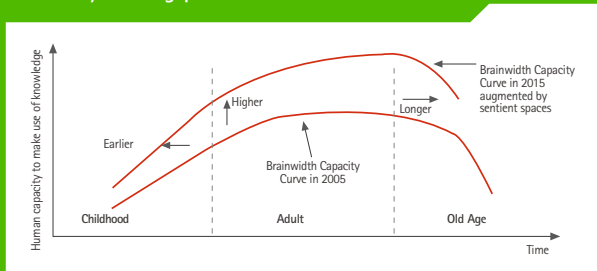
Along with this, paradigm shifts will occur with intelligence gravitating towards the edge of networks, morphing itself from the role of resource control to that of understanding of needs. Cognitive intelligence in networks, IT devices and software, and embedded sensor devices in our environment, allows better servicing of our needs via machine-assisted intuitive and proactive computing that can in turn allow service providers to execute content packaging that is critical in the economy of services (as we move away from products to services).

2.3 Impact on Government

Relevance to strategic national government concerns.

In a previous IDA internal study on "People Technologies" (technologies that empower humans to exploit digital knowledge), we noticed an emerging unsustainable trend whereby knowledge accumulation is exponentially increasing with the Internet. However, population demographic growth is lacking behind thus revealing a shortage of talents to absorb and integrate mankind's pool of knowledge, ideas and invention. Today, there are perhaps over one billion computers and 30 billion embedded processors. The Web has accumulated 8 billion pages of information. To worsen the situation, specialisation of labour, and sub specialisations of labour (example from a physician, to a radiologist, to paediatric radiologist, to a paediatric neuroradiologist) are placing even more stringent demands on specific individuals to absorb and share an exclusive domain of knowledge. We needed a team of 20 specialists and 50 nurses to operate on a pair of Siamese twins.

Figure 5. Strategic Benefits to a Talent Based Knowledge-Economy like Singapore



While machine automation may not be able to replace the roles of medical specialists or nurses, it closes the gap between global knowledge generation and a nation's ability to make use of it. Machine assisted environments, or smart spaces, advanced human-computer interfaces, faster and more accurate computer processing and mining of knowledge, automated sensor networks, learning machine agents and

programmes, can all help to boost performance in a knowledge-driven economy.

Regulatory impact. Using sensors or SensorNets in homeland security applications or other commercial applications may have implications in privacy issues in different countries. In the chemical industry, some countries have strict regulatory requirements, such as the mandate to use online measurement techniques, pH analysis using probes based on ion-selective FET and biosensors. This promotes the development of such sensors. In some cases, like BP Chemical, US\$1.2 million is saved annually when it switched to online near-infrared spectroscopy in its plant, which is much faster than conventional infra-red spectroscopy. In certain categories of vehicles, strict emission controls are done via self-check on-board diagnostics integrated with gas sensors to comply with regulatory requirements. Government regulations in construction safety, emission of toxins and others may also encourage the use of sensors.

Intellectual property protection. Governments can provide patent protection and a good intellectual property framework, which is pivotal to benefit research innovations. In a 2004 IEEE Technology Leaders Survey, an overwhelming 51% of respondents felt that established companies will lose out to start-ups in developing new technology, against 26% who do not think so, and the remaining 23% being neutral in opinion.

Developmental programmes. The government plays a key role to promote technology development, manpower training, public research support and policy formulation. Given the varied trends in business and technology, many of which are highlighted in this report, promotion agencies will have to devise plans for building ecosystems around strategic areas identified. In particular, system integrators stand to benefit from the sensor revolution, since the differentiator in future sensors will be weighted in favour of software rather than hardware. As the global market opens up, global companies will flock to emerging growth markets like Asia Pacific according to market analysis reports, and this will open up opportunities for local companies to partner foreign companies and forge alliances.

We have seen that the EU Commission dedicated €3.6 billion on a R&D programme for Ambient Intelligence, which dominates its information technology R&D priorities. Related research funded by EU Commission on Future and Emerging

Technologies include themes like Disappearing Computer, Beyond Robotics, Quantum Information Processing, Bio-I³, Autonomic Communications. These are summarised in the figure below (see original at <http://www.cordis.lu/ist/fet/areas.htm>):

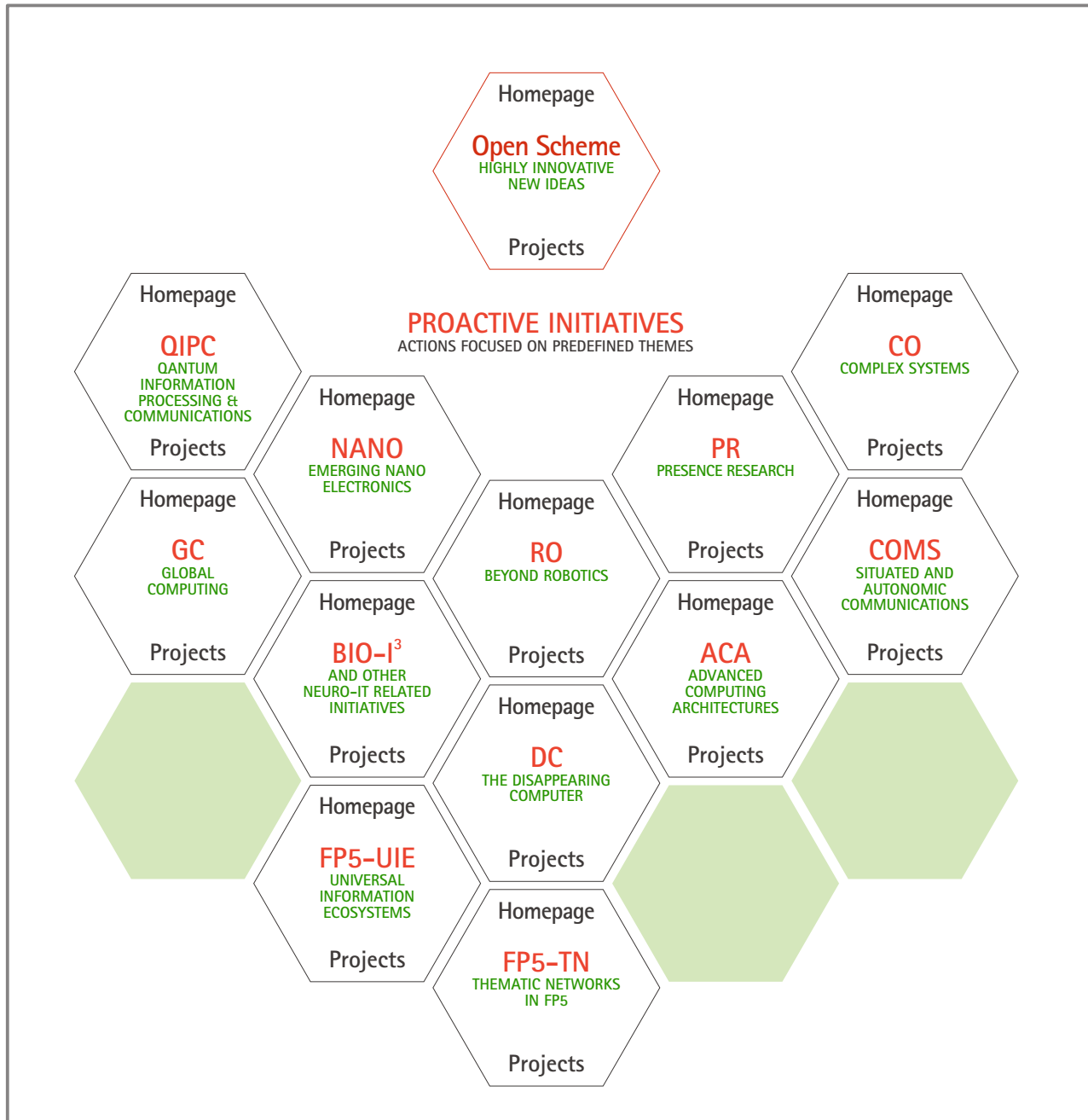


Figure 6. Information Society Technologies

Source: European Union

Nearer to home, South Korea, one of the growing markets in Asia Pacific launched a government-initiated programme called "Ubiquitous Korea" in Jun 04. It includes technologies like sensor networks, wearables, RFIDs, IPv6, embedded software and artificial intelligence services. According to their report, success of the programme would reap immense rewards for the IT sector, in particular, creating 290,000 new jobs, doubling export figures from US\$57.3 billion in 2003 to some US\$110 billion by 2007, and paving the way towards achieving US\$20,000 dollar per capita GDP by 2007. Subsequently, the Korean Ministry of National Defense (MND) also announced the vision of 'ubiquitous national defence' with a '5 Any' policy – referring to anytime, anywhere, any device, any contents and any warrior. It aims to set up a unified information system based on ubiquitous computing concepts.

The Australian Communications Authority (ACA) convened its national Vision 20/20 communication technology Masterplan in 2004. Technologies include quantum computing and cryptography, machine-to-human interaction, virtual reality, augmented reality, holographics (telepresence), RFIDs, software agents, artificial intelligence, pervasive wireless computing, open source, viral communications, etc. Many of these technologies are suitable for sentient spaces.

2.4 Impact on Society & Individuals

Today, some have noted the trend of products and services to be environment-friendly and disposable technologies can play their part to sustain the environment we live in. As movies like "The Day After Tomorrow" portray the colossal calamities of nature such as global warming, return of the ice age, air pollution, water pollution etc, we are becoming increasingly concerned about the impact of human activities on the environment we live in. Some expert authorities think that there are abundant opportunities for Singapore to create a green industry. Sentient technologies will play an important supporting role to protect, monitor, and automate many tasks that humans may not carry out efficiently in dealing with the environment. Harsh operating environments in the real world will in turn demand robust architectures, hardware and software that are resilient and adaptive to disruptions in communication breakdowns.

A quote from Fortune Magazine, dated 23 Feb 2004, wrote "A Dust Age is upon us". It referred to Smart Dust, where billions of invisible sensors are dissipated into our environment. This raises concerns for security, health and individual privacy concerns for many.

The issue around personal privacy is a complex topic and has seen lengthy dissertations in many countries without much conclusion and hardly a one-size-fits-all solution. Today with the advent of Internet, we see technical working groups in international bodies deliberating on security and privacy guidelines, and we see e-businesses adopting best practices for safeguarding privacy to win over customers. Tomorrow with the Internet of Things, who can enforce

policies in a world where an uncountable number of data transactions is taking place every second? Would there ever be a practical solution to privacy issues? Some will ponder and be left behind; others will speed forward to take advantage of the new opportunities. Nevertheless, it is also perhaps more constructive to move towards the investigation and establishment of data privacy and protection laws. Like what Fortune concluded, privacy advocates can worry about microphone or camera motes embedded into a system but those concerns won't slow this storm, and a dust age is dawning upon us.

Interestingly, technology itself is being used to counter information tapping and protect privacy. These are called by some as Privacy Enhancing Technologies (PET). While there are people who develop sensors, there are also others who are cashing in on developing technologies and software for sensors and embedded devices to counter privacy intrusion. Some can detect nearby sensors and the type of information these sensors are drawing from the owner. Others like RSA Security developed RFID Blocker Tags, which work by 'spamming' any unauthorised reader from sniffing. There is indeed an intricate web of complexity between embedded technologies, convenience and privacy.

There are many international organisations that promote and document good privacy guidelines and policy recommendations. For example, the OECD Working Party on Information Security and Privacy (WPISP) promotes an internationally coordinated approach to policy making in security and protection of privacy and personal data. It also maintains an inventory of PETs. More information can be found on their website at http://www.oecd.org/document/49/0,2340,en_2649_33703_19216241_1_1_1_1,00.html

Reports from the Computer Science Corporation's Leading Edge Forum also highlighted other impact to individuals related to technologies in this report, including:

- **Becoming cyborgs.** Computing, biotechnology and robotics can create a world in which humans may be a rare breed.
- **Creating a sixth sense.** When computers become embedded, cheap, abundant and wearable, they will provide the knowledge, reasoning and sensing to form a "sixth sense".

On the positive side, we should also look at the application opportunities that impact society and individuals. There are many sentient space application scenarios possible. However, we list of some the key ones below for illustration.

- **Security is an emerging driving force for sentient technologies.** Security will remain a key application area in the future, be it for automobile security, parks and environmental security, industrial & personnel security, building and structural security, healthcare security, military defence, border control in anti-terrorism, port and cargo security, or in smart home security monitoring for elderly,

physically challenged or kids. Anti-terrorism will be a long-term challenge to many countries, be it in the real world or in cyber space. To provide security monitoring and protection, many of these applications require intimate knowledge of abnormal physical environment changes and human behaviours. This is where smart space technologies like sensors can come in. Sensor networks can be used to monitor the structural safety of buildings and construction works, tunnels and bridges, in fire fighting (sensors predict fire paths) and even in drug interdiction systems.

Healthcare Security. Used in healthcare security, sensor networks can help in early detection of health epidemics in mass public places, buildings and air-con networks to detect flu strains or new strains. Combined with smart software and IT networks in a sentient space, we can pinpoint viral zones the moment they appear and can also be integrated with other healthcare systems like hospital reports, school absentee lists and clinic alerts. We may then use WebServices to integrate databases in disparate locations.

Area Security. In parks security, or similar systems for homes, factories, protected areas like in ports of entry, wireless RF sensor security system solutions from organisations like Lawrence Livermore National Laboratory (HIPPROTECT Sensor System) demonstrates the usefulness of wireless sensor networks comprising of multiple sensor technologies. In the example below, multiple low-power, battery-operated personnel and vehicle detecting sensors are designed for protection of park and archaeological sites; sensors communicate by wireless RF data links to a central system that relays alarms by way of cellular or RF communication to a police or park headquarters. Intrusion-detection sensors include a low-power, high-sensitivity magnetometer for detection of vehicles and ferrous tools, a seismic sensor for footstep and vehicle detection, and passive infrared motion-detecting sensors. The solution was developed with commercially available components along with in-house low-power magnetometer and low-power microprocessor-based data-acquisition and data-processing modules.

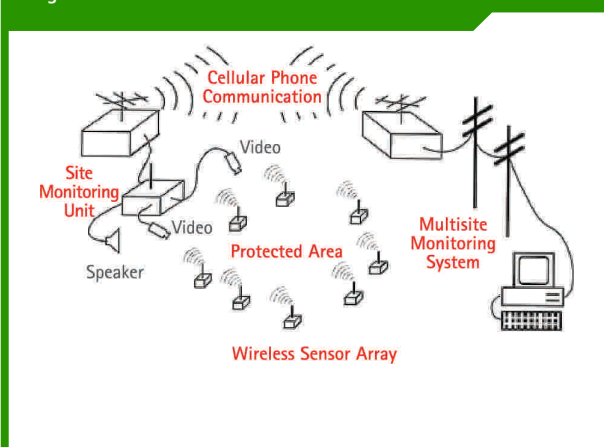
Homeland Security. In homeland and defence security, new sensor technologies include inexpensive microarrays of DNA sensors on a chip that can detect multiple pathogens, such as anthrax and smallpox. Acoustic sensors can use sound waves to determine the chemical composition of materials in closed containers for port security. Portable handheld radiation detectors are now commercially produced and deployed in homeland security activities.

In the USA, the government and industry are linking sensor and mass spectrometry technologies, wireless and wired networking, meteorological instruments, remote telemetry, relational databases, web service interfaces, Java technologies and computer modelling to build SensorNet (<http://www.sensornet.gov/>). It is a nationwide incident management system for homeland security for near-real-time detection, identification, and assessment of chemical, biological, radiological, nuclear, and explosive (CBRNE) threats. The goal of SensorNet is to bring together and coordinate all necessary knowledge and response information quickly and effectively. This will be done by providing a common data highway for the processing and dissemination of data from CBRNE, meteorological, video and other sensors in order to provide near-real-time information (e.g. nature, severity, likely dispersion of harmful agents) to emergency management decision makers and first responders. Infocomm partners include Sprint, Verizon and Oracle. Open standards are used in this initiative, like IEEE P1541, XML, and the platform nodes operate with a customized Linux distribution and agent software for monitoring sensor data.

The National Institute of Standards and Technology (NIST) is also developing Web-based technologies for integrating sensors, real-time video, smart tags and embedded microprocessor devices in a future distributed information-gathering and interactive communications system for field deployment by first responders.

In homeland border security, biometric sensors will see worldwide deployment to the populace in the next few years due to the rise in terrorism threats starting with biometric passports for border control and travel facilitation, with billions of dollars in total expected to be budgeted worldwide for such implementations. Together with this growth, software operating systems, system integration services, distributed data acquisition, mining and analysis software, microprocessor chips, cryptographic products (like RSA and elliptic curve products), ISO/IEC 14443 contactless smart chips and readers, will also see a strong potential for growth. The demand will also drive new technology innovation and standardisation in areas such as embedded biometrics on-card matching, integrated fingerprint sensors on smart cards (combats effectively both security and privacy issues). The global adoption of such biometric sensor systems will further drive downwards the current decreasing cost trend for sensors.

Figure 7: Wireless Area Protection



Source: Lawrence Livermore National Laboratory

Building Security. Tiny sensors and wireless networks make it possible for civil engineers to study the process of damage to structures (building, bridge, ships and air-planes) by various sources such as vibration and wind. Such an application may be very useful to Singapore. The USA and Europe have launched various research programs in this area. A typical application such as that by Los Alamos National Laboratory can be found at: http://www.lanl.gov/projects/damage_id/Complete_Description.htm.

Environment Security. In light of the disastrous Asian earthquake and tsunami in end 2004 killing an unprecedented number of victims, sensors can be applied to coastal and marine monitoring applications as well, as commonly practised by countries with long sea coasts. Recently, Neptune – an acronym for North-East Pacific Time-Series Networked Experiment – completed in Canada and the USA 3000 kilometres of fibre-optic cable and power lines buried three kilometres under the ocean floor to monitor the entire Juan de Fuca tectonic plate running from Vancouver to Oregon. Sensors and instruments will measure everything from currents to fluids in the seabed to tremors on the sea floor. Robotic submersibles will shuttle the area to perform experiments on command, docking themselves at underwater power stations when they are done.

- **Smart IT applications in lifestyle, gaming or work spaces.** Today in Munich, taxi meters are displayed on the rear view mirror like in the below illustration:



Tomorrow somewhere in a smart home of the future, Philips will transform into mass consumer products, the same technology concept from a coloured text style above (think SMS) into a fully embedded animation (think transition to MMS/live video). In fact, Philips would have commercialised the mirror TV called MiraVision debuting at about S\$5,000 at end 2004, which is a 23-inch LCD that acts as both a mirror using unique polarised film technology, and a high-resolution LCD TV. The product can change its frame style and colour to suit any décor in the home, and also boosts a FM radio capability and

the ability to be connected to the computer for both work and play. The following picture shows this concept:

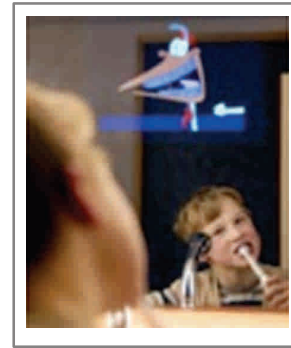


Figure 8. Personal Health Coach for Children
Source: Philips

In this above example, sentient systems using embedded sensors with an artistic tint of creative media can make our lives and learning more entertaining. The same animation shown here can in future be hyperlinked via voice, touch or eye-movement control commands to relevant Internet services that offer further creative learning packages and commercial shopping. Such examples are the next step beyond just sensors for HVAC & Building Control (Heating, Ventilation and Air-Conditioning).

Furthermore, nanotechnology can create a mirror display that is coated with nanoscale materials to prevent it from steaming up, unlike conventional mirrors, so that it stays clear. This has been demonstrated by Onid Technology Corp in Taiwan's Nanotech 2004 show in Sep 2004. In fact, the role of nanotechnology here is a necessity than luxury, because with it, such an infocomm-centric application would have not been practical for household sentient spaces. With the many wonders and future unknowns that nanotechnology can bring about, we are just seeing the tip of the iceberg today about the creative and practical confluences of different disciplines in particular within biotechnology, infocomm and nanotechnology.

Other than smart home living applications, we can also create sentient spaces in the areas of:

- smart and lively education spaces (e.g. embedded mixed reality in books);
- mixed reality tourism (for indoor museum visits or outdoor historical narration);
- creative entertainment spaces (e.g. outdoor networked gaming in mixed reality);
- smart offices (e.g. BMW and HP's wireless office-on-wheels)...

In fact, the automotive electronics space itself is worth US\$81 billion in 2000. We would find more infocomm technologies in the smart car of the future, such as sensors and wireless networking, and software services to the car. BMW and Hewlett Packard have plans for a wireless office concept on wheels. Smart sensors built into vehicular structures can also initiate changes to the structural characteristics of the vehicle upon electrical, thermal or impact stimuli. Many technologies will have to come together to make sentient spaces a mass reality.

- **Meeting the healthcare challenges for the aged and physically challenged.** One of the major challenges in future global demographics concerns greying populations especially in advanced economies like Singapore. Sensors and RFIDs can be designed into a sentient space to fit specific needs of certain segments of the population, such as to take care of elderly living alone and for the physically challenged.

Healthcare for elderly. To improve healthcare for the elderly, caregivers can receive data via the Internet from RFID readers which can monitor seniors' daily activities by recording which tagged items they have picked up, and when. By comparing real-time data with a record of an individual's normal daily routine, caregivers can easily spot any significant changes. Changes in an individual's daily routine often signal the onset of illness and cognitive decline, according to physicians and experts on aging. Such a new system like Intel's Caregiver's Assistant and Georgia Tech's Memory Mirror, will also ensure that forgetful seniors take their medication on time and stick to their prescribed diets. The Caregiver's Assistant automatically fills out a daily activities form, which is normally completed by caregivers for the elderly when they make home visits.

IEEE published in Dec 2004 a cover story entitled 'Managing care through the air', whereby growing old in a wireless world will mean not just keeping our bodies healthy but keeping it online. As the world is about to see in future a more aged population, aging technologies that keep this population healthy with lower costs would be crucial, and preventive healthcare would be the way to go. Wireless sensor technologies will drive the development of smart applications for this purpose, from wireless remote monitoring, to prevention of disease (some of which like Parkinson's disease can only be diagnosed through behavioural changes that begin very subtly and are not noticed by human observations until 5 to 10 years late. Sensors and smart people-centric software in sentient spaces can help to monitor such subtle cognitive decline and changes in elderly behaviours).

In 2002, companies like General Electric, Hewlett Packard, Honeywell and Intel teamed up to develop such technologies in the Centre for Aging Services Technologies (CAST) based in Washington. This wireless networked version is still in prototyping stage. A wired home version of technologies for home elderly care is already commercially available by companies like Living Independently Group Inc based in New York. Other healthcare monitoring projects include remote heart monitoring systems from companies like CardioNet, Medtronic and Biotronik. These systems are often also linked to a healthcare network that doctors can access.

Well-being for the physically challenged. Many physically challenged individuals will require various sensing technologies to get by daily routines. What one lacks in a sensing ability (e.g. sight, touch, hearing...) may be machine assisted by a suitable type of sensor solution. Smarter, networked wireless sensors that are online can come in handy for the physically challenged in emergency scenarios or simply to get assistance.

Preventive and personalised healthcare. Paul Saffo predicted that we will see in 2008 the world's first targeted nanomedicine on prostate cancer, with nanotechnology-enabled drug dispenser that releases the drug when tumour-specific proteins are detected. The development of biosensors, nanotechnology, non-invasive biomedical computing (DNA computer enabled drugs) can provide personalised monitoring of healthcare. Today, a sensor equipped jacket worn by a baby can also help to prevent Sudden Infant Death Syndrome (SIDS) by monitoring the vital signs of the baby.

Even mobile phone evolutions by LG Electronics (new KP8400 model) include sophisticated diabetes care phones which monitor the owners' diabetes or obesity any time and anywhere. The phone is equipped with a microchip sensor on the battery pack, and can measure the human body's glucose levels. The reading can be uploaded into an online database. The phone is co-developed with health care equipment company Healthpia. It will sell at about US\$380 in Korea. There are also plans to commercialise diet phones containing sensors which can measure human-body fat and beauty phones which will be incorporated with a massaging function and a gauge function for skin humidity level.

Japan's NTT DoCoMo handset (F672i - Raku Raku PHONE III) is equipped with a pedometer function integrated with emailing system to combat obesity. There are also today Internet portal services for personalised healthcare monitoring. Combined with these mobile services enabled by advanced miniaturised biosensors, we can envisage a different world of preventive healthcare everywhere, anytime.

- **Meeting the challenges of manpower scarcity.**

Manpower in Singapore is precious. In Singapore, simple motion sensors coupled with RFID tags, have produced automated test stations that can machine speak, count, do accurate timing and give reminders, and being networked together, also provide online real time result query via kiosk in IPPT for NSmen (example in Bedok Camp). This simple illustration shows how a smart system like this has replaced tedious daily tasks, reducing downtime (less queuing, less waiting), increase productivity (immediate computation of IPPT results, immediate credit of monetary awards), providing convenience through automation, and reducing the need for manpower in a human capital precious city like Singapore, allowing humans to focus on the softer side of tasks that machines cannot undertake.

- **Other sensor applications for building sentient spaces.**

From process control, environmental protection, waste classification and management, counterfeiting prevention, hazardous material management, habitat monitoring, protection of endangered species, food contamination control, to aerospace, manufacturing, packaging, logistics, chemicals, next generation intelligent transport and traffic management systems and the list goes on, sensors can indeed apply to many scenarios to bring about network - centric automation, as well as online real time data management and distributed intelligence for sentient spaces.

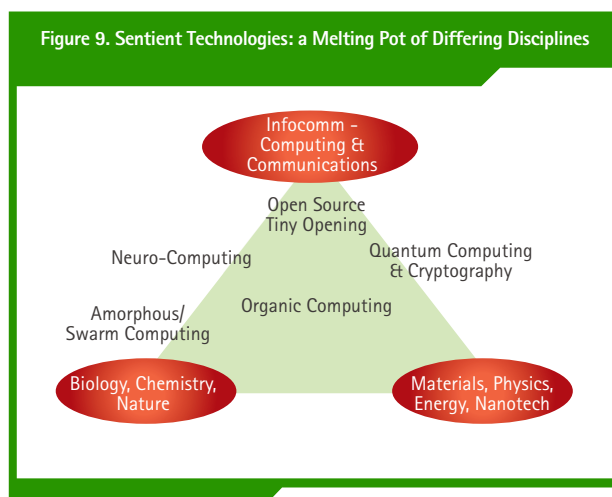
Technology and Standards Development

3.1 Introduction

Software applications, system integration and intelligence are important to smart sentient spaces. Key advances in nanotechnology and smart hardware will form a robust foundation to revolutionising embedded systems and device capability. The confluence of smart materials, energy and infocomm will also be pivotal in improving the much needed power source for embedded systems in smart spaces, especially for mobile devices and sensors. Communication technologies are also very fundamental to connectivity in sentient spaces.

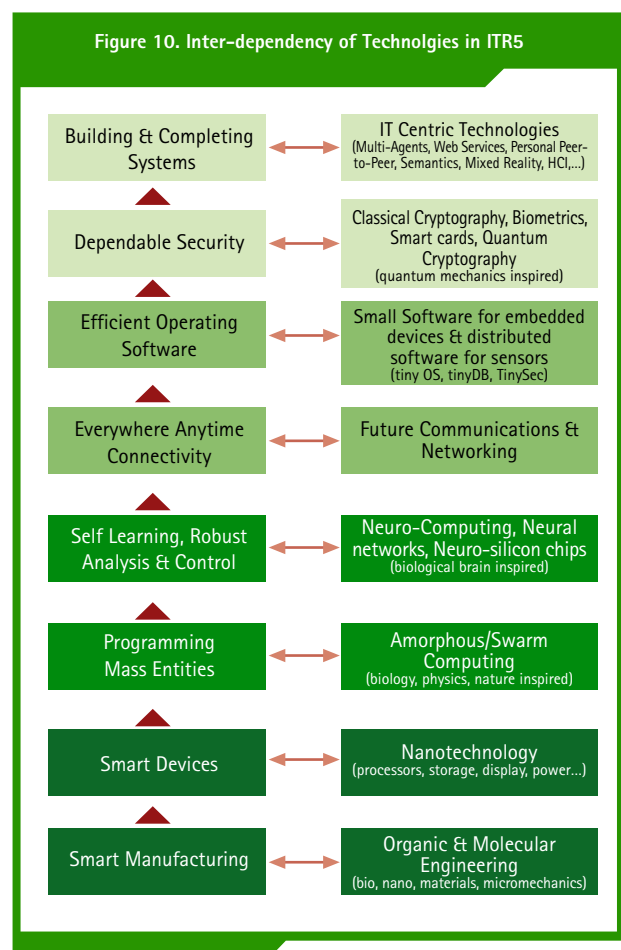
In the research arena, we are seeing the creation of new software and computing paradigms suitable for cooperative mass sensors, new IP connectivity protocols for sensor networks, smart hardware with smart materials and organic engineering thanks to the advent of biotechnology and nanotechnology. In many cases, we witnessed a trend in research efforts to adopt a multi-disciplinary approach in search of breakthrough. Even unconventional science and engineering techniques are sought, from social engineering to nature inspired concepts like botanical science and biological systems in order to create smart sentient spaces.

Figure 9. Sentient Technologies: a Melting Pot of Differing Disciplines



We describe below a framework to summarise the inter-dependency of technologies for building sentient spaces. These technologies comprise of those from computing, communications, distributed sensing and embedded systems. The right column shows outstanding technologies used or researched upon today to fulfil the functions on the left column. Most of them are disruptive in nature.

Figure 10. Inter-dependency of Technologies in ITR5



Technologies described in the track on 'Computing Revolutions with Nano & Bio':

- Starting from the basics, manufacturing can be made smarter with molecular self assembly techniques. The self-assembly process at room temperature by DNA and proteins using microbes could replace the much costlier process of making semiconductor circuitry today. Investments from the US Army, universities, companies from Aerospace Corp, Dupont to IBM are going into bio-inspired self-assembly for use in areas like future sensors, displays, magnetic storage devices, energy production and information processing.
- At the device level, basic functions of processing, storage, display and power can be revolutionised by nanotechnology. Nanoscale molecular electronics has the potential to perform better than pure polymer electronics which had not been able to produce enough gain. Nanotechnology will have a wide impact over many vertical industries and applications.
- Having a mass of computing and communication devices working in a sentient space to fulfil some system level mission would require new programming algorithms like swarm computing or amorphous computing. Such a programming paradigm aims to develop an intelligent goal oriented software that is network self-adaptable to unanticipated changes and using small inexpensive drones or unmanned robotic entities. This is suitable when we are deploying for example mass sensor-enabled entities for a particular application and mission. Even back to the device and manufacturing level, amorphous computing can be used to build and programme living cells to achieve conventional IT functionalities. Research in this area looks at inventing new programming paradigms, languages, and algorithms for controlling amorphous computing agents, as well as to investigate prototypes, both in traditional silicon technology and in molecular biology. Work includes the engineering of mix and match genetic components that can give added functionalities like signal and control, sensing and actuating, and communication.
- Neuro-computing or neural networks contribute to the cause of creating autonomous self-learning and analytic systems in smart spaces. Neural networks are used to analyse odours in electronic sensors for industrial and medical purposes. This can be used to tell the freshness of perishables and raw ingredients, or to detect venous ulcer infection. CET Technologies in Singapore has a patented cetrac™ Traffic Management System that is based

on neural networks. The system uses advanced image-processing techniques and traffic engineering know-how to process and analyse 'live' video signals and GPS-based traffic information. Furthermore, a living neural network of 25000 rat cortical brain cells was grown by University of Florida on a 1.6 mm² silicon chip. In a test application, the neural network learned how to stabilise the F-22 military fighter plane and was able to fly the plane 'true' in about 15 minutes even under simulated hurricane wind forces. It was noticed that the neuron cells sent out feelers to see what other neurons are nearby and then within 15 minutes, the cells started to self organise into an interconnected network that works towards stabilising the plane.

Technologies described in the track on 'Communications in the Future':

- Be it for devices, mass sensors, intelligent neural network systems, or in fact, any computing device in a smart space, communication and network connectivity is needed for building useful systems. Computing components in smart sentient space system can interact and communicate with each other via wireline or wireless connectivity. In this track, we will describe developments in future communication technologies.

Technologies described in this track on 'Sentient Technologies':

Finally, we have to look at the system perspective to see how we can actually build deployable and secure systems in a sentient space, and what other technology elements are still missing from the above mentioned.

- Software applications would be one obvious area. Devices, mass sensor entities, intelligent systems are not operational, and cannot be connected without having any software application or operating system running inside them. Enterprise software are useful for big systems, data virtualisation and can find usage in sentient spaces. One revolution will however come from small software. This is because small embedded devices or thin computing interfaces cannot host conventional big software, due to resource limitations and power limitation. Hence, embedded operating software like tiny open source computing for operating system, tiny database, tiny security in devices will emerge. Furthermore, there is potential for software growth in managing and processing distributed data in highly networked sentient spaces between diverse computing and embedded devices.

- With increasing security threats both in physical and cyber space, we need more dependable security technologies for sentient systems to work round the clock without being compromised or attacked causing costly downtimes. Classical cryptography like Public Key Infrastructure, encryption technologies, intrusion detection systems, firewalls, virus protection software, smart cards, RFIDs, biometrics will be important to future sentient spaces. Yet, one revolution is emerging from non classical cryptography, which is quantum cryptography. While quantum computers are still a faraway vision, quantum cryptography is already commercialised but not yet widespread. Towards 2015, such network security systems may have a role to play in highly secure sentient spaces, especially in security and financial applications.
- Finally, when we examine the deployment issues of sentient spaces, we will realise that many project installations will require also other technologies, mostly from the Infocomm space to plug missing gaps and make complete practical end-to-end systems. For example, SensorNet for a nationwide sentient security system in the USA uses a host of different technologies, ranging from video sensors, mass spectrometry technologies, wireless and wired networking, meteorological instruments, remote telemetry, relational databases, web service interfaces, Java technologies, computer modelling, Linux clusters, agent software, semantics like XML. In other applications, we may need mixed reality interfaces, embedded data technologies on physical objects, location based services, peer-to-peer software, social software and smart wearables. While we are not able to anticipate what a particular future sentient space application may need for operational deployment, we try to describe as many interesting technologies as possible in this track that can lend themselves to sentient spaces.

The following sections will now focus only on the technologies described in the track of 'Sentient Technologies'. For other technologies, please refer to the detailed respective tracks in this roadmap report.

3.2 Embedded Data Technologies (EDT)

We have mentioned about the relative immaturity of human computer interfaces (HCI) to cope with the progress made in the area of hardware, software computing and communication technologies. One of the key innovations in past decades in HCI is the Graphical User Interface (GUI) that became widespread with the advent of home computers. We are used to navigation, command and control on a

computer screen via the manipulation of the mouse for pointing at and clicking on icons, for drag-and-drop, for selecting in pop-up menus. Similarly, we use the stylus for navigating on a PDA screen.

How can we provide a convenient and intuitive user experience in the real world to manipulate physical objects in a similar 'GUI' manner? Can we embed information or knowledge, relationships, actionable commands or hyperlinks to physical objects to transform them into 'living' smart machine readable objects?

The solution lies in Embedded Data Technologies (EDT). Xerox terms these as Printed Embedded Data Graphical User Interfaces (PEDGUIs). These technologies imprint individual customisable machine readable codes on any object that can then be captured by scanning or camera devices (e.g. handphones, sensor systems) for decoding to interpret the embedded data to automatically execute various forms of interaction. Types of information can include for instance:

- object identifier (e.g. RFID and barcodes are simple forms of EDT);
- context and relationship information;
- action and instruction codes;
- digital pointers (like urls, hyperlinks, network paths, links to other resources, e.g. circular codes imprinted on posters indicate product-related urls and work well with handphone cameras without having to orientate the handphone in a particular direction to read the codes unlike horizontal barcodes);
- object position and orientation in real and virtual spaces;
- content information (e.g. portable data files).

With the above expanded capability, these technologies provide more than just identity tagging functionality. They provide structured data information (e.g. a semantic XML description of object) and action command links to seemingly unstructured objects in our real chaotic world, and hence allow machine to machine automation. PEDGUIs generalise the user interaction domain to objects found in the real world such as on printed documents (forms, memos, books, catalogs, etc), as well as intangible images like projections on a wall, and active computer displays.

There are different companies dealing with EDTs. Xerox sells Dataglyph solutions with much higher data density than ordinary barcodes and 2D barcodes. It can make form filling and processing, the handling of physical paper documents a breeze.

AirClic, Connect Things, Motorola and Symbol Technologies partnered in a half-billion-dollar venture to introduce scanning technology into wireless devices. Digital Convergence looks at using conventional barcodes as a means to link advertisements and marked products to vendor web pages. Digimarc's pictorial watermarking technology is also used for magazine ad linking via camera. Sony's Computer Science Laboratory researches on embedded data marking for identification and registration in 3D spaces with applications for augmented and augmentable reality such as:

- **InfoPoint**, a universal handheld device for remote command of various internet and non-internet appliances. Its functionality changes accordingly to the appliance in question after it recognises the latter via a visual ID marker. More importantly, it supports classical 'point-and-click' or 'drag-and-drop' actions in the physical space for enabling information exchange between these appliances;
- **Navicam**, a video device that detects colour-coded IDs in real environments and displays situation sensitive information on its video screen;
- **Pick-and-drop interfaces**. A user can select or create text on a PDA and pick-and-drop it at the desired location on a whiteboard. The data is then transferred through the network and displayed accordingly. Hence, we pick and place digital data just like we do with physical objects (e.g. post-its).

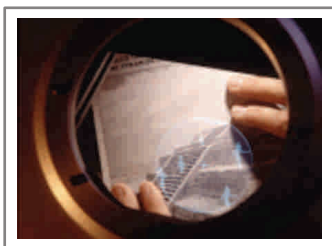


Figure 11. Glyph-O-Scope

Source : Xerox

Xerox's Glyph-O-Scope magic lens invention allows augmented reality applications. It was invented originally for use in interactive museum exhibits. The device resembles a large magnifying glass mounted over a table surface. After placing a document printed with embedded data under the scope's view, the user sees a computer generated image (generated from the embedded data) overlaid onto the physical image on the document. The technology could be extended into any real world implementation of a smart space augmented by virtual reality in other form factor.

3.3 Human-Computer Interfaces (HCI)

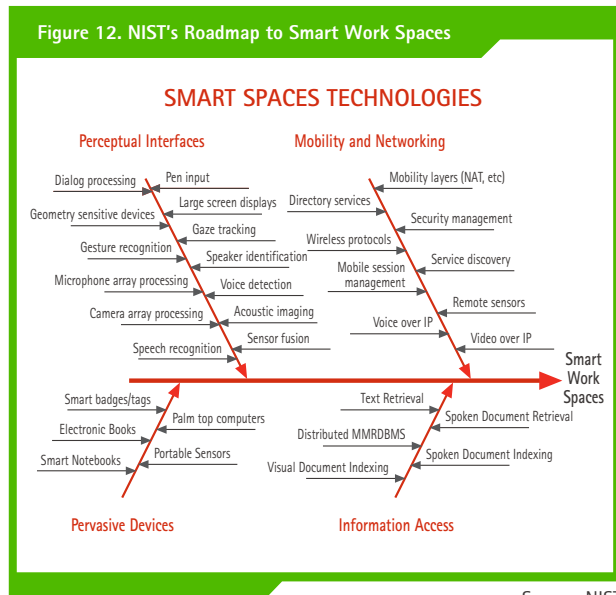
There are also many other types of HCI technologies in the conventional sense of interaction with different human senses: sight, hearing, smell, voice, touch and even brain thoughts.

Examples of such HCI computing technologies are:

- 3D capture;
- 3D displays and holograms;
- biometrics;
- digital ink;
- linguistic and expert to layperson translators;
- gesture recognisers;
- handwriting recognition;
- haptic interfaces (like ipod's touch sensors);
- virtual keyboard projection onto any surface (e.g. i.Tech, Virtual Devices);
- freedom to type anywhere with sensor and AI enabled touch-typist gadgets (e.g. Senseboard);
- breath input for pointing and navigation applications;
- robotic toys that are interactive with kids – can also be connected with GPS, to the internet and used for advertising, purchase discounts...
- lip movement recognisers;
- multi-modal capture/output and fusion;
- odour sensors;
- optical sensors;
- voice browser;
- speech to text, text to speech interfaces...

In USA, the National Institute of Standards and Technology (NIST) hosts a Smart Space Laboratory (www.nist.gov/smartspace) in which we can also see many HCI related technologies as below:

Figure 12. NIST's Roadmap to Smart Work Spaces



The majority of technologies in this HCI cluster can yield promising benefits in the short term, while some may need 5-10 years more of development and maturity. Digital ink is one example of a technology that Gartner deems to be entering the Plateau of Productivity in 5-10 years' time.

Digital ink technology is a paper-like thin film display that functions like our daily newspapers but it is formed by embedded tiny electronics that can host changing contents in different colours, in text, image or even videos. Hence, we can imagine a future whereby we do not need to throw away our newspapers, but contents will be transmitted wirelessly to our digital ink newspapers and even updated in real time. Xerox's Smart Matter Integrated Systems programme looks into such developments. While the technology may reach its productivity level in the medium term, Gartner also sees its first commercial applications in mobile devices within the next 2-3 years, because of its advantage in low power consumption. Other applications may be in retail signage and product packaging.

Keyboard interfaces are seeing new products. One from Senseboard Technologies involves typing on a virtual air keyboard, requiring sensor technologies such as gyroscopes or muscle sensing rubber pads. There are also other cheaper and practical technologies based on image sensing such as Virtual Devices' Virtual Keyboard meant for PDAs and mobile handsets. This is a compact flashlight projecting a keyboard image on any surface and

allows users to type on the image while tracking the location of their fingers. Similarly, i.Tech is sold in Singapore for S\$338 and claims to be the world's first Bluetooth enabled virtual keyboard that can be projected onto any surface, and connects to PDAs, handphones, laptops and PCs, and typing is even accompanied by tapping sounds.

Voice technology is widely used in call centres and automated phone services. Voice commands are also used in mobile devices. Speech recognition desktop products are also available to translate our speech into text. In 2003, the speech recognition market was worth \$119.6 million, according to Gartner. The leading vendors in 2003 were ScanSoft and Nuance Communications, which together held over 75 percent of the market. Voice biometrics is however still relatively immature both in technology and standards development compared to other biometrics like facial recognition, iris recognition or fingerprint recognition. Natural language processing and real time language translation for mobile applications are still relatively immature.

Biometrics authentication in user interfaces has been given an accelerated move towards maturity and wide deployment by applications in homeland security. Strong candidates for growth are facial, iris and fingerprint biometrics, which are amongst the more accurate and faster technologies, with better maturity in standards.

In particular, iris technology is amongst the most accurate. Future directions will see iris-on-the-move non invasive products. This will herald a new age of precise and fast biometric identification and recognition at a distance and with the person on-the-move (non stationary), that can be applied in various scenarios, such as for greatly enhancing processing time for authentication and payment applications. "Iris-On-The-Move" (IOM) is invented by Sarnoff (formerly known as RCA Laboratories), which is a 500 R&D strong organisation with the majority of staff having two and more PhDs. The organisation primarily serves the US government agencies and does R&D on multi-disciplines. The technology of iris scanning was invented by Sarnoff who then sold the invention to Iridian. Sarnoff has now gone a step further and successfully demonstrated the capability of performing iris detection, scanning and comparison against an enrolled database at an object distance of two metres. This was achieved without the person in a stationary position. Thus the name was coined "Iris-On-the-Move". The person also does not need to remove his glasses. This capability was even tested up to a distance of 10m. Interestingly, the ability to perform this was derived from the military technology used on flying UAVs (unmanned aerial vehicles) tracking ground moving targets – another proof point that military inventions will contribute strongly to future inventions.

The International Biometric Group (www.biometricgroup.com) provides some market data on biometric technologies, in particular the revenue growth potential and market share of each biometric technology (see website). Total biometric revenues are projected to grow from US\$719 million in 2003 to US\$4639 million in 2008. Fingerprint (48%) followed by face technologies (12%) are currently enjoying majority market share, accounting together for 60% of the entire market.

Another area of research is accurate multi-modal fusion of biometrics. Similarly, multi-modal fusion of different HCI modes also opens up more convenience to users to suit different or more demanding application scenarios. Depending on device capabilities, context of application, user handicaps if any, we may need to use one or another HCI. Hence, multi-modal fusion and switching allows both accuracy and flexibility, but is of course more costly too and might not be practical for all.

3.4 Location Based Services

We have covered in previous roadmap reports in our ITR series different location technologies from GPS to network assisted location methods, mobile wireless applications, standards for mobile services such as OSA/Parlay applicable to location based services. Hence we would not repeat them here. In brief, these are common types of location technologies:

- Directional methods such as Angle of Arrival method (AOA);
- Time based methods such as Time Difference of Arrival (TDOA);
- Global Positioning System (GPS);
- Network-assisted GPS;
- Cell of Origin (COO);
- Enhanced Signal Strength (ESS);
- Location fingerprinting.

Location sensing and tracking is critical to building smart spaces. Many of the above are outdoor applicable technologies. In a smart space that is indoors, technologies like ZigBee and UWB will play a greater role. UbiSense's UWB tags for example can pinpoint the user's location within 15cm accuracy, enough to differentiate if a person is on a particular floor inside a building and also fairly usable inside a room for most applications.

In Intel's programme for Proactive Computing – Deep Networking, there is also a sub programme for Precision Location. It aims to develop standardized protocol stacks for location-aware ubiquitous computing, in particular to resolve issues with location information loss when fusing multiple different sensor technologies for these deeply embedded sensors in our physical environment.

3.5 Personal Peer To Peer

Virtualisation technologies like peer to peer (P2P), Web Services and grid are key trends for future Internet

applications. In our third roadmap report (Release Feb 2002) on Next Generation Internet Applications (NGIA), we had covered these technologies, including P2P technologies.

There are convergence traits to P2P, web services and grid technologies. We expect some level of convergence among them in the form of standards and shared services such as directories and registries. Web services standards will be adopted in P2P and grid communities. UDDI registries will host not only pointers to web services but grid computing resources in the future. P2P architecture will be used extensively in web services and grid computing applications. The core of the convergence will embody conceptually distribution and decentralisation, services and metered computing.

On its own, P2P will target niche applications in resource provisioning, distributed processing, distributed storage and edge computing. The current Internet has everything concentrated at the network centre. Content, processing, and storage are hosted on servers, while PCs are used mainly as presentation-level devices. The next stage of evolution will see the unravelling of the centre, where the edge devices no longer function as simple consumers of content and computing resources, but become more participative in nature. Edge resources will become more dominant, interacting and collaborating with fellow peers and network centres alike, thereby creating a more decentralised and distributed architecture, and enabling a personalised experience for affective computing in a smart space.

Personal or local P2P applications and technologies can play a key role in a smart space. In particular, Gartner thinks that personal P2P is the next step. When computing devices proliferate in consumer personal user space, there will be opportunities for adjacent devices, sensors and embedded computers to communicate. Applications can range from gaming, to messaging, to searching (search engines incorporating P2P technologies are more personalised).

In a local region of densely populated personal platforms, one pocket of devices may also communicate with another pocket within the same region via direct networking through two intermediate devices that act as the leader node of each pocket, forming a gateway for mutual communication between the two pockets of smart space devices. When device nodes move around or for some reason are turned off, the role of the leader node may change dynamically from one device to another in split seconds. This is but one theory of dealing with dynamic reconfiguration and adaptability to environmental changes in sensor research. There is research to develop a common middleware to encompass various communication architectures possible. Within these various networking and communication research for wireless sensor pockets, P2P technologies are relevant for enhancing distributed intelligence.

3.6 Security Tokens – RFID & Contactless Chips

Together with biometric technologies, RFID, smart cards and increasingly contactless smart chip cards play a key role for building a secure authentication and payment infrastructure within a smart working space.

RFID can also bridge the real world and the digital realm. Radio Frequency Identification (RFID) has become a key technology of focus today for many applications such as supply chain management and inventory tracking, creating smart global spaces. Intel also has a vision of front-end intelligence for RFID readers with more processing capabilities, instead of dumb readers, in order to add more services to RFID systems for supply chain management. In general, we may see the trend towards sensor-enabled RFIDs with such increase in processing capabilities for more demanding applications beyond identity sensing. More on RFID wireless technology can be found on the communications track.

Contactless IC technology. For short range RF contactless identification technologies, other key standards are ISO/IEC 14443 contactless smart cards, and ISO/IEC 18092 Near Field Communication (NFC) technology targeted by consumer devices by Philips and Sony. We could also envisage their user-oriented applications in a smart space such as for identification and payment purposes. Other than using RSA encryption technologies, increasingly popular and strategic is Elliptic Curve Cryptography for such contactless security and authentication. Working with biometrics, on-card biometric matching algorithms and standardisation are also important. In Singapore, efforts by the Cards & Personal Identification Committee (CPITC) are working towards the publication of a Singapore Standard that is ISO compliant for a multi-application smart card framework that can provide a common platform for interoperability between different card services and issuers.

3.7 Small Software – Open Source Tiny Computing

In IEEE's interview with the world's top 40 thinkers on future technologies in the next 10 years that will change our lives, Mark Bregman from VERITAS Software Corporation said that, "I think it's software: embedded systems in lots of stuff. I think the biggest impact will be from small software (not big software like SAP, Oracle databases, or big operating systems). Small software – putting intelligence in your phone or your door knob – will have a big impact, and for much further than a decade out." In addition, he opined that the future of database management and storage would be towards ways to store and retrieve unstructured data in a distributed and ubiquitous manner within a heterogeneous infrastructure. Some technologies would be content-aware storage and self-managing distributed data technologies.

These are relevant technologies towards building smart IT spaces where data can sit anyway in any embedded computer or device. Currently, in the world of embedded spaces and small devices like mass sensors, the most notable research and initial product commercialisation by new start-ups on tiny computing are based mainly on open source.

Open source software is free in public domain as in 'freedom to use and share source code' and not assumed to be free of charge. To be exact, there are different degrees of freedom defined as:

- 0 = freedom to run and use the program
- 1 = freedom to study how the program works and adapt it
- 2 = freedom to redistribute copies to friends
- 3 = freedom to improve the program and distribute your improvement to public

The accessibility to source code is a precondition to freedom degrees 1 to 3. There are also two types of OSS licenses, namely, BSD (Berkeley Source Distribution) and GNU (GNU Not Unix). The former license allows us to do what we want with it at our own risks, but do not sue anyone, while the latter says we must include the source code if we want to distribute the software.

Open source technologies have made several important inroads into IT and enterprises are increasingly using LAMP:

- L = Linux operating system
- A = Apache (web server)
- M = MySQL (database)
- P = PHP/Perl/Python (server side scripting language)

In fact, open source technologies are found not only in enterprise servers, storage and network devices, mainframes, desktops, but also in grid engines, development tools, databases, application software, web content management tools and application servers. A growing number of software and hardware vendors are developing products and applications to run on open source platforms. There are over 75000 choices available from sources like Freshmeat and SourceForge alone.

Standards bodies are working actively to ensure interoperability of open-source software. Today, Linux backers like Red Hat, Novell, China's Red Flag and Turbolinux have agreed on a standard version so that written programmes can interoperate across different Linux distributions, with support also from chip makers like AMD, Intel, HP, Dell and IBM. We also witness efforts within the legal community to collaborate on licensing and legal issues involved in open source.

For a detailed timeline roadmap to conventional open source software and applications, one can refer to Gartner's Hype Cycle for Open Source Technologies.

Open Source Tiny Computing. Building software into tiny sensors with their own unique requirements has given birth to open source tiny computing. Open source tiny computing is open source software for tiny sensors. Its areas of coverage include tiny operating system, database, compilers, simulators and a tiny version of IPSec (IP Security) called TinySec. In general, we are not discussing here whether open source will find its way ultimately to desktops. We are looking at open source for use in resource-limited devices like mass sensors, or even in little smart card type chips that can be embedded into computing interfaces and devices. We refer to Intel's Proactive Computing and Deep Networking with UC Berkeley as example:

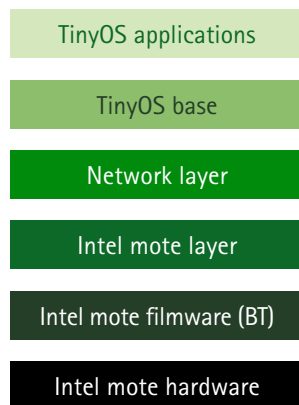


Figure 13. Intel Mote and Sensor Net Software

Source: Intel

Intel Mote software is based on Tiny OS, a component-based operating system designed for deeply embedded systems that require concurrency-intensive operations and which have minimal hardware resources. The software stack includes an Intel Mote-specific layer with Bluetooth support and platform device drivers, as well as a network layer for topology establishment and single/multi-hop routing. The software will also incorporate security features, including authentication and encryption in the near future. Intel also makes available a host of open source performance libraries for digital signal processing, speech recognition, image processing, computer vision, advanced 3D computer graphics and more.

In the smart dust project, the operating system (TinyOS) and database (TinyDB) are both open source software, so as to allow open collaboration in R&D by multiple parties. Sensors in the smart dust concept are meant to be scattered in billions. There is a perceived lower total cost of ownership in using open source software. It is difficult to pay for expensive individual licenses for each sensor based on proprietary platforms and technologies when these are to be deployed in masses. Using open source software, money can then be diverted to other productive usage like support services, technology and service development rather than paying for software licenses, which may ultimately make a

positive impact on economy. In a niche area like tiny sensor nodes, open source tiny computing is more attractive as being a new commercial domain, everything can start from scratch on open source and there is no competitive proprietary alternative to start with, nor existing applications to be compatible with. In fact, the closest example of the smallest operating system by Microsoft is in the domain of smart chip multi-application operating system. In particular, Windows for Smart Cards (WfSC) saw no successful competition against existing heavyweights like Global Platform mainly by Visa driven consortium, JavaCard by Sun Microsystems or MULTOS by MasterCard. Nevertheless, it is always possible in future that alternative proprietary operating systems may emerge to compete especially if this sensor sector gains strong momentum. But for now, it is much focused on tiny open source operating system.

Commercial companies like Crossbow Technology (www.xbow.com) already sell smart dust sensor motes with TinyOS. Crossbow Technology's motes are coupled with radio modules to support the global 2.4 GHz ISM band, IEEE802.15.4 and ZigBee, as well as 315,433,868/900 MHz configurations and frequency agile operations. Commercial offerings also support a wide range of data collection and network management software for wireless sensor networks. Companies like these create and deploy smaller, smarter, wireless sensing devices and mesh networking platforms for large scale defence, environmental, agricultural, industrial monitoring and control, building automation, security and asset tracking applications.

3.8 Social Software

From blogging to Wiki, social software facilitates human interaction in a smart space. This provides collaborative and human-touch experience in a sentient space. Social networking technologies and software have a short term potential such as WIKIs for open source collaboration work and Really Simple Syndication (RSS) technologies used in web blogs to inform subscribers of new contents on web sites. RSS technologies are yet to be tapped for enterprise applications according to Gartner.

There is a growing trend for software and sales applications on the Internet today to be socially engineered. Social behaviour is often based on P2P relationships and referrals, resulting in swarm or mob behaviours. Here, collective behaviour is manifested via the grouping of common interests or common goals.

For instance, Eyebees.com's software allows two or more people to surf the Internet together. As such, it is entirely a different real-time Internet experience when you get to see where your friends surf, and vice versa, and you also get to send instant messages. For Nokia's future visions for research, such social trends are called buddy or social networks, which will bring the right digital mobile contents automatically.

On many popular websites online, simple instantiation of swarm computing can be defined as "you get to know new friends through friends of friends of friends", so unless you have a common friend or common link of friends, you are unable to know other people. The rule sounds simple, but in no time, your network of friends will expand exponentially.

Instant Messaging & Presence Services (IMPS) solutions are available today. Corebridge is for example useful and convenient to enterprise unified communication needs as well as for instant presence management within enterprise LAN workgroups. Their applicability in smart spaces is evident where multiple channels of communications like office email, office phone, mobile phone co-exist. Such technologies enable human-centric services to users such as find-me and follow-me type of services or allow always-on alerts anytime anywhere we may be via one easy-to-use single interface and control. This enhances ad hoc, dynamic buddy networking or enterprise workgroup networking. The OMA (Open Mobile Alliance) also defines the IMPS specification to enable seamless exchanging of instant messages and presence information between mobile devices, mobile services and internet-based IM services.

3.9 Web Services

Much has been said in our previous roadmap publication on service-oriented architecture like Web Services. Web Services has been identified by IDA as one of the five Infocomm clusters that offers high growth potential for Singapore. In key sensor projects like SensorNet, technologies like web services form part of the critical building blocks.

The nature of software development will change from local teams of development in a closed environment and proprietary solutions to an open concept of exposing code functionality to other departments, business partners, vendors and the open public. Service-Oriented Architecture (SOA) and the Services-Oriented Development of Applications (SODA) are two related concepts that best describe the characteristics of delivery and development of software services for this new paradigm. These two models will significantly shorten software development life cycle, increase reusability, and enable static code structures to be more dynamic. The integration of services in a smart space can make use of Web Services.

3.10 Distributed Wireless Sensor Networks

Market Landscape. Sensing technologies form one of the key components to building sentient spaces that are interactive with our physical context and environments. According to DS3 and LightWave Advisors, a firm focused on investing and advising companies in Distributed Sensor

Networking, the market for distributed sensor network applications is expected to be over US\$18 billion by 2008. There are about 50 000 different types of sensors in the world today, with major manufacturers in USA, Germany and Japan. This wide variety of sensors indicates its fundamental importance to the marketplace. Obviously, we cannot list them all but some examples are below:

Technology Examples	How it works?
MEMS sensor	One of the increasingly popular areas of development. Duplicates real world objects on a micro-scale chip using bulk micro-machining, thin film deposition etc, to produce low cost sensors. As such, MEMS sensors can incorporate different types of sensing technologies: chemical sensing, capacitive sensing, pressure sensing etc depending on applications. It just gets smaller, better, faster and cheaper.
Acoustic Sensing	Acoustic sensors can use sound waves to determine the chemical composition of materials in closed containers.
Capacitive Sensing	When an object comes into presence, its electrical property causes a change in capacity value detected by the sensor.
Infrared Sensing	Detects presence via passive heat and temperature originating from the object.
Microwave/ Radar Sensing	Based on transmission of radio frequency. Can be monostatic (based on reflected energy beam) or bistatic (based on kink in energy beam).
Ultrasonic Sensing	Emits an ultrasound that is beyond our audible range and detects for movement that causes frequency shifts in the ultrasound wave.

Table 1. The Way It Works for Some Sensors

The key hardware sensor technologies today are MEMS, fibre optic, semi conductive, magnetic, SQUID (Superconducting Quantum Interference Device), electromechanical, CMOS, chemical and biosensor types.

From market analysts¹². Sensors see the highest rate of technological diffusion in emerging markets of Asia Pacific and Latin America, with lower cost technology being developed. Market analysts believe that successful commercialisation outweighs the high risk of sensor technology investments. Risks include high R&D barriers, lack of customer awareness in new technologies compared to existing ones, and intense competition. While initial costs are currently high, costs of sensor products are expected to drop dramatically in the long run, and will not be a key issue in the far future.

¹² Market data and statistics are supported by Global Industry Analysts Inc's research report entitled "Sensors: A Global Strategic Business Report", surveying a total of 919 leading companies worldwide in this industry. Details of report are not provided here and prudence is advised in relying on such statistics for your own use.

USA, Germany and Japan still remain the top three countries in technology innovation in the sensor space. However, disruptive technologies from infocomm and biotechnology can allow latecomers to have a share of this market. A good intellectual property environment is also important in this field. As sensors can be deployed in mass in practically every industrial sector, even home and workplace, and even into space, potential untapped applications and markets in emerging countries for new smart sensor services is an immense draw for future long-term investments.

Market Size & Growth. The global market for sensors saw an estimated sales figure of US\$35 billion in 2000, according to Global Industry Analysts. This is projected to grow at a compound annual growth rate (CAGR) of 4.46% for the period 2000-2010, attaining an estimated US\$54 billion by 2010. We see that the conventional hardware sensor market has been around for a long time and is mature without a strong growth potential, perhaps moving into the commoditisation phase as what PCs have become. However, there are still new areas of growth in hardware sensors. Amongst those sensors that will see double digit CAGRs are biosensors, CMOS sensors, accelerometers and motion detectors. But even these risk being commoditised in future.

Asia Pacific sees the world's fastest growth rate while USA and Europe will see moderate growth rates. The largest sensor market is currently USA, followed by Japan, then Germany, and in fourth place Asia Pacific (worth US\$3.2 billion in 2000, expected to grow to US\$5.4 billion in 2010, CAGR of 5.3%). Europe as a whole is the world's largest sensor market at US\$11.1 billion in 2000. In Asia Pacific, the promising pioneering countries identified by Global Industry Analysts Inc are China, Korea, Taiwan and Singapore (outside Japan).

Some global market trends in sensors are:

- **Sensor as commodity and its implication.** Market data shows that hardware sensor components are experiencing a trend of being commoditised. As sensor experts we interviewed would say, the greater opportunity is not in the hardware sensing components, but in the system integration of these sensors into useful sentient system solutions (into emerging areas like consumer space, healthcare, security, etc). Today, most hardware sensor vendors usually sell along data management suites and network management solutions.

In using biometric sensors for biometric passports and border control, the USA alone estimated that they need to equip 3950 inspection stations at 400 ports of entry with biometric terminals. The US General Accounting Office (GAO) estimated their biometric security programme to cost between US\$4.4 billion and US\$8.8 billion for one time set up, with an annual recurrent cost of US\$1.6 billion to US\$2.4 billion. Australia is also expected to spend A\$160 million on a similar biometric passport programme.

Yet, a fingerprint sensor hardware reader in the market today costs only S\$100 or so and a facial recognition sensor camera

hardware can cost as low as S\$70. The higher one time cost for these biometric sensors is the software application integration that vendors sell along with the hardware, which includes software licensing for smart algorithm for biometric verification and identification, software application for matching against watchlist, which can range from S\$10K to S\$50K. Other system requirements would be Public Key Infrastructure and key management systems, terminal network connection to databases, data storage and management. Hence, conventional sensor technology like biometric sensors can lead to huge IT spending and demand for system setup and yearly maintenance. The hardware itself is a small though valid business by itself but perhaps more sound for those established hardware vendors who compete in a saturated market heavily distinguished and protected by patents. Unless one has a unique patent for a differentiated sensor performance, it would be hard to compete in a saturated market marked by rapid technological advances.

- **It's e-commerce in Internet but sensor-commerce in the Internet of Things.** In the Internet of Things, machine to machine transactions will dominate as we move towards more automation of processes and tasks. This paves the way towards sensor-commerce. Such network-centric transactions are smart in the sense that they are automated between machines, and recalling Xerox's Calm Computing, humans can now live to live, and not to compute. Technologies like Semantic Web will facilitate device automation. The sensor industry is already gearing up towards this new era of Internet of Things. Overseas ventures, alliances, acquisition and mergers saw through the 1990's, with strong poles of activities occurring in USA, Japan and Europe. There is a current consolidation trend in sensors across all segments, to offer a wide range of products and for cost containment.

- **Sensor industry and e-commerce.** The sensor industry faces increased competitiveness stimulated by globalisation, the demand for faster response time and price reductions (in automotive sensors, price will drop by as much as 32% over next few years). For customer retention, many sensor manufacturers are facing the need to streamline inventory systems to offer shipping delivery on the same day as orders are received. To reduce delivery time, one of the business growth areas is to transform the sensor industry manufacturers and end users with online e-commerce and integrated supply chain management. Sensors used in inventory management itself can also reduce costs via self-diagnostics, programmability and increased accuracy. In 2000, only a meagre 0.2% of sensor sales originated from online sales. Global Industry Analysts forecasted a strong growth and a CAGR of 41% for revenue increment via online e-commerce for sensors, and amongst those companies who are already online, they are ABB, Honeywell, Fisher-Rosemount, Invensys and Siemens.

Market Segmentation & Players. The global market today is highly fragmented with many players in sensor systems but less key suppliers and manufacturers. The table below summarises the market:

Sensor Category	Technology Examples	Application Examples	Market Size in 2000	Market Size in 2010	Examples of Players
Pressure Sensors (measure pressure)	Dominated by silicon type technology (~50% of market) • Absolute • Gage pressure • MEMS • Fibre Optic • Piezoresistive • Capacitive • Vacuum • Electronic	Big spenders: biotech and automotive customers looking for high accuracy, repeatability and reliability. • Process control • Avionics • Robotics • Medical equipment (mainly disposable MEMS sensors) • Infusion pump • Automotives • HVAC equipment • Data storage • Gas chromatography	US\$8.1b (23% of market share)	US\$12.4b (CAGR 4.41%)	• Advanced Control Technology • Dwyer Instruments • Endress + Hauuser • Fujikura • Greenspan • Lucas Control Systems. • Sensor Systems • Sensotech • Strain Measurement Devices
Chemical/Gas Sensors (detect chemical constituents)	Rapid developments in piezoelectric and acoustic wave technologies. • Infrared • Chemical bead • Thermal conductivity • Ionisation • Semiconductor • Biosensors (potentiometric, amperometric, optical, other physicochemical sensors)	Highly affected by safety and regulatory controls. • Aerospace • Chemical process control • Defence (agent detection) • Environmental monitoring & pollution control • Medical diagnostics (point of care healthcare devices, e.g. blood and urine diagnostics) • Food contamination control • Home consumer space (detection of CO, also in carparks) • Office space (detection of CO₂)	US\$6.95b (~20% of market share)	US\$10.4b (CAGR 4.11%)	• Elan Technical Corp • General Eastern • McNeill International • Panametrics • Seatronics Biosensors: • Abbott • Bayer • Boehringer Mannheim • Roche
Flow Sensors (read mass and volume flow rates)	Traditional technologies like positive flow and differential pressure flow are replaced by newer ones like ultrasonic and vortex. • Magnetic flow • Mass flow • Ultrasonic flow • Vortex flow	Mature industry with traditional technologies turning obsolete. MEMS promising area of growth. • Manufacturing • Pollution control	US\$3.7b	US\$7.1b (CAGR 6.67%)	• Endress + Hauser • Hanateck Ltd • Intelligent Controls Inc • McMillan Co • Namco Controls Corp • Squitter Electronics
Proximity & Displacement Sensors (detect materials in proximity)	Photoelectric technology is in favour • Inductive • Photoelectric • Magnetostrictive • Capacitive • Ultrasonic • Potentiometric	Saturated market in USA and EU. Industries in • Automotive • Packaging production lines • Aerospace & defence	US\$2.3b	US\$3.3b (CAGR 3.88%)	• Banner • Honeywell • Hyde Park • Keyence • Lucas • Omron • Pepperl & Fuchs • Siemens • Sunx • Turck

Sensor Category	Technology Examples	Application Examples	Market Size in 2000	Market Size in 2010	Examples of Players
Image Sensors (capture images)	90% of market via CCD but slowly replaced by CMOS • Couple charge devices (CCD) • CMOS	Growth driven by consumer electronics. • Consumer electronics • Optical biometrics/security • PC imaging • Videoconferencing • Automotive blind spot detection	US\$1.95b	US\$3.3b (CAGR 5.35%)	• Agilent Technologies • DALSA Corp • Eastman Kodak • Hamamatsu • Hewlett-Packard • Hyundai Electronics • Loral Corp • Matsushita • Omnivision • Photobit • Photon Vision • Sharp • Sony • Toshiba
Level Sensors (measure level of fluid)	Non contact sensors like radar ~2/3 of market share • Ultrasonic • Radar/microwave • Nuclear • Vibrating rod • Mechanical	Industries in • Chemical • Metal castings • Petrochemical • Food	US\$1.86b	US\$2.5b (CAGR 3.12%)	• Bindicator • Clark-Reliance Corp • Drexelbrook Engineering • E-enraf • Endress & Hauser Instruments • Gems • Lundahl Instruments • Magnetrol • Millitronics • Ohmart/VEGA • Pepperl + Fuchs • Ronan Engineering • Scientific Technologies • TN Technologies • Whessoe Varec
Temperature Sensors (measure temperature)	• RF • Infrared • Thermistor • Thermocouple	Industries in • Automotives • Medical products • HVAC controls • Consumer electronics & Household appliances • Manufacturing & processing • Scientific research • Defence • Meteorology	US\$1.7b	US\$2.7 (CAGR 4.98%)	• Agema Infrared Systems • Alpha Thermistor & Assembly • Auxitrol • Coltek • Heraeus Sensor • Johnson Controls • Kamstrup A/S • Raytek • Sensor Scientific • Temperature Specialists
Position Sensors (measure positioning)	Moving towards non contact technologies • Mechanical • Potentiometric • Optical • Electromagnetic, magnetostrictive • GPS	Automotive industry driving innovation. • Automotive • Machinery • Metalworking • Industrial processing	US\$1.67b	US\$2.3b (CAGR 3.27%)	• AB Elektronik • CTS Corp

Sensor Category	Technology Examples	Application Examples	Market Size in 2000	Market Size in 2010	Examples of Players
Force & Load Sensors (determine performance of production equipment and machine tools)	MEMS is transforming the technology landscape • Torque • Vibration • Accelerometers	• Inspection controls in load and compression measurements in paper, chemical, petrochemical and processing industries • Vehicular applications • Medical applications	US\$614m	US\$1.14b (CAGR 6.38%)	• A.L. Design • Analog Devices • BLH Electronics • Computational Systems • Crossbow Technology • Honeywell • Intercomp • Interface Inc • Miyota • Motorola • Philtec • Shinmei Electronics • Strainert
Fibre Optic Sensors (convert light into electrical energy)	Technology is free from electrical interference • photoelectric	Small but growing market driven by communications and networking demand. • Monitoring structural health of tunnels and bridges • Medical diagnostics • Optical navigation • Remote sensing in industrial automation	US\$390m	US\$645m CAGR 5.16%)	• 3M • Alcatel • Fiso Technologies • General Electric • Hamamatsu Photonics • Ralcom Automation
Others	• Humidity • Magnetic • Motion • Gyroscopes • Oxygen • Ultrasonic • Squid (Superconducting Quantum Interference Device) • Film force sensors (touch sensitive devices)	• Motion detectors in video games and simulators, security surveillance, home automation • Detect leaks • Automotive • Car navigation • Factory automation • Magnetic inspection of nuclear plants, airplanes • Touch screen products	US\$5.9b	US\$8.4b (CAGR 3.59%)	• 3M • Able Instruments & Control • Advanced Custom Sensors • Advanced Optics Solutions • Cherry • EME Systems • General Electric • Hero Electronics • Siemens

Table 2. Conventional Sensor Landscape Today

Source: Global Industry Analysts Inc (edited)

Technology Landscape. There are many component technologies involved in building and deploying useful distributed sensing services and networks. These are :

- At sensor level:
 - **Sensor hardware:** MEMS sensors, chemical signature sensing, odour monitoring, optical sensors, microphotonics
 - ultra-short pulse nonlinear optics, nanoscale sensing
 - biosensors, protein processors, infrared imaging, focal plane array imaging, quantum sensing, smart micro-arrays, sensor memory and storage, power module, low cost packaging, wearables with integrated sensor interfaces;
 - **Sensor software:** embedded sensor algorithms and reasoning for accurate feature capture, efficient algorithms for software to reduce hardware footprint requirements for micro-sensors, low power computing and standards (e.g. chip level low power computing standards are developed for integrated WLAN and WWAN switching);
- At application level: embedded audio/video coding and compression, pattern tracking and recognition, data analysis services for detection, classification, estimation, tracking, optimisation, cognitive technologies like applied psychophysiology, collaborative signal processing, array processing, beamforming, distributed programming and control, use of genetic algorithms, bayesian methods for intelligent supervisory systems;
- At system/network level: network integration protocols like IEEE P1451, wireless networking technologies like ad hoc networking, ZigBee, UWB, WLAN..., networked tasking, distributed inference and fusion systems (fusion can take place at raw sensor level or at higher levels after processing), decision making and reporting tools, diagnostic systems, fault tolerance systems, real time systems and scheduling, security, location and time service, energy and resource management.

Development work in sensor networks is difficult as we deal with codependent devices. Scientists use programming language to solve these issues. The goal is to develop smart sensor network service libraries. System designers build parameterised libraries for various functions required by sensors with more flexible application components than C language. Libraries are then plugged together to build applications, weaving themselves into an efficient programme.

For example, there are hardware programming languages like Stargate, or software programming languages like Emstar programming for sensor networks. Software languages like Emstar are designed to support heterogeneous embedded networked sensor applications. These software systems are built on Linux processors and equipped with finely decomposed modularised software to perform various sensor functions like link estimation, time synchronisation, routing, etc. Intelligent run-time environments for deep debugging are also integrated.

TinyOS is written in NesC, a programming language for motes developed at Intel Research and UC Berkeley. It is an extension of the popular C programming language, NesC (pronounced "NES-see") is a natural lingua franca for motes. Motes are a unique species of computers, primarily because they are asleep most of the time. That means their processing is event driven, occurring only when the sensors acquire data or a new message arrives. NesC supports the motes' reactivity to their environment with a component model that simplifies the creation of applications and the aggregation of data.

There are also developments in information theory for sensor networks. Ad hoc network technologies for example only deal with data transmission while sensor networks have the potential to exploit the temporal and spatial properties of the source field, other complementary features of different sensors. Other areas include R&D into efficient models for the transport capability and scalability of sensor nodes.

The technology trends in sensors include:

- **Disruptive technologies on the rise.** Emerging non-conventional sensor technologies are predicted to grow at an annual rate of 19% for the next couple of years. Technology innovation in the field of sensors is rapid and buoyant, moving towards plug and play sensors for easy installation and convenience. MEMS sensors are ready for low cost mass production. Analysts predict future market trends to be led by discontinuities in technology, and that manufacturers in developing markets can leapfrog mature ones based on these discontinuities. In fact, software will drive sensor growth more than hardware and electronics.
- **Sensing towards the last inch.** Today's Internet is like an octopus without the sensing pads on its tentacles, without its smart spaces and connectedness to the real world. Wearable computing devices, sensors, body area networks and software are the next step in closing the gap towards the last inch, to help create the smart individual spaces. The Internet might even extend into the skin or body¹³. All of these embedded computing interfaces and technologies should aim to help humans interface better with the digital world.
- **Sensor fusion, or multimode sensing systems.** Increasingly popular are dual or multimode sensors, which are sensor systems that incorporate two different types of sensing technologies or more. One technology plays contingent to the other in case of failure, but also different technologies perform with different accuracies or are of varying suitability in different user environments. As such, multimode sensor systems are more flexible but more expensive too. Sensor fusion techniques can also lead to

¹³ Computing devices or smart nanocapsules might be implanted into the skin or taken into the body if the value proposition is right for the right person under appropriate circumstances such as when it is life saving, or life extending for an increasingly aging population.

more accurate readings and measurements if done properly, as we attempt to compensate the inadequacy of one sensor technology with another. The demand for multimode sensing also drives the trend of modularisation in product design. In the long term, integrated circuit technologies are also evolving to incorporate multiple types of sensors for hybrid or monolithic systems.

Fuzzy logic theory is also used in expert systems to fuse data from multiple sensors. Lawrence Livermore National Laboratory is one such organization which has developed a multi-sensor data fusion system to make classification decisions for objects in a waste reprocessing stream, in response to needs by Department of Energy for waste processing, clean-up and reclamation technologies. It was found that a fuzzy logic system is rather easy to design and use, and that with proper training, classification accuracy is quite high. Such systems are also often used in conjunction with advanced automated robotic systems for materials sorting. Fuzzy logic has also been used in other sensor systems like non-invasive (eye-safe without laser) stereo 3D surface imaging to capture 3D images for applications in manufacturing automation, CAD/reverse engineering, robotics, virtual reality and medical measurements.

- **Towards cheaper, better, faster and smaller wireless online sensors.** Noisy contact sensors that are prone to physical wear and tear are increasingly being replaced by non-contact electronic sensors and wireless sensors, which are also more reliable and accurate. Wireless communications are being integrated into sensors and will be a key dominating trend in the future. Ad hoc and mesh networks of integrated wireless sensors resolve the issue of single point of failure with peer-to-peer links. The benefits come in terms of lower cost for radio devices, miniaturised size, overall power saving with integrated chip, online maintenance, testing & upgrade, robust resilience and distributed intelligence.

Wireless and MEMS sensors are increasingly being used in automotive industry today. A miniaturised single-chip sensor can detect up to hundreds of gas types and transmit their levels wirelessly. A fully integrated wireless temperature sensor with processor can now process raw data, detect abnormal behaviours and trigger off alerts to the central host system to report on the equipment's possible impending failure.

Smart miniaturised sensors account today for about 10% of the total sensor market according to Global Industry Analysts Inc. They are expected to grow to a lion share of more than two-thirds of the total market share in the next 4 to 10 years. MEMS and system-on-chip technologies are favourite candidates towards miniaturisation. IT companies like Motorola produced postage-stamp sized chips with e-field motion sensors not only for IT computer interface applications (like a virtual keyboard, remote control or virtual gaming), but also for vehicular applications. Such microprocessor based sensor designs used to be as huge as racks years back, but IT innovations inspired from nature (mimicking sensing

functions of a fish brain) have shown how rapid and dramatic technological advances are in this industry. Nanotechnology or DNA processors will drive advances even further. Miniaturisation is driven by constraints of space, and is useful so that more space can be allocated to power source that is often the hardest to miniaturise. Innovations in power sources such as fuel cells, solar energy, smart materials are important efforts to future technological advances with sensors. The other major challenge is to provide low cost and reliable packaging for sensors as packaging still accounts for a major portion of total cost.

Sensors are increasingly connected to provide online capabilities for real time processing and central supervision. Being networked, they can self identify to the network or system, do self-documentation, bring about improved accuracy and reliability using digital communication, offer enhanced product functionality from diagnostics to remote programmability. They also save costs in wiring, installation and maintenance, and reduce process design cycle or commissioning time.

- **Towards microprocessor-based sensors.** Embedding local intelligence, processing and signal controlling capabilities in sensors avoids the need to do massive communication to and from the central processing system. In doing so, we save on power and transactional overheads for every sensor node in the network. With digital communication schemes replacing analogue ones in sensor control networks, more conventional sensors are rapidly being replaced by microprocessor-based sensors. Embedded digital processing capability improves the smartness, user-friendliness and accuracy of sensors, and will also be compatible with Software Defined Radio.
- **Rise of biosensor technologies.** According to Global Industry Analysts, biosensors are part of those emerging areas that will see double digit CAGRs in the coming years. Biosensors occupy a market value of US\$489 million in 2000, with initial commercialisation in the 1970's for glucose diagnosis. Surface Plasmon Resonance (SPR) technology is dominant in biosensors. Another emerging technology is DNA chip. Biosensors can detect tumours, viruses, explosive ingredients like TNT and RDX, pesticides, and are useful for health monitoring purposes against various illnesses and diseases. One of the challenges that are facing this new industry is the integration of chemical and biosensors onto a silicon chip via lab-on-a-chip concepts. The Freedonia Group estimated that in USA alone, the demand for biochip products and services will increase at 20% yearly to reach US\$2.1 billion in 2008. Demand for biochips (microarrays) will amount to US\$875 million, while demand for related products and services, such as reagents, instrumentation, software, technical support and contract services, will total US\$1.2 billion.

- **Technology inspirations from defence.** It is very likely in the future that many interesting sensor technology innovations into the commercial world would originate from defence R&D. The latter had always and is still investing heavily in sensor and sensor network R&D due to strong emphasis on network-centric warfare, unmanned systems, Command Post of the Future for battlefield and information dominance, not only to reduce manpower needs, replace humans in risky missions, but also to gather information intelligence and track targets. Network-centric warfare requires collaborative information processing between sensors over a communication network, hence it will drive many distributed computing technologies potentially applicable to IT services today too in smart spaces. Numerous military sensor programmes by different names today are built around network-centric warfare.

DARPA in USA is a leader in advanced concepts and co-funds many current university and commercial R&D (example: smart dust). DARPA's DSN (Distributed Sensor Network) followed by SensIT (Sensor Information Technology) programmes in the 1980's and 1990's could be considered as the source of many sensor innovations in new networking technologies, localised algorithms, directed diffusion routing algorithms, distributed software like mobile agents for information query and processing, as well as artificial intelligence. DSN was driven by K Kahn, co-inventor of TCP/IP (foundation of Internet), and the Director of IPTO (Information Processing Techniques Office) at DARPA then.

Examples of innovative R&D in defence that are relevant for commercial world include smart materials in zero-power displays for air pilot headgears, virtual reality and simulators, MEMS, smart dust, self-organising wireless sensor networks and mass intelligence, chemical and biological sensors, self-regenerative portable power for soldiers. Even remote sensing technologies (sensing of geographical surfaces and underground hideouts), a forte of military systems, can be employed in economic sectors such as tourism, location-based gaming, disaster and crisis handling, forest fire fighting, construction or for town planning in image mapping applications.

Defence related industries also contributed strongly to technology development. Lockheed Martin Corporation developed SnifferSTAR in a project with the Department of Energy. It is a half-ounce sensor unit operating on half a watt of power and is designed to ride on UAVs (unmanned aerial vehicles) to detect nerve gases and blister agents by sampling the inflow air-stream.

The Internet today is largely credited to military research and it is hence not surprising that continued military research might be also the key contributor to the next generation Internet. As such, close interaction with this field of research, in terms of policy making, multi-agency cooperation, technology transfer schemes, manpower training, and educational exposure to innovations in military R&D, is important for success.

- **Patents rule.** Many sensor innovations are patented. One shining example is iris recognition biometric sensor by Iridian. The company owns the patent such that it is the only legitimate player in this field, giving it the monopoly over the global iris recognition market. The technology is highly accurate and has good market potential.

Conclusion. The future of sensor networks lies in wireless sensor networks. This report bears emphasis that wireless sensor networks enable a unique capability: that of monitoring over vast spaces with a very fine temporal granularity. With conventional wired sensor nets, something like this can never be cost effective. At the same time, inference technologies that can deal with the flood of data, and new applications (software) that can deal with the data streams, will become growth areas once sensor networks become the norm.

The US Department of Defense is now asking a fundamental question – 'how do we change the way we think about regular operations to take full advantage of the new networked sensor technology?' In the past, someone may ask – 'how do I use sensor networks to better do what I do today?' This trend deserves watching, because if it leads to new insights on how operations and processes can be fundamentally changed to take maximum advantage of new technologies, they can be as powerful as what the first spreadsheets did to the desktop PC.

Challenges ahead include the following:

- **Power.** Advancement in power is necessary to derive the full value of distributed wireless sensor nets. This can be made in hardware (e.g. new materials, new source of energies) as well as software (e.g. optimised power-friendly architectural designs, optimised power switching algorithms and standards). Low power, low cost, low energy actuators (such as advanced piezo-actuators, artificial muscles, etc.) coupled with the sensor networks will allow distributed actuation in the future;
- **Sensor-on-chip.** To create the close linkage between the real world and the Web, sensing applications would call for the development of tiny, effective, yet energy efficient sensors. Hence, developing new sensors, and sensor-on-chip will be necessary;
- **Robustness.** Situations in the real world have their variety and diversity, and application demands may vary from time to time and from task to task. This poses tremendous challenges to communication architectures for sensor networks, with respect to coverage, reliability, re-configurability, and adaptability;
- **Collaborative Sensing.** Data collection and information processing require embedded computing functions within smart sensors (possibly microprocessor-based and/or low cost off-the-shelf MEMS sensors) and networked computing. Groups of sensors are required to work together to collect, process and analyse data collaboratively on common tasks. Today, there is little work done on collaborative embedded processing;

- **Building Cognitive Systems.** On the system level, an autonomic "cognitive system" should be aware of its available resources and tasks, perform self-diagnosis and conduct re-organisation if necessary for the most efficient computation method. It should also be able to recover when there is a failure or attack. Existing systems have little "cognitive" features;
- **Inter-disciplinary Challenges.** This roadmap direction points out opportunities for inter-disciplinary research to promote the advances of many application areas. Application areas can include structural monitoring, diagnostic and warning systems (e.g. for buildings, bridges, marine constructions), health monitoring, machinery self-diagnosis, proactive healthcare, defence and environment protection. Experts and researchers in these application areas need to work together with infocomm research community to model the real world and value add their domain knowledge in the computation models and system design. Effective sensor network designs require efficient and realistic models of computation.

Other key areas of development and challenges as pointed out by the National Research Council in USA in its Embedded Everywhere report for EmNets include many details in the following areas:

- Self-configuration and adaptive coordination;
- Building trustworthy networked systems and research into privacy issues;
- Research into safety versus usability;
- New models of computation for sensor networks;
- Standards and business models.

3.11 Mixed Reality

As our brain-width is limited, the mode of interface with the virtual world also needs to be re-examined in sentient spaces. A computer screen in front of us is not always the ideal mode of interface for us to absorb the increasingly multimedia and multi-dimensional information available. Today, many are researching and proposing advanced concepts on interface technologies towards mixed reality environments such as augmented reality, augmented virtuality and virtual reality. These define the new digital media.

In the new world of intermixed realities, services and contents are delivered via a clever play of virtual interfaces with real world environments, in the most intuitive way for humans to absorb, interact and use the digital information extracted from networks and the Internet. From smart living homes, to smart gardens and parks, to outdoor virtual gaming, to virtual workplaces and factories, the imposition of virtual reality onto the real world opens up new service possibilities and demand for IT services and systems. The way we deliver services and contents in this omnipresent mixed world would be different and likely disruptive in nature. For example, a walk through the park can see virtual reality beaming out and telling stories about its historical and monumental past, or educating you on nature conservation, or acting as a

playground for virtual outdoor gaming environment.

In NTT Docomo's mobile vision for the future, we see how projected 3D virtual reality display functions of a handphone can be put to good use in a mixed reality environment, and becomes part of an overall vision of enabling smart mobile services coupled with many other technologies like automatic real time language translation by mobile devices such that one can speak to another in different languages and actually see the person in 'virtual reality' in front of him.

In a mixed reality application, we could read Hamlet and see a 3D human actor appear physically on the book delivering a soliloquy, or watch a live 3D ballet from Moscow appear in one's own living room, or see animals from exotic lands, and play with them in their real physical space. Even increasingly in the industrial and engineering spaces, we are moving from 2D, 2.5D to 3D computer assisted modeling and manufacturing. Mixed reality presents a cognitive interface to our senses the way it should be for human communication.

Developmental work focus on many areas such as: distributed virtual environments, face to face collaboration, remote collaboration, transitional interfaces (like MagicBook), hybrid interfaces, 3D real time animation, head mounted displays for virtual reality viewing, hand gloves equipped with positioning and motion sensors, haptic sensors, etc. There is also work in applications for simulators for machine assisted training, or for e-learning, affective videoconferencing, immersive telepresence for online commerce and tele-healthcare. The disciplines of interest can range from computer technologies to ergonomics, to communication and even to psychology.

While we focus on enabling technologies and research into mixed reality, we should equally focus on future directions to integrate and operate software applications and services commonly used today into 3D environments and research into business models in mixed reality environments.

Key players in mixed reality systems are mainly from USA, Europe and Japan. They include:

- **USA:** Brown University, Columbia University, Georgia Institute of Technology, University of Illinois, MIT MediaLab, NASA Ames Laboratories, University of Carolina, University of Southern California, University of Washington;
- **Europe:** Fraunhofer Institute's laboratories in Darmstadt e Stuttgart, Lausanne Laboratoire d'Infographie, Delft University of Technology, French National Institute for Audiovisual Applications, European Space Agency in Netherlands, and strong pole of activities in UK - University of Edinburgh, University of Nottingham, University of London;
- **HITLab New Zealand;**
- **Japan:** Mixed Reality Lab (started by Canon and METI).

In Europe, the focus is mainly to enable industrial, manufacturing, automotive design applications. In USA, the focus may shift towards medical applications (e.g. wearables for doctors to avoid looking up to screens). In Asia, the sweetspot may be in collaborative industrial design, architectural design, building and town planning, and entertainment applications. Virtual reality applications are also useful for simulators and training. The key aspect is to develop a virtual reality system with the highest degree of realism, and coupled with actual physical machines and equipment, and navigation sensors for gaming and defence.

To view mixed reality, head mounted displays may be niche for sectors like defence, as most consumers or users may not like to wear additional gadgets to walk around under normal conditions. Hence, for layman applications, such as for arts and heritage services, it may be more practical to use handheld screens that can project virtual reality onto the real world, for instance for a walk in a museum. Augmented reality handheld display devices of this sort can be used to build smart mixed reality spaces in nature parks like those described in IEEE's Sensor Nations, without expensive IT or projection systems being installed in the park itself. Applications can also include virtual outdoor gaming or HDTV screens used in indoor applications which we can swivel with, to see 3D effect on actual real world landscape. Mixed reality booths equipped with camera arrays can capture our image and re-project it into another virtual city, so that we can physically be in a room in Singapore, but actually taking a 3D stroll of Berlin. In most mixed reality applications, capturing the image input is key and camera technologies are used. The choice between CMOS and CCD cameras depends on the degree of resolution needed and cost. Array processing of multiple camera inputs are also usually done. Even today, mobile phone screens are moving towards those with 3D effect, and soon, with virtual reality projections.

3.12 Proactive Computing

Intel's Proactive Computing research programme is very comprehensive and offers deep insights into the future of web computing with sensors. In the era of proactive computing, we will see the following changes in computation trends:

- From human-centered to human-supervised;
- From deterministic to stochastic;
- From managed to autonomous.

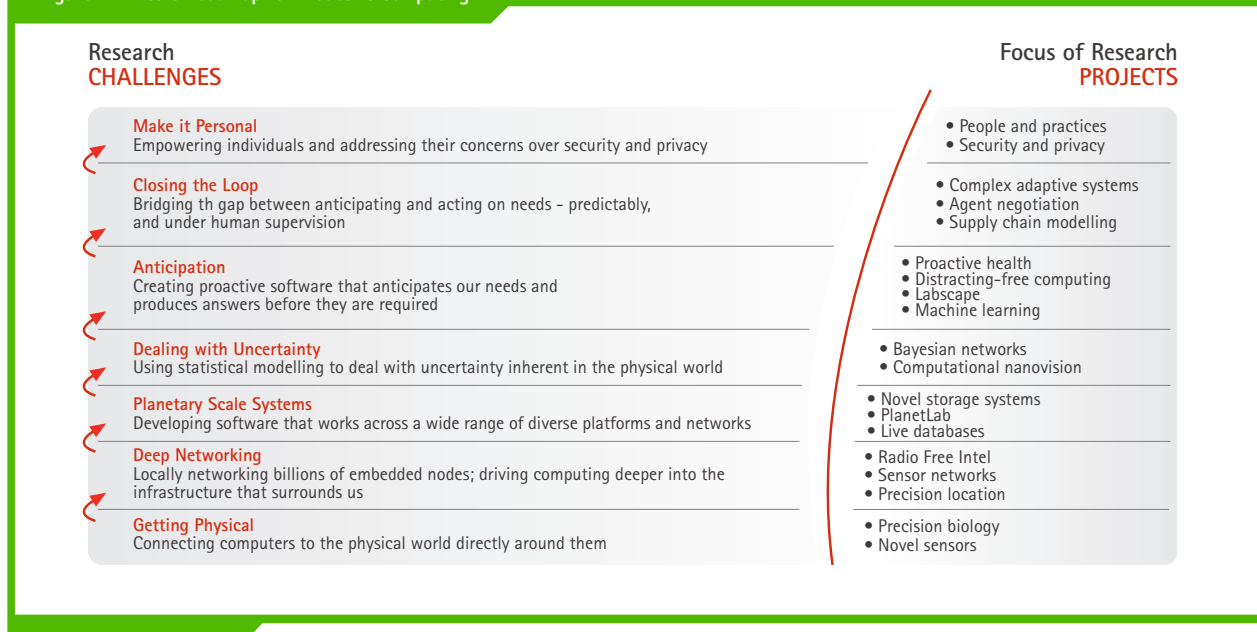
These are desired characteristics of a smart sentient space where computing becomes painless and efficient (refer to Figure 14)

Intel's roadmap to Proactive Computing comes in seven phases.

1. Getting Physical. In this phase, we create smart novel sensors like tiny motes and biological sensing and diagnostic devices. Today, humans are the primary source of data input and synchronisation. To move beyond that role, computers must be better connected to the world around them and to each other. Researchers are focused on new types of sensors and actuators, especially MEMS and biosensors. The goal is to enable computers to sense things that are dry and solid state, as well as things that are wet, such as biological materials. As such, we can vastly expand the range of places where computers can be installed and networked and enable a variety of important wetware applications in areas such as health, pharmaceuticals, chemicals, and refineries. Getting Physical with billions of devices will relieve human beings of burdensome I/O devices and vastly expand the flow of raw data into information systems.

2. Deep Networking. In this second phase, we create future distributed sensor and actuator networks embedded deeply into our physical environment. Sensor devices will be enhanced

Figure 14. Intel's Roadmap for Proactive Computing



Source: Intel

with software like tiny open source software and applications built on this open source operating system, while the hardware will be enhanced with communication, processing, storage capabilities and equipped with a power source. The deep networking programme will then have to take into account the ultra low power operations needed for sustainable applications, the system level integration and reconfigurable hardware for efficient power/performance adaptation. As the micro devices are networked, the Internet will be pushed not just into different locations but deep into the embedded platforms within each location. This will enable a hundredfold increase in the size of the Internet beyond the growth we are already anticipating. New and different methods of networking devices to one another and to the Internet must be developed.

One of the interesting sub programmes under Deep Networking is IrisNet project or short for Internet-Scale Resource-Intensive Sensor Network. Webcams are everywhere, collecting vast amounts of potentially useful data. However, there are no effective tools for querying the data. The goal of IrisNet project is to create an architecture for sensor-based Internet services by developing a scalable software infrastructure that will enable users with Internet access to data mine the wide world of webcams. IrisNet will facilitate the deployment of webcam services that leverage both real-time and historical video feeds from any number of webcams, from other data sources, and from other types of sensor data. Each sensor is locally attached to a computer that is capable of resource-intensive processing such as image recognition. A key design goal is to facilitate dynamic reconfigurability in the sensing agent network.

Wireless sensors are in demand as we have seen from business trends. Another sub programme called Radio Free Intel looks at addressing 802.11 wireless products and Intel is aggressively driving research into affordable ad hoc wireless networking, especially in the networking of sensors. Ultra wideband radio is also being explored as a new networking technology that will provide greater density and bandwidth. New types of antennas and new ways of integrating radios with MEMS and CMOS devices are also being explored.

3. Planetary Scale Systems. In this third phase, Intel looks at developing software that works across a wide range of diverse platforms and networks. Some people may term such software as Liquid Software – being able to flow in an interoperable manner from one device/network to another. In Novel Storage Systems sub programme, new edge nodes will have new types of storage and file systems. The challenge is to connect those devices with our personal servers, and then to connect the servers, using peer-to-peer computing, to form totally global, persistent, secure file stores.

In Personal Server, it is a new class of mobile device that utilises advances in processing, storage, and communication technologies to provide ubiquitous access to personal information and applications through the existing fixed infrastructure.

Another key initiative is PlanetLab, a global open testbed with 65 sites worldwide supported by companies like HP, Intel and Sun. A new kind of networked system is emerging in which nodes spread over much of the planet to form a coordinated service, with content distribution networks and peer-to-peer applications being the first examples. Intel researchers are working with the academic community to build an open, distributed laboratory in which to explore new planetary-scale services.

Data querying is a key application in distributed sensor networks. In Querying "Live" Data, Intel looks at database-like queries using live data from sensors embedded throughout the environment. Live query tool research is being conducted at in a project called Telegraph. In Singapore, the Institute for Infocomm Research is also conducting novel research into efficient database methods for distributed sensor networks.

4. Dealing with Uncertainty. In this fourth phase, Intel uses statistical modelling to deal with uncertainty inherent in the physical world. Increased access to data is necessary, though not a sufficient condition if we are to achieve greater productivity gains from human endeavours. The physical world does not exhibit the deterministic behaviours computer scientists have come to know and model. Technologies include stochastic methods like Bayesian networks (a mature technology used widely by Google) and Hidden Markov Models. In Computational Nanovision, the sub programme aims to develop novel computer vision techniques for quantitative, high accuracy nano-feature analysis in nanoscale images and image sequences, such as by combining statistical models of physical processes and image formation with model-based data analysis.

5. Anticipation. In the fifth phase, anticipation is about creating proactive software that anticipates our needs and produces answers before they are required. Excess computation and communication capacity will be used to fetch and manipulate information, producing answers, before they are required – much like a chess champion anticipates moves many steps ahead. Glimpses of anticipation are here today through the speculative execution features of Intel's processors and in some of the most advanced web proxy engines. The sub programmes in this phase include:

- **Proactive Health** – exploring ways in which ubiquitous computing can support the daily health and wellness needs of people in their homes and everyday lives. Investigating proactive systems that anticipate a patient's needs, improve the quality of life for both the patients and their caregivers;
- **Labscape** – distraction free computing that helps cell biology researchers in their laboratory environment. It seeks to make critical information available when and where it is needed to minimize user distractions and errors. It also makes data that is generated in the process of completing experimental work easy to capture and organize so that it is immediately placed in context and is searchable and sharable;

- **Machine Learning** – looking at the emergence of a new exciting genre of machine learning tools firmly grounded in statistical methods. Systems such as those under development by (Stanford), (University of Washington) and (Carnegie Mellon University) use uncertainty to support robotic hypothesis generation, a key stepping stone to anticipation.

6. Closing the Loop. In the sixth phase, we bridge the gap between anticipating and acting on needs – predictably, and under human supervision. The difficulty is not so much in determining the action to be taken, but to develop the feedback and control mechanisms essential to the stable operation of any closed loop system. Today, most systems rely on human beings to close the loop and provide stability, placing human beings under stress. For this, two sub programmes are in place to investigate technologies for complex adaptive systems and supply chain modelling. At the Internet scale, software agents are used to close the loop. The challenge is to engineer systems in which billions of computers and an unlimited number of software agents are simultaneously closing many intertwined loops.

7. Making it Personal. The final phase makes computing personal for a smart space. This may need ethnographic research in different cultures to examine how different people interact with technology. Security and privacy concerns must be managed not just for a single, homogeneous society, but for a world filled with different cultures and differing expectations. Intel's world-leading group of ethnographers and social scientists are engaged in studying people in small numbers, analysing in detail what they are doing with technology, why they are doing it, how it can help them in their lives, and how it can improve their quality of life. The knowledge of people practices is then translated into concepts for technology that can fit naturally into truly human-friendly smart spaces.

3.13 Quantum Cryptography

A smart space must also be a secure space. As we move from products to services, trust in service providers will become a key differentiator of businesses. Services can transcend geographical boundaries with the advent of communication technologies and global connectivity. Security is important to building trusted services. Quantum computers may be a faraway future, but quantum cryptography is a disruptive technology ready for commercialisation within a 5-year timeframe, and perhaps will reach its plateau of productivity in 10 years. It can be tapped for secure key exchange over open networks.

Mainstream PKI solutions and classical encryption methods will not go away in the foreseeable future, but we investigate here an emerging technology that will likely find its way into commercialisation with this medium term timeframe. Its association often with "unbreakable security" fascinates many.

In physics, quantum is defined as the smallest quantity of a physical system. From here, several related terms are derived as follows:

- **Quantum theory** is a physical theory that claims that certain properties can exist only in discrete amounts or quanta, the plural of quantum.
- **Quantum Dot** or single-electron transistor is a location capable of containing a single electrical charge (a single electron of Coulomb charge). In reality, quantum dots are nanometer-size semiconductor structures in which the presence or absence of a quantum electron can be used to store information. Individual electrons can be trapped by semiconductor impurities or 3D optical lattices of laser beams.
- **Quantum Cell** or quantum dot cell is a structure comprising four quantum dots arranged in a square, with two diagonally opposed dots containing electron charges. One diagonal containing charges is arbitrarily defined as representing a value of '1', the other as '0'. In a five-dot cell, the fifth, central dot contains no charge.
- **Qubit.** Binary information can be represented in the form of two-state quantum systems (e.g. quantum cell), such as: two distinct polarization states of a photon; two energy levels of an electron; or the two spin directions of an electron or atomic nucleus in a magnetic field. A single bit of information in this form is known as a "qubit". With two or more qubits, it becomes possible to consider quantum logic operations in which a controlled interaction between qubits produces a (coherent) change in the state of one qubit that is contingent upon the state of another.
- **Quantum Computer** is a type of computer that uses the ability of quantum systems, such as a collection of atoms, to be in many different states at once. Quantum cells and logic gates are the basic building blocks of a quantum computer or chip. In theory, such multi-state superpositions allow the computer to perform many different computations simultaneously. This capability is combined with interference among the states to produce answers to some problems, such as factoring integers, much more rapidly than is possible with conventional computers. In practice, such machines have not yet been built due to their extreme sensitivity to noise. The quantum states of atoms and subatomic particles that prototype quantum computers use to represent the 1's and 0's of computer are so fragile that energy from small amounts of heat, light and magnetism can change them, effectively snuffing out the information they hold.
- **Quantum Cryptography.** The elements of quantum information exchange are observations of quantum states; typically photons are put into a particular state by the sender and then observed by the recipient. Because of the Uncertainty Principle, certain quantum information occurs as *conjugates* that cannot be measured simultaneously. Depending on how the observation is carried out, different aspects of the system can be measured, for example: polarisations of photons can be expressed in any of three different bases: rectilinear, circular, and diagonal,

but observing in one basis randomises the conjugates. Thus, if the receiver and sender do not agree on what basis of a quantum system they are using as bases, the receiver may inadvertently destroy the sender's information without gaining anything useful.

This, then, is the overall approach to quantum transmission of information: the sender encodes it in quantum states, the receiver observes these states, and then by public discussion of the observations the sender and receiver agree on a body of information they share (with arbitrarily high probability). Their discussion must deal with errors, which may be introduced by random noise or by eavesdroppers, so as not to compromise the information.

Quantum cryptography uses light sources for transmission such as a light-emitting diode or a laser, and a photo-detector to receive. Transmission can be through a fibre network or wirelessly through free space optics.

There are potentially several benefits of quantum technologies.

- **Incredible Processing Power.** The number of distinct states that qubits can hold increases exponentially. Two qubits can hold four distinct states that can be processed simultaneously; three qubits can hold eight states, etc. As such, a miniaturised system with 40 qubits can execute 2^{40} or one trillion simultaneous operations, and with 100 qubits, the system can be an immensely powerful computer that can do one trillion trillion simultaneous operations. And according to Computer Science Corporation's Leading Edge Forum reports, a system with 333 qubits can represent a googol of states (the number 1 followed by 100 zeros), and this is more than what is required to simultaneously represent every atom in the universe. Tasks glamorised by supercomputers are a mere trivial task for quantum computers. Some stunning illustrations in the R&D community in the factoring of prime numbers estimated that it may take IBM's Blue Gene supercomputer 10 million years to resolve the factoring while a quantum computer can do it in a mere 10 seconds.
- **Trusted Computing & Networks.** Quantum cryptography leads the trend in hardware security, whereby software is no longer the trusted tool for implementing security. As hardware becomes so powerful, fast and cheap or even disposable, engineers will prefer to implement hardware security modules instead of software. It will be much harder to reverse engineer a hardware chip than to crack a software code. Quantum light sources used in secure networking can be applied to network security, and quantum properties can practically ensure a trusted communication.
- **Quantum Storage.** Similarly as for processing, due to the immense information of distinct states that a discrete number of qubits can store, we can design quantum storage devices that can one day perhaps offer 'unlimited' storage

capacity from an application point of view in a miniaturised device.

- **Nanotechnology Simulations.** Nanoscale modeling and simulations require vast amounts of computing power. Some research scientists surmise that exact calculations of future nanoscale systems can only be performed using a quantum computer. Furthermore, this ability to simulate at mesoscopic and nanoscopic levels can open up new understanding of physical phenomena and could lead to new devices and technologies.

Quantum Roadmaps. The major players in quantum technologies are USA, Europe, Japan, China and Australia. Quantum cryptography was discovered in the USA by Steven Wiesner in the early 1970's (based on quantum uncertainty) and, independently, in Europe in 1990 by Artur Ekert (based on quantum entanglement – E91). Currently the most popular quantum key distribution protocols are BB84, proposed by Bennett and Brassard in 1984 (based on Wiesner's original idea) and E91. The two protocols were experimentally tested in 1991 and 1992; BB84 at the IBM TJ Watson Research Center in Yorktown Heights (USA) and E91 at the Defence Research Agency in Malvern (UK). In 1991, the first working prototype implementing this protocol was developed and operated over a distance of 32 cm. Today, this can reach over hundreds of kilometres over fibre, while over the air transmission has achieved a record of 23.4 km by Christian Kurtseifer, who is currently working with a team of researchers in NUS in Singapore.

A direct application of quantum cryptography is in secret key exchange and distribution. Quantum cryptography is an excellent replacement for the Diffie-Hellman key exchange algorithm. However, quantum cryptography is unlikely to totally replace current cryptographic technologies. Crude systems are available today with budgets varying from \$20K to \$100K, but mass commercial products can only be expected within the next few years. For now, it may still be applied more in niche sectors like security agencies, for instance NSA in USA, as well as for military applications, like DARPA.

Amongst its key early players is BBN Technologies (www.bbn.com) which is also associated with the invention of ARPANET (the forerunner of today's Internet), the first router, the first person-to-person network email, and the invention of the @ sign by Ray Tomlinson, a principal scientist at BBN.

Another key company is MagiQ (www.magiqtech.com) which sells commercial quantum based information security solutions such as quantum private networks, and has shipped its first quantum key distribution products in Oct 2003. MagiQ is also the winner of the World Economic Forum's 2004 Technology Pioneer Award and was voted by IEEE as one of the top ten companies for next decade.

Other companies include Telcodia Technologies, Lockheed Martin and Eltag Plc, which is based in Genoa (Italy) and owned by Finmeccanica. Even HP is working on quantum cryptography. NIST in USA has also launched the world's first series of standards meetings on quantum cryptography in 2004.

Quantum Computers. Unlike quantum cryptography, quantum computers would need many more years to mature. In fact, scientists are looking at 20 years or beyond to make general-purpose quantum computers. Perhaps in 10 to 20 years, quantum computers of 50 qubits can be designed, which would be much better than classical computer systems. For practical quantum computers, which may consist of thousands of qubits or more, we would be looking at more than 20 years.

QIST roadmap. In Apr 2004, a quantum information science and technology expert panel was formed in USA, to develop a roadmap for quantum computing. The work was funded by US government agencies. It included experts from Los Alamos National Laboratory, IBM, National Institute of Standards and Technology and many prominent universities.

Amongst its desired high-level goals are the following targets:

- A 10-qubit computer by 2007;
- A 50-qubit computer by 2012.

Quantum Display. Researchers at MIT have created a 'quantum-dot' organic light-emitting device (QD-OLED) that may one day replace LCDs as the flat-panel display of choice for consumer electronics.

Quantum Lithography. Other researchers in MIT and Cambridge University are also looking at quantum lithography such as erasable electrostatic lithography. It allows quantum dot devices to be etched in a matter of hours rather than weeks with advanced techniques such as electron beam lithography. The researchers estimated that this method of lithography, upon further refinements on its resolution, could be made practical by around 2008.

Entanglement Measurement. A key phenomenon in quantum technology is entanglement that allows properties of quantum particles to remain linked despite the physical separation between the particles. It is a very sensitive phenomenon to measure, as a slight disturbance can disturb the quantum states of qubits. Researchers in Italy have also demonstrated methods to detect and measure entanglement, which can be used to determine if an entanglement has survived the transmission over fibre, or measure entanglement in superconducting devices. Practical measurement systems may only be realised five to ten years away. Other researchers elsewhere around the world are also looking into developing measurement systems for precision control in quantum devices.

Some issues and challenges in quantum technologies include:

- **Decoherence.** A key challenge is to prevent quantum qubits from decohering. Hence, error correction techniques are critical to the roadmap of quantum computing to build robust and trusted systems.
- **Precision Engineering & Control.** Quantum mechanical systems require unprecedented technology advancements in precision engineering and control.
- **Quantum Cryptography.** To ensure the integrity of quantum cryptographic systems, truly single photon light sources are preferred to prevent man-in-the-middle eavesdropping attacks. Today, such single photon sources are expensive. However, some protocols, e.g. B92, may even operate better on coherent rather than single photon states (recent work by Koashi et al). Single photon sources are hence desired but not essential for proving the integrity of the system.

3.14 Semantic Web

Semantic Web is one of the early initiatives towards building an autonomous web with machine intelligence. As its founding father Tim Berners-Lee phrased it, "The Semantic Web is an extension of the current web in which information is given well-defined meaning, better enabling computers and people to work in cooperation". Semantic Web will also pave the way for artificial intelligence in a much stronger manner. This fits into the goal of creating sentient spaces where computing is made easier. Semantic Web can put some order and automation into the 8 billion pages of Internet information out there. W3C (World Wide Web Consortium directed by Tim Berners-Lee) also develops accessibility standards for disabled people and software for mobile devices under Semantic Web.

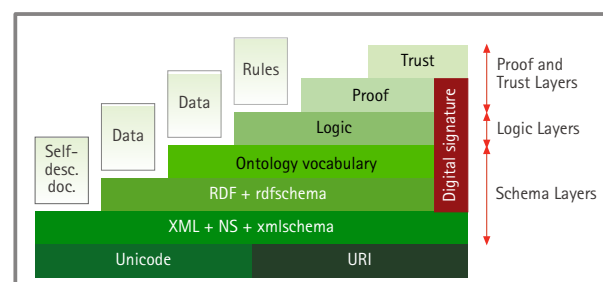
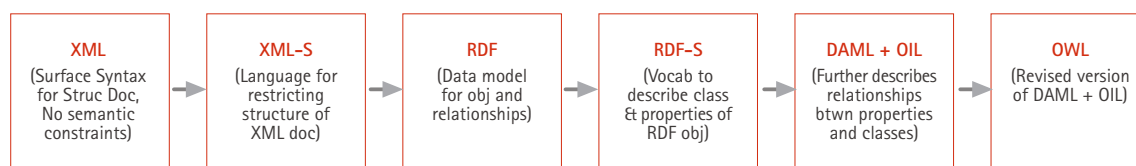


Figure 15. Semantic Web Architecture
Source: W3C

Amongst the technologies used in Semantic Web, there are metadata, resource description framework (RDF), ontologies summarised in the basic architecture framework by Tim Berners-Lee above.

Figure 16. Development Milestones of Semantic Web Schema Layers



In its schema layers, RDF was developed by W3C in 1999, about the same time as XML, providing a language for modeling semi-structure metadata and enabling Knowledge Management applications. RDF, being very similar to basic directed graph, is successful because of its simplicity. RDF-S was then developed by W3C to provide basic structures such as classes & properties.

In Aug 2000, a non-W3C initiative (but Tim Berners-Lee participated in the development), the DARPA Agent Markup Language (DAML), was developed via a US-government sponsored effort for expressing more sophisticated RDF class-definition. DAML group soon pooled efforts with the Ontology Inference Layer (OIL). The result of this effort was DAML+OIL in 2001 with far more sophisticated classifications and properties.

In early 2003, W3C working group developed OWL, a revision of DAML+OIL incorporating lessons learned from the design and application of DAML+OIL.

Today, the work status in Semantic Web has sufficiently progressed up to the schema layers. The three upper layers of logic, proof and trust are less developed and in early stages of development. Time is needed to gather the critical mass of semantic data and applications on the Web before the network effect can bring to fruition the vision of the Semantic Web.

There are also 'countless' industry and academic players in Semantic Web R&D and commercialisation. Semantic Web technologies can enhance the future capabilities of web services and grid computing. In fact, work is ongoing to develop semantic grid applications and semantic web services by various parties around the world. While Semantic Web is a long term vision, some of its technologies like ontologies and OWL have short term potential.

Interestingly, in its next step, the Semantic Internet will break out of the virtual realm and extend into our physical world. URLs can point to anything, including physical entities. This means we can use the RDF language to describe devices such as cell phones and TVs. Such devices can advertise their functionality, what they can do and how they are controlled, much like software agents. Being much more flexible than low-level schemes such as Universal Plug and Play, such a semantic approach opens up a world of exciting possibilities.

For instance, what today is called home automation requires careful configuration for appliances to work together. Semantic descriptions of device capabilities and functionality will let us achieve such automation with minimal human intervention.

The first concrete steps have already been taken in this area, with work on developing a standard for describing functional capabilities of devices (such as screen sizes) and user preferences. Built on RDF, this standard by W3C is called Composite Capability/Preference Profile (CC/PP). Initially it will let cell phones and other non-standard Internet clients describe their characteristics so that Internet content can be tailored for them on the fly. Later, when we add the full versatility of languages for handling ontologies and logic, devices could automatically seek out and employ services and other devices for added information or functionality. We can imagine our Internet-enabled microwave oven consulting the frozen-food manufacturer's Internet site for optimal cooking parameters.

3.15 Wearables

According to Venture Development Corporation, the smart fabrics industry is worth today US\$340 million and growing at 19% annually to reach a projected market value of US\$720 million by 2008. Pioneered in the 1970's, wearables can form smart wireless personal area networks (WPAN) or body area networks via short range wireless technologies like Bluetooth or ZigBee and interact with other smart spaces via off-body networks often based on WLAN technologies and MANETs (mobile ad hoc networks with origins from military domains). Wearable networks form a key area of research by scientists. Perhaps in the medium term, we would see the wide proliferation of embedded wearables to a productive level. In fact, in some countries, Gartner expects about 75% of their teenagers to use wearable PCs in five years' time. Gartner also sees inkjet processes that can deposit semiconductor materials onto a flexible substrate reaching its Plateau of Productivity in the medium term (5-10 years). This inkjet technology can also be used for embedded RFIDs and wearables.

Power source such as micro fuel cell is important to embedded sensors, mobile devices and wearables. There are also other techniques to bring power to computing wearables such as woven conductive fibre grids using common textile production

methods, or regenerative power sources embedded into shoes that tap on the conversion of kinetic energy into mechanical energy into electrical energy. Low power computing research in electronics and standardization development are key to the advancement of wearable computing. Other areas of power research involve power dissipation in smart fabrics, photovoltaics and solar cells and flexible power sources.

Many smart wearables are not just for lifestyle applications, but can also save lives by monitoring vital signs or detect airborne contaminants by embedded sensors. For instance, proactive healthcare applications available today can monitor the vital signs of babies via a smart baby sized jacket to prevent Sudden Infant Death Syndrome (SIDS), or can also have sensors woven into an underwear to monitor the heart to warn of impending stroke symptoms. The sensing outputs can also be used to control external robotic systems for appropriate actions or send wireless alerts for nursing care, etc.

Many wearable inventions are also washable with innovations in smart materials. Wearables are also often integrated with location positioning features like GPS, or positioning sensors, infrared sensors, temperature sensors, motion sensors, microphone sensors, and probably in future biosensors too.

Display wearables like smart sunglasses can host a variety of components in future, such as GByte chips for storing life moments, camera input, microphone and wireless MEMS transmitter chips for connectivity to home, friends and work, as well as miniaturised CPU and motherboard to run software services, etc.

Smart Fabrics. One of the specific areas of potential for wearables is smart fabrics with flexible input and output electronics. Solar-powered fabrics can act as touch sensitive display and even fold itself with embedded artificial muscles fibres, or can be used to recharge mobile devices like iPods. Nanotechnology like carbon nanofibres and nanotubes can be used for smart textile and membranes. They can be washed too, but we would need to unplug the sensors from the fabrics before washing as most of the latter are not water proof. The nanomaterial technology itself is used to make faster/stronger/cheaper/lighter products, and also to inject new features such as the ability to conduct electricity, from making conducting to semi-conducting fabrics, making glues with optical properties (optoelectronics) & making ferrofluidic refrigeration systems (environment friendly unlike CFC), resistance to chemicals and heat, better recyclability and impermeability to fluids. Strands of cheap nanomaterial can be sewn into normal fabrics to create circuitry and smart computing wearables (a meter today of nanofibre can cost about US\$0.40).

3.16 Standards Development

Some important relevant activities in standards development have already begun, which is a sign of technologies to come into the global marketplace. New standards will emerge in the future as research and commercialisation activities intensify.

3.16.1 Collaborative & Distributed Agent Systems in Smart Spaces

The vision for smart spaces naturally implies the possibility of distributed sensors, distributed applications, software, hardware, networks, involving multi-vendor technologies and products being used. Distributed smart agent technologies become a natural fit in this type of distributed infrastructure and networks, and hence constitute a key enabling pillar to building smart sentient spaces.

A multi-agent based solution that reaps the benefits of agent collaboration will allow simpler computing individual agents to be deployed at nodes. This distributed collaborative approach is akin to peer-to-peer model compared to a centralised agent intelligence approach. Its advantages are:

- Avoiding single point of failure in a centralised model;
- Avoiding power-intensive overheads in repetitive communication with a central entity especially when we are dealing with power sensitive sensor nodes;
- Enabling the use of different agent techniques within an open standard agent infrastructure like FIPA (see below) that can complement each other's strengths and weaknesses, from rule based to statistical modelling types. Agent fusion allows the solving of complex problems, for fault diagnosis, or for fault-prevention proactive diagnostics (prognostics) using the interaction between simpler individual agents. There is also the possibility to deploy different lightweight or heavyweight computing agents at different nodes depending on each node's computing resources (be it a tiny sensor, a more powerful computing appliance or other computing platforms in this network in question).

Foundation of Intelligent Physical Agents (FIPA at www.fipa.org). FIPA is a non-profit organisation formed in 1996 and registered in Geneva, Switzerland. Its membership includes companies like British Telecommunications, IBM, KDDI, Mitsubishi Electric, Motorola, NIST, NTT, Siemens, Tohshiba and others. It aims to produce end-to-end software standards across multi-vendor platforms for heterogeneous and interacting agents, as well as agent-based systems.

Work in FIPA is done via the technical committees, working groups and special interest groups. Its repository of specifications represents a collection of standards which are intended to promote the interoperation of heterogeneous agents and their services. The standard areas cover agent architectures to support inter-agent communication, communication languages and content languages for these inter-agent messaging, interaction protocols for messaging and complete transactions. There are also future plans to extend protocol standards to include the coping of longer term relationships between agents. Readers can find the entire list of many specifications at FIPA website.

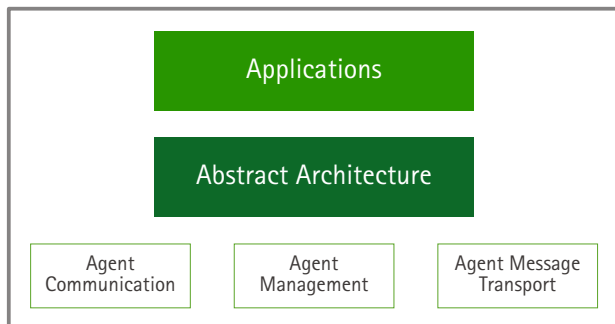


Figure 17. FIPA's Repository of Specifications

Source: FIPA

According to FIPA, their emphasis is on practical commercial and industrial uses of agent systems, but they also focus on intelligent or cognitive agents (software systems that may have the potential for reasoning about themselves and/or other systems that they encounter). The core message of FIPA is that through a combination of speech acts, predicate logic and public ontologies, they can offer standard ways of interpreting communication between agents in a way that respects the intended meaning of the communication. This is much more ambitious than, for example, XML, which only aims to standardize the syntactic structure of documents.

The various technical committees (TCs) of FIPA currently are the Ad Hoc TC, Methodology TC, Modeling TC, Security TC, Semantics TC and Services TC. Their scope of work can be found on the official website of FIPA.

3.16.2 Data & Application Related Standards

In the world of smart sensing and distributed sensing, a lot of data may be churned and shared. Data may be passed from one input device to another output device, flowing from one system to another. Data and application centric interoperability and standardisation may be useful. Standards in MPEG7, MPEG-21, semantic web, XML etc are relevant to much of the data processed in the smart space. There are also developmental efforts towards standardisation in human machine interface specifications for mobile devices. This is already completed for desktop devices in a series of ISO standards (ISO 14915, 9241, ISO-IEG 11581, 13714 and 11580) and would require an equivalent to be established for mobile devices according to the UMTS Forum.

Other standards may still be lacking for building seamless smart spaces such as in areas of:

- End-to-end security (e.g. standards like PKCS are developed but more testing are required, as well as the need for a reliable and interoperable user authentication and non repudiation platform);
- Privacy;
- Billing & payment;
- QoS.

Location based services and instant messaging are also often found in smart spaces. In the mobile space, we have the Open Mobile Alliance (OMA). The Open Mobile Alliance (OMA) Ltd. (www.openmobilealliance.org) was established in Jun 2002 by the consolidation of the WAP Forum and the Open Mobile Architecture Initiative, with participation from about 200 companies representing the world's leading mobile operators, device & network suppliers, information technology companies and content providers. It aims to promote interoperable services across countries, operators and mobile terminals that will meet the needs of the user.

MPEG Standards. MPEG-4 formats seem to be the de facto standard for video data applications. In fact, 3GPP has chosen MPEG-4 as the open multimedia standard for 3G. MPEG-4 is highly scalable and can adapt ingeniously to different platforms like mobile handsets or PCs. It also incorporates digital rights management. In general, MPEG-4 has many profiles and versions. Each profile specifies what coding features that the decoder can support. So far, there is no known successful attempt to stream real-time video using MPEG-4 core profile in which video-object segmentation is required. Most of the video-conferencing applications use MPEG-4 simple profile or MPEG-4 advanced simple profile. Although there are many profiles, each profile is created by adding new features to the baseline profile (MPEG-4 simple profile). The MPEG-4 part 10 standard is very much a new algorithm that has an entirely new bitstream format. The baseline profile is totally different from MPEG-4 simple profile. MPEG-4 part-10 is developed together with ITU and is known to ITU as H.264.

There are many different proprietary and open media formatting standards for audio, graphics and video contents. For audio, there are MP3, MP3 Pro, RealAudio, Windows Media Audio, iMelody, MPEG Advanced Audio Coding (AAC). For graphics, there are JPEG, JPEG 2000, GIF, Macromedia Flash, Wireless BitMap (WBMP), W3C's Scalable Vector Graphics (SVG) and Binary Format for Scenes (BIFS). For video, there are ITU's H.263, MPEG-4/H.264, QuickTime, ActiveMovie, RealVideo and Windows Media Video (WMV). According to UMTS Forum, we will see in future the convergence into integrated multimedia standards such as MPEG-7 and MPEG-21 amongst others.

Markup Languages. Markup languages began in 1986 when SGML (Standard Generalised Markup Language) was developed for electronic documents. SGML is used for describing markup languages. HTML (Hypertext Markup Language) for the Internet, an ISO 8879 compliant SGML application developed in 1990, then popularised markup languages as the entire world became connected online.

As more vertical applications come onboard, HTML began to show insufficiency in catering to the needs of specific industries. Thus, XML was created and accepted as a W3C standard in 1998 to expand the capabilities of markup languages to meet our increasingly demanding needs. The Extensible HyperText Markup Language (XHTML) is a family of current and future document types and modules that reproduce, subset, and extend HTML, reformulated in XML. XHTML family document types are all XML-based, and ultimately are designed to work in conjunction with XML-based user agents. There are also other markup languages like Voice XML. More information can be found at www.w3c.org.

Life Sciences markup languages. When sentient technology systems and applications are deployed, these have to take into account the various community vocabularies in the application environment in question. In the biotechnology sector, there are standards like BioML, Bioinformatic Sequence ML (BSML), GAME, GEML and in healthcare, there are standards like HL7 (Health Level 7) and ISO TC215 standards. Similar markup language standards exist in other clusters from finance to land/construction, to travel/food, publishing and print, as well as to legal, government, education and even in maths and sciences.

3.16.3 Digital Living Network Alliance (DLNA)

A newly formed Digital Living Network Alliance driven by 145 technology companies was founded in Jun 2004 by members like Fujitsu, HP, Intel, IBM, Kenwood, Lenovo, Microsoft, NEC, Nokia, Panasonic, Philips, Samsung, Sharp, Sony, STMicroelectronics and Thomson (noticeably Apple is missing from this Alliance at the point of drafting this document). It was actually introduced in Jun 2003 as the Digital Home Working Group (DHWG) but is now formalised into an Alliance. This Alliance aims to promote standards in the seamless sharing of digital contents across different wired and wireless platforms, networked devices found in the smart digital home. Beyond the Digital Home, its concept of Digital living extends interoperability to include sharing content while travelling, from the office, or any other possible scenario outside of the home.

A first version of its specification "DLNA Home Networked Device Interoperability Guidelines v1.0" can be found on its official website (www.dlna.org). The specification aims to simplify the sharing of digital content, such as digital music, photos and video, among networked consumer electronics, mobile devices and PCs. By establishing a platform of interoperability based on open industry standards, DLNA delivers technical design guidelines that companies can use to develop digital home products that share content through wired or wireless networks in the home. Certification programmes are also part of the overall plans and vision of DLNA. Compliance workshops or Plugfests are also regularly hosted.

Today, digital home products cover intelligent source devices such as advanced digital set-top boxes, PCs, and access platforms like residential gateways (RG), as well as simple sink and source devices that provide media acquisition, recording, playback, rendering, storage, sourcing capabilities and content protection. Some examples include PDAs, notebook PCs, broadcast tuners, networked storage units, CD/DVD players and recorders, TV monitors, stereos, multimedia mobile phones, home theatres, wireless monitors and game consoles as well as other video, audio and image capturing devices. This could very well extend into embedded computing platforms with advanced human-computer interfaces or sensor-enabled devices in future that handles digital media. In fact, DLNA believes that over time, as new technology and standards become available, the DLNA Interoperability Guidelines may broaden to cover other usage areas such as home control, network communications, and more advanced entertainment service.

The IP family of protocols is the foundation of DLNA spectrum of technologies. IP is also the basic means for establishing communications among all devices on the Internet. The Internet of Things will likely be based on IP too. Amongst the technologies DLNA promotes from 2005 onwards are IEEE 802.11x, uPnP version 2, JPEG 2000, digital management rights interoperability etc. Soon, as sensors make their way into the modern homes, more sensor related standards may emerge in this Alliance especially when founding companies like Intel are also heavily involved in sensor R&D such as their Deep Networking & Proactive Computing initiatives. Security and business related standards for authentication and payment protocols may also be needed in future, such as those based on two or more factor authentication.

3.16.4 IPv6 Sensor Networking Consortium

IPv6 (www.ipv6.org). IPv6 stands for "Internet Protocol Version 6". It is designed by the Internet Engineering Task Force (IETF, at www.ietf.org) to replace the current version of Internet Protocol - IP Version 4 (IPv4) - that is about 20 years old, and which is what most of us are using today to surf the Internet. IPv6 is undertaken specifically by the Next Generation Internet Protocol (IPng) working group in IETF. The 6bone is an IPv6 testbed to assist in the evolution and deployment of IPv6. It is currently a worldwide informal collaborative project, informally operated with oversight from the "Ngtrans" (IPv6 Transition) Working Group of the IETF. More details on IPv6 are mentioned in the communication roadmap track.

IPv6 Sensor Networking Consortium. The Japanese government has mandated the transition to IPv6 by 2005. Eight companies namely, Fujitsu, Hitachi, Internet Research Institute, Matsushita Electric Industrial, Matsushita Electric Works, NEC, Nikken Sekkei and NTT Communications have also formed a consortium called the IPv6 Sensor Networking Consortium in Jun 2003 that will promote and propose standards for sensor networks in smart homes and intelligent buildings. Their aim is not to promote IPv6 technology per se but to examine the possibility of creating a business out of networking electric equipment and embedded sensors in buildings, factories, home or local communities, as well as to solve relevant problems. This consortium is supported by the Application Working Group of IPv6 Promotion Council of Japan.

3.16.5 IEEE Standards – P1451 and 802.x series

Sensor networks will also drive new wireline and wireless protocols that define the Internet in the future. In fact, IEEE engineers and researchers have been publishing articles on the future of sensor networks and various architectures are proposed for more efficient handling of sensor clusters. For instance, new energy-efficient routing protocol like Directed Diffusion is particularly interesting. There are also others like SPIN and LEACH. The latter is a cluster-based protocol where one head aggregates information from sensors in its own cluster and passes it on. Sensor networks present great challenges in communication paradigms, as it is now not one-to-one type of communication between two devices, but clusters of many-to-many communication in terms of hundreds, thousands and possibly millions and beyond. Wireless sensor networks typically require new developments in networks that are data-centric and application-aware.

The 802.x family of wireless communication standards are described in details in the other communication track in this report and relatively well known to the infocomm industry. Related 802.x protocols are:

- IEEE 802.15.1 Bluetooth (7 nodes per network, range 10m);
- IEEE 802.15.4 ZigBee (65000 nodes per network, range 75m);
- IEEE 802.11a,b,g WLAN (30 nodes per network, range 100m);
- IEEE 802.6b Wireless High-Speed Unlicensed Metropolitan Area Network (Wireless HUMAN).

There are also European-only standards like Network Technology for Intelligent Homes and Buildings.

We would focus here on the IEEE P1451 family of standards by IEEE and NIST (National Institute of Standards and Technology in USA).

Background. Sensors or actuators are termed as transducers in this standardisation effort. Transducers are used today in a diverse gamut of industries and manufacturers seek to build low-cost, networked smart transducers. These transducers are deployed in networks and guided by control networks. However, there are many differing sensor control networks or fieldbus implementations available, with their own pros and cons for each application environment. With no common standard to interface the transducers to a wide range of control network protocols, implementations to manufacturers can be very costly. A universal standard interface is needed.

Also, the universal standard needs to take into account the trend towards digitisation. With the advent of digital communication schemes, there are less and less tedious parallel analogue wirings in transducer networks, saving upgrading costs, easing installation and the maintenance of systems. With digital schemes, micro processors are increasingly embedded into these transducers. This is what we noted before on the trend of online sensors getting smarter with embedded processor intelligence. Furthermore, many transducer networks are becoming more reliant on embedded wireless communications.

The above reasons give rise to what IEEE P1451 aims to develop – a smart transducer interface standard for analogue and/or digital interfaces, as well as wireless interfaces. This standard is to make it easier for transducer manufacturers to develop smart plug and play devices and to interface those devices to networks, systems, and instruments by incorporating existing and emerging sensor- and networking technologies. Established industry standard like P1451 is useful and often used in building sentient spaces.

After discussions initiated in Sep 1993, the first working group meeting for standardisation for smart sensor technology began in 1994 under the collaborative auspices of IEEE and NIST(www.motion.aptd.nist.gov/). It then led to the development of the family of IEEE 1451 (Draft Standard for a Smart Transducer Interface for Sensors and Actuators). It is a pragmatic approach to standardising networked sensors today.

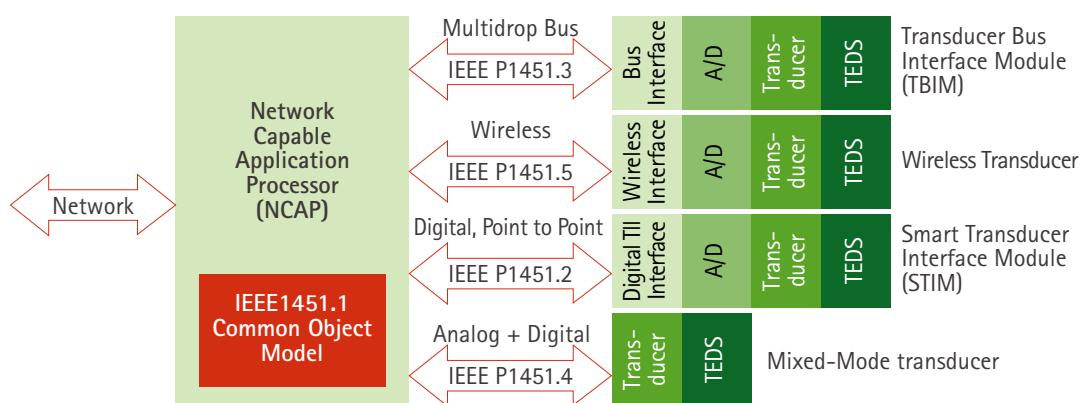
Recognizing that smart sensors will inevitably take a number of different forms with different levels of integration, the IEEE 1451 standards define a set of complementary interfaces designed to work together or independently. For instance, an IEEE P1451.4 mixed-mode sensor could plug into an IEEE P1451.3 transducer bus interface module that digitises the transducer signal and communicates the data over the IEEE P1451.3 sensor network.

- **IEEE 1451.1 – (approved 1999) "Network Capable Application Processor (NCAP) Information Model specification".** This includes the definition of a common object model, with standardised software interface specifications, of a networked smart transducer. A common object model will simplify the support of multiple sensor/actuator network protocols. It is complementary, not competitive, to any existing object models and will not define individual device algorithms or specifications of what are implemented using the model. Little or no changes would be required to use different methods of A/D conversion, different microprocessors, or different network protocols and transceivers.
- **IEEE 1451.2 – (approved 1997) "Transducer to Microprocessor Communication Protocol and TEDS Formats".** This defines a digital point-to-point interface to connect a smart transducer module with digital output

to a microprocessor-based network adapter. Although the standard has enjoyed limited commercial success, the general concept of the Transducer Electronic Data Sheet (TEDS) introduced by this standard has been adopted widely in various forms. A working group has reconvened to investigate revisions of the specification, including an alternative physical layer.

- **IEEE P1451.3.** This draft defines a digital communication interface for distributed sensor networks with multidrop systems. The standard defines electrical interfaces, transducer electronic data sheet (TEDS), channel identification protocols, hot swap protocols, time synchronization protocols, and read and write logic functions used to access the TEDS and transducer data. The standard will not specify signal conditioning, signal conversion, or how an application uses the TEDS data. The standard will allow multiple, time-synchronized, high-bandwidth sensor data channels to occupy a single transmission medium that is based on Home Phoneline Networking Alliance (HPNA) technology. The specification is being balloted.

Figure 18. IEEE 1451 Standards for Smart Sensors and Actuators



Source: NIST

- **IEEE P1451.4.** The P1451.4 Working Group was formed to define an interface specification for analogue transducers, to make it easy for adding smart, plug and play capabilities to traditional analogue transducers. Currently the Working Group proposes a mixed-mode interface for analog transducers with analog and digital operating modes. When a transducer first comes online, it will go into digital mode and send out TEDS data. Then it goes into analogue mode for normal operation.

- **IEEE P1451.5** "Wireless Communication Protocols and Transducer Electronic Data Sheets (TEDS) Formats". With the trend towards wireless online sensors, this draft proposal in progress will address the need for a standardised wireless communication methods and data format for transducers. It will also address the integration of sensors with various communication protocols such as 802.11 (WLAN), 802.15.4 (ZigBee), Bluetooth, etc.

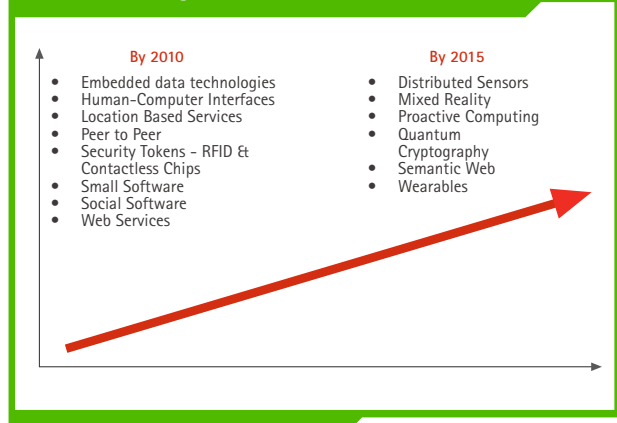
3.17 Summary: Technology Roadmap

We have above many technologies and standards in sentient spaces. In tabulating the timeline for technologies, market data reports like Gartner's Hype Cycle for Emerging Technologies 2004 are used as reference and expert consensus is sought.

Gartner's methodology defines a Plateau of Productivity, which signifies a maturity period where the real-world benefits of a technology are demonstrated and accepted, and it means approximately 30 percent of the technology's target audience has adopted or is adopting the technology. We group technologies into two categories according to currently known circumstances, those with potential to reach its Plateau of Productivity in 5 years (2010) and in 10 years (2015). The actual accuracy of these timeline milestones

depends on many factors, and the commitment and resources dedicated to their fulfilment. Nevertheless, this timeline below aims to give a broad sense of how these technologies can be comparably positioned in terms of timeline readiness.

Figure 19. System and Application Technology Roadmap for Sentient Technologies



The above timeline will work together with other roadmap developments in communications & networking technologies, and computing technologies with nano & bio. For these roadmaps, one can refer to the respective detailed track reports.

Singapore Landscape

4.1 Introduction

Singapore is fortunately well poised to embark on this technology roadmap. We will see in this chapter key illustrations from various research and industry activities to support the development of smart sentient spaces.

In synergy with efforts in the research community in Singapore, driven mainly by the Agency for Science, Technology and Research (A*Star, www.a-star.gov.sg), one of the future research roadmaps proposes specifically smart space technologies in Singapore, entitled "Intelligent Systems and Sensor Networks (ISSN)". Another roadmap on Information Management is equally relevant on information retrieval and processing technologies, as we mentioned before that data software and distributed data management is useful to deploying sentient technologies. In a quick snapshot, the local research capabilities offered are:

- Data Storage Institute (DSI): advanced storage technologies like microsystems and nanosystems, network storage technologies.
- Institute of High Performance Computing (IHPC): immersive virtual technology, supercomputing.
- Institute for Infocomm Research (I²R): wireless communications, sensor networks, signal processing, decision making tools, brain-computer interface, semantic web, biometric sensors and algorithms, privacy and identity management.
- Institute of Materials Research and Engineering (IMRE), Institute of Microelectronics (IME): sensors, displays, new smart materials.
- NUS, NTU, SMU: sensor middleware and management, quantum cryptography, computer graphics, intuitive user interfaces, artificial intelligence, mixed reality, ontology, metadata, open source, semantic web.

- Polytechnics: digital media design, wireless sensor & Tiny OS applications, biosensors & bioMEMS, robotics, multi-modal fusion of sensors...
- Singapore Institute of Manufacturing Technology (SIMTech): robotics, sensors, actuators, haptics, hardware packaging.

In the following section, we will describe activities in Singapore related to technologies depicted earlier in this report.

4.2 Key Players in Singapore

Infocomm Development Authority of Singapore (IDA).

In Singapore, IDA also drives the WEAVE (Web Services Add Value To Enterprises) programme. A Web Services Chapter was also set up under the Singapore infocomm Technology Federation (SITF). The Chapter aims to accelerate the adoption of Web Services applications and services. It works with the public and private sectors to promote Web Services as an emerging technology in the industry. Various initiatives under the Chapter are designed to realise business opportunities and enhance interoperability.

Authentication and Payment for smart spaces. IC-based technology will play a key role in the future smart home and embedded smart space for authentication and payment purposes. In the age of proactive computing and automation, non-repudiation may also be needed at some point and IC technologies can enable this.

In Jun 2004, four founding countries (China, Japan, Korea and Singapore) inaugurated the first Annual General Meeting to launch the Asia IC Card Forum (www.asiaiccardforum.org). This Asia Pacific wide initiative aims to promote IC-based common platforms across member countries, promote ISO standardisation of IC technologies and applications, and to leverage on the immense market in the Asia Pacific. Cross border trials on selected services are used to test and deploy common platforms and standards derived by this Forum. For a start, the Forum is setting its sights on e-passport

collaboration with biometric sensors as well as a contactless chip-based multi-application platform for transit and payment services, under the motto of One Card One Asia. More ideas abound for future projects.

IDA is leading the participation in this Forum as the national representative agency from Singapore, along with the local industry via our national IT Standards Committee's CPITC (Cards and Personal Identification Technical Committee). In Singapore, the CPITC and Biometrics Technical Committee (BTC) are also driving applied biometrics and biometric format related standards.

National University of Singapore (NUS). NUS researchers are working on power design technologies which are key to wireless sensors. An on-chip power management platform was integrated with MEMS on another chip, which further includes sensors for light and temperature detection for surveillance applications. Work is in progress to integrate wireless communication capability to interact with a network of wireless sensors.

NUS School of Computing. The Computer Science department is working on sensor middleware and management. Sensor middleware is a key area of work by many including the UCLA-WINMEC RFID Research Lab (www.wireless.ucla.edu/rfid/research/) where the focus is on sensor middleware and also on reconfigurable wireless interface for networking sensors (REWINS). The department has also organised successful workshops such as MOBWISER (Workshop on Mobile, Wireless and Sensor Networks), supported by IDA.

Wearables. Similar to DARPA's research efforts in self-regenerative power technologies, NUS and the Defence Science and Technology Agency (DSTA) are also researching into using our body movements to generate electricity and power that wearable computers may need. For instance, smart materials are built into the soles of a pair of shoes and can be used to generate power for wireless applications when one walks. The next step is to adapt the technology for commercial and military applications. Interesting ideas include taking cue from a handshake to mean an automatic exchange of electronic business cards between the computing devices of both persons.

The NUS has also developed a smart shirt that can send out wireless alerts to a designated person should the wearer slip and fall, especially suited for the elderly to get immediate help. Such a patented innovation that has received local and overseas media attention is based on a sensor-transmitter MEMS based device which measures 2cm by 2cm. By 2005, they hope to commercialise warning devices that can be clipped onto a shirt or jacket at a low cost of \$100. Further into the future, we can see such devices being woven into clothing or even integrated as an iron-on patch.

NUS Mixed Reality Lab. Another strong area of research in NUS is on mixed reality, new media and human-computer interfaces (<http://mixedreality.nus.edu.sg>). The Mixed Reality

Lab Singapore at NUS fronted by Professor Adrian David Cheok, a Young Scientist Award winner (2003), is aiming to push the boundaries of research into interactive new media technologies through the combination of technology, art, and creativity. They have developed technologies to superimpose output from a 3D virtual viewpoint camera system into the real world. Users see life-sized live 3D virtual images of remote collaborators standing in the real world in front of them, paving the way for mixed reality conferencing. The researchers are also developing unique tools and interaction techniques to support remote collaboration.

To demonstrate the potential of mixed reality for entertainment applications, the research team in NUS has also developed a 'Human-Pacman' game project. The technology opens up exciting new opportunities in the areas of computer-graphics and human-computer-interface development. There will be applications in a great variety of areas such as education, architecture, military, medicine, training, sports, computer games, tourism, video conferencing, entertainment, and human welfare.

The same NUS team has also spun off two companies in 2003, Real Space and Brooklyn-Media. Real Space was funded by Mr. Sim Wong Hoo (CEO Creative Technologies) and is producing mixed reality systems for military and industry. Brooklyn-media is commercialising systems for digital games and mobile entertainment using novel interactive technologies.

The Mixed Reality Laboratory in NUS also works closely with the Human Interface Technology Laboratory established in 1989 in the University of Washington, USA, headed by Professor Thomas Furness. The HIT Lab US has spun off or helped to start 23 companies over the past 13 years.

NUS Physics Department – Quantum Information Laboratory. Led by world record holder in free space quantum cryptography, Professor Christian Kurtseifer, the team in NUS is actively researching, experimenting and promoting awareness in quantum cryptography.

To garner industry view in Singapore on quantum cryptographic products for integration with communication systems, a local industry survey was conducted in conjunction with a public seminar on "Quantum Cryptography – Status and Updates", jointly organised by NUS and IDA, attended by some 60 staff from various security companies and government agencies. The audience came from both supply and demand sides of technology. The survey results showed that:

- 80% thought quantum cryptographic products are relevant for their businesses;
- 59% sees its mass commercialisation by 2015, while 100% thinks by 2020, it will be mass commercialised. Amongst this, 24% sees its mass commercialisation by 2010;

- A whopping 97% opined that quantum cryptography will make a worthwhile impact on communication networks and value to businesses. In fact, we see quantum secured networks making inroads into finance, government, defence, telecommunications networks, and may one day become the preferred secured infrastructure over the Internet.

Centre for Advanced Media Technology, Nanyang Technological University. The Centre was established as a joint research and development centre by the Fraunhofer Institute for Computer Graphics (IGD) Darmstadt, Germany, and Nanyang Technological University (NTU), Singapore. Its key competencies include the following areas - Multimedia in Education and Commerce, Geographical Information Systems, Scientific and Medical Visualisation, Next Generation Learning Environments for Life Sciences, Virtual Engineering and Manufacturing, Virtual and Augmented Environments for Medical Applications, New Media for Edutainment and Cultural Heritage and 3-D Modelling and Reconstruction of Incident Scenes. NTU also has a Virtual Reality Centre at its Technopiazza developing virtual reality applications.

Nanyang Technological University (NTU). The NTU and global defence contractor Thales have set up a joint research laboratory to develop cutting-edge defence technologies with an initial funding of S\$2 million. The Thales@NTU lab will work on areas like wireless sensor communications and photonics, which also have civilian applications like using sensors to detect airborne toxic elements or flammable gases for homeland security.

Institute for Infocomm Research (I²R). Dr Wu Jian Kang, principal scientist and department manager of New Initiatives for I²R, leads R&D work in the area of brain-computer interface and embedded networked sensing systems. While UC Berkeley works on TinyDB (tiny database technologies like TinySQL – optimized code from SQL for sensor applications), Stanford on Data Stream, Cornell on distributed database and cross layer optimisation, I²R works distributed data processing and management. I²R also works on collaborative tracking and distributed data fusion.

I²R's approach is to leverage on event-based transmission compared to 'proactive and on-demand' data sending strategy by some others which drains heavily on each sensor as they need to rely on a smarter central system to compute data. As sensors and nodes are increasingly equipped with processing power and getting smarter themselves, it is easier to allow local computations by individual sensors and do less communication transmissions which are power-intensive. By sending only changes in data, the need to constantly

transmit to and receive from the central system is reduced for applications like database queries. Change-based data compression will not affect the performance of further analysis results.

Interesting prototypes and applications are developed in I²R. Some of the tracking and monitoring wearable sensor applications developed are also suitable for healthcare applications to the elderly or handicapped. They have demonstrated the use of sensor networks and wearable sensors to monitor the activities of people and to produce activity status such as how many hours of sleep or exercises per day are observed, alert warning system to aides in case of elderly users in danger.

A lot of other research and development is also underway. I²R is also working with MEMS experts to develop new sensor-on-chip which is easy to wear or as a fashion item. They are also working with physiology experts to develop good physiological models.

DSTA, DSO, ST. For the Defence Science & Technology Agency or DSTA, sensors are the eyes and ears of a defence system and are critical in enhancing early-warning capabilities. The survival and operational effectiveness in warfare strategies are reliant on the sensor suites as they provide situational awareness and target information. DSTA and several other local defence related industry organisations like Singapore Technologies and DSO National Laboratories (DSO) have strong expertise in sensor technologies, sensor acquisition, system customization and integration. They together can form a formidable centre of excellence for smart space type of commercial platforms. Dr How Khee Yin, Head of DSO's Centre for Decision Support has been instrumental in building up DSO's applied research capability in artificial intelligence, data fusion, decision support, modelling and simulation. A network with the best sensor houses in the world is also established through close global collaborations.

Linux Enterprise Applications Porting (LEAP). In Jun 2004, Oracle and Red Hat invested S\$20 million for the subsequent two years to set up a world's first regional center in Singapore to assist companies to develop programs for Linux. The LEAP center aims to fast track more Linux-based software in the Asia Pacific region. It is staffed initially by employees from the two founding companies. Other companies like Computer Associates believe that this initiative will open up the Linux software industry. Major nationwide sensor projects like SensorNet in the USA uses Linux clusters of computers.

Conclusion

We have seen in this report on sentient technologies the following:

- The vision for sentient spaces;
- Busy global activities in this area;
- Impact of sentient technologies and application examples;
- Strategic business trends, technologies, standards development;
- Technology roadmap for sentient technologies;
- Highlights of key activities in Singapore.

Many sentient and security applications we envisage in the future will require sensor technologies. Two key areas in sensors are (1) physical networks and (2) distributed & small software.

- **Physical Network Domain:** Wireless sensor networks for distributed sensing – i.e. networking technologies, middleware architectures and new algorithms that provide efficient wireless sensing. Innovations are needed to meet technical challenges in
 - (i) security, trust models and reliability,
 - (ii) models of computation for sensor networks,
 - (iii) self-reconfigurability and adaptability, autonomic cognitive systems,
 - (iv) safety versus usability.

Examples of developmental programmes like Intel's Proactive Computing, Xerox's embedded collaborative computing and sensing, US EmNet, SensorNet.

- **Software Intelligence Domain:** Distributed Intelligence & Small Software – i.e. software technologies for sensors & networks for distributed data inference, management, query, processing, storage and retrieval, as well as small software optimised for embedded networked devices like

tiny open source computing. Mobile agents and agent collaboration for proactive computing are also important. Distributed intelligence can be enabled by localised algorithms. Personal peer-to-peer applications will grow within dense pockets of computing devices. New programming languages are also important for sensor development (hardware programming example like Stargate, software examples like Emstar and NesC), and so is the building of an inventory of customisable & parameterised libraries and development kits that people can use to build applications and programmes.

There are also other technologies that enable end-to-end system building and integration like:

- **Enabling Technologies:** Web Services, system clustering, Semantic Web, location based technologies, tiny efficient sensor-on-chip with power efficient designs. There are technologies that can contribute to affective and useful computing like intuitive human computer interfaces, mixed reality and smart wearables – smart fabrics, embedded data technologies, social software. There are also privacy enhancing technologies, network security technologies like quantum cryptography and common authentication infrastructure using biometrics or contactless smart cards.

Communications in the Future

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Communications Landscape 2015

1.1 Introduction

This track focuses on communications. Communication refers to the basic human need to be connected to other humans and its surroundings, anytime, anywhere, and via various platforms and devices. Over the last ten years, technology innovations in communications have transformed our lives significantly. In particular, we have witnessed the number of mobile subscribers surpassing the number of fixed-line subscribers and the birth of broadband Internet, all of which lay the essential foundations for many new applications and services, like peer-to-peer collaborative applications, web services, and grid computing, that we enjoy today.

In this chapter, we will start with painting a vision for communications in 2015. This is followed by a discussion on the global outlook of this sector, where we highlight the economic impact of communications on nations, and more importantly, key growth areas in the communication landscape over the next ten years.

The rest of the document will be structured as follows: To provide a more holistic view of things, we will discuss the impact of communications on businesses, government, society and individuals in Chapter 2. In Chapter 3, we will discuss the key technology trends that will drive the communication landscape over the next ten years. This is followed by a snapshot of the Singapore landscape in Chapter 4, before we conclude in Chapter 5.

1.2 Vision for Communications

In 2015, we envision the existing communication landscape of public switched telephone networks, broadcast, cellular, and fixed line access to all converge onto a single unifying platform based on Internet Protocol. The communication landscape will still be vibrant, characterised by many different network systems, ranging from fibre-based fixed line access to fourth generation cellular

mobile systems and short range wireless sensor network systems. To the user, roaming between all these heterogeneous systems will be seamless, with high levels of end-to-end quality of service and security.

For cellular networks, most operators have deployed Fourth Generation (4G) mobile systems that can deliver data rates of 100Mbps and beyond at high mobility and 1Gbps at stationary. The bulk of the traffic is still being delivered over Third Generation (3G) mobile systems. In many regions, 3G systems have evolved into the more advanced Third and the Half Generation (3.5G) systems capable of providing data rates above 10Mbps. At the same time, the old Second Generation (2G) and Second and the Half Generation (2.5G) systems are slowly being de-commissioned. Wireless coverage is also provided by various broadcast and multi-casting systems. Handheld devices that can view live broadcast transmission of news, concerts and even World Cup soccer matches have become the norm.

Complementing the cellular and broadcast systems are the highly flexible broadband wireless technologies that are used for setting up wireless local area network (WLAN) and wireless metropolitan area network (WMAN). In rural areas, where it is costly to provide access with fibre and/or cellular services, alternative low cost wireless infrastructure consisting of broadband wireless technologies are common. In urban areas, city-wide wireless hot-zones that provide users no-frills leisure and entertainment surfing can also be found.

There is also an abundance of very short range wireless systems, personal area networks, body area networks, and wireless sensor networks. Most electronic devices come with one or more network connectivity interfaces. Ultra-Wideband makes it possible to do high speed data transfer of 1Gbps and beyond in close proximity to the user. Radio frequency identification is used in the tagging

of almost all items for efficient supply chain management. ZigBee or similar standards are used to create highly scalable wireless sensor networks for remote monitoring and control of our physical environment.

Handheld devices are software re-configurable, able to take on different wireless standards and handle multiple frequency bands. Depending on the user preference, agent programmes can be used to assist the user in making day-to-day decisions.

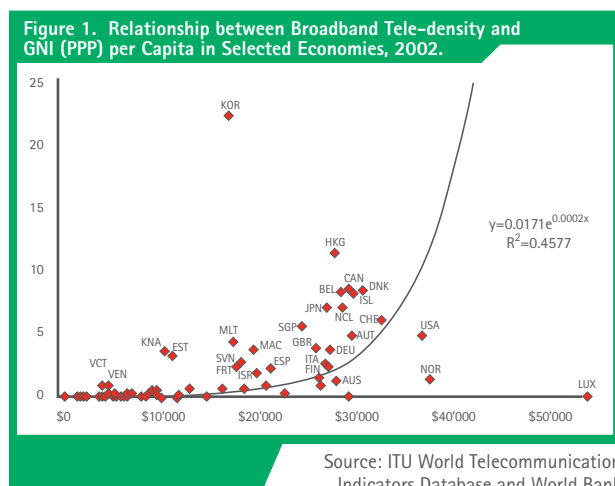
For fixed line broadband access, fibre-to-the-home has become the norm in most developed countries. Hybrid-fibre coaxial (HFC) cable remains a valid competitor to fibre, but digital subscriber line (DSL) is no longer an attractive access option for users.

1.3 Global Outlook

1.3.1 Economic Benefits

Telecommunication services set the essential foundation of a healthy information economy, being both a creator and an enabler of wealth in related service sectors. Generally, countries with high broadband penetration levels also have high levels of gross national income (GNI) per capita (see Figure 1). Likewise, countries that have been most successful in tapping into the potential of the information economy, like South Korea, have succeeded in growing their information economies as a percentage of gross domestic product (GDP) at a much faster rate of 4.6 percent than the global average of 3.1 percent (2002 figures).

The potential economic benefits of widespread diffusion of broadband Internet access have always been one of the strongest arguments for government investments into a broadband infrastructure. A 2001 Brookings Institute study has even concluded that universal broadband in US would provide a US\$500 billion annual benefit to the US economy.



Another Sep 2003 study commissioned by Ericsson showed that "true" broadband (over 10Mbps) will result in national productivity growth of over 6-8%. If competitive true broadband is available, then national productivity growth of 10-12% can be expected. This provides the justification on why governments should give utmost priority to investment in research networks, information communication technology, and competitive telecommunications because no other technologies, such as nanotechnology and bio-informatics, have such a direct and measurable impact on productivity.

All over the world, various nations have invested huge amounts of money into broadband research. Canada has its famous CA*net4, a national broadband research and education network interconnecting high-speed regional optical research networks in each province, and through them universities, National Research Council institutes, other government laboratories, hospitals and schools across the country. CA*net4 also links to research networks in other countries including Internet2 in the US and Geant in Europe and is a partner along with SURFnet in the Netherlands and the STAR LIGHT in Chicago of the International Lambda Grid Testbed.

In US, there are the Internet2 research networks and the 100 X 100 Project. Internet2 is a consortium being led by 205 universities working in partnership with the industry and government to develop and deploy advanced network applications and technologies, with the aim to accelerate the creation of tomorrow's Internet. Separately, National Science Foundation's Information Technology Research program has also funded the 100 X 100 Project, which aims to make an affordable 100Mbps broadband connection available to 100 million American homes and small businesses by 2010. This project aims to conduct the basic research and develop the blueprint designs that will guide decision-makers in the construction of a network that is dependable and secure; understandable to users and operators; and both economical and scalable.

1.3.2 Biggest Market Opportunity

The telecommunication service sector is one of the biggest business opportunities in the world, growing from a market value of below US\$0.5 trillion in 1993 to around US\$1.1 trillion in 2003, at an average annual growth rate of 8.8% according to International Telecommunication Union (ITU). Moving towards year 2015, we believe the greatest opportunity in the telecommunications market over the next ten years (2005 to 2015) will be in the space of Broadband Wireless Internet¹. Why do we think so?

Taking a snapshot of the landscape at end 2003 (see Figure 2), we can see that there were approximately:

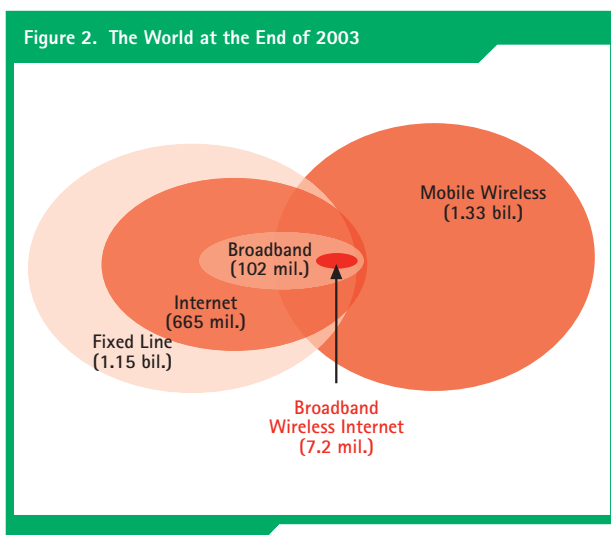
- 1.15 billion fixed telephone lines growing at a Cumulative Annual Growth Rate (CAGR) of 6.4% from 1998 to 2003;
- 1.33 billion mobile subscribers growing at a much faster CAGR of 33.8% from 1998 to 2003;

¹ Broadband Wireless Internet refers to technologies that can deliver high speed Internet access in excess of 1.5Mbps to the user via wireless means. 1.5Mbps is based on ITU's existing definition of broadband.

- 665 million Internet subscribers;
- 102 million broadband Internet subscribers accounting for around 15.3% of the total Internet population; and
- 7.2 million broadband wireless Internet subscribers. This figure is approximated based on the end 2003 Third Generation (3G) mobile subscriber data: 4.4 million Code Division Multiple Access (CDMA) 2000 1xEV-DO subscribers, according to the CDMA Development Group (CDG), and 2.8 million Wideband CDMA (WCDMA) subscribers, according to Global Mobile Suppliers Association (GSMA).

Fast forwarding to 2015 (see Figure 3), according to Nokia, the number of mobile subscribers is expected to reach 4 billion. This translates to a potential broadband wireless Internet market of 4 billion subscribers. We believe that there are several broad trends that will make "Broadband Wireless Internet" the single biggest market opportunity. They are:

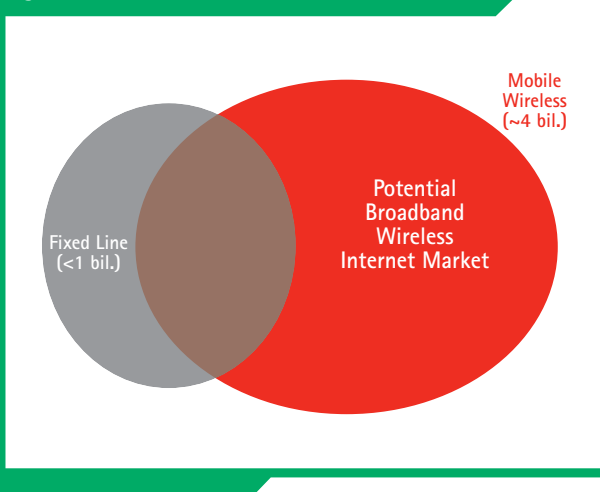
- **Majority of Internet connections will be broadband.** The assumption here is that the definition of broadband does not evolve over the next ten years. Today, the most common definition of broadband is that given by the ITU. ITU defines broadband as transmission capacity faster than primary rate Integrated Services Digital Network (ISDN), which implies access speed of 1.5Mbps. These speeds can already be considered loosely met by today's technologies, for example, WCDMA and CDMA2000 1xEV-DO can theoretically deliver 2Mbps and 2.4Mbps respectively for stationary users. New technology innovations are definitely going to push this speed much higher over the next ten years. For example, the Fourth Generation (4G) mobile system target set by the Wireless World Research Forum (WWRF) aims to achieve 100Mbps for high mobility and 1Gbps for stationary users. 4G prototypes developed by Japan's NTT DoCoMo that can better these targets has already been demonstrated.



- **Mobile Wireless is substituting Fixed Line installations.** The mobile wireless communications sector is experiencing remarkable growth, outstripping and in some countries replacing the traditional fixed line telephones. In 2002, the global number of mobile subscribers reached the 1 billion mark and also surpassed the number of fixed line subscribers. Over the last few years, growth in the fixed line installation for the developed countries has more or less stagnated. In certain European countries like Finland and Portugal, the percentage of households with only mobile connections is over 20%.
- **From "broadband to the home/business" to "broadband to the individual".** At the end of 2003, the leading broadband nation of the world, South Korea, has a broadband tele-density of 23.3%. Some analysts are saying that South Korea is showing signs of saturation because its penetration growth of around 2% in 2003 is the lowest among the top ten broadband nations. For the telecommunication operators to further grow their market, they will have to change their target audience from household/business to individuals, and the means to deliver broadband to the individual will be through the wireless platform. At the end of 2003, there were around 102 million "broadband" subscribers globally. This translates to around 1.7% broadband subscribers per 100 inhabitants. It is, therefore, reasonable to say that broadband is still at the start of its growth cycle with the main phase of market expansion still to come.
- **Internet Protocol (IP) is going to "rule" the world of communications.** For several years, IP has been touted as the unifying platform for data, voice, and broadcast media. Today, we are finally seeing concrete evidence of this taking place. Voice over IP (VoIP) allows users to talk to each other for close to nothing. There is therefore, little doubt that VoIP will eventually replace the traditional Public Switched Telephone Network (PSTN) telephony. According to Forrester, the complete western European migration to VoIP is expected to take place by 2020. However, the actual timeline may be much earlier given the recent announcement by British Telecom (BT), in Jun 2004, of plans to begin mass migration from PSTN to IP in 2007. BT expects to transform its United Kingdom (UK) telecommunication infrastructure into a pure IP-based network by 2009. On the mobile front, IP version 6 (IPv6) is also expected to be built into the next 3GPP (The Third Generation Partnership Project) specifications. This will make Internet access a de-facto feature on both the wired and wireless platform. On the broadcast front, companies like Texas Instruments have developed digital Television (TV) chip² for mobile handsets. Early field trials are expected in specific cities of Europe and Japan in 2005. Mass deployment of mobile digital TV infrastructure can be expected by 2007.

² Note that most common digital broadcast TV standards like Digital Video Broadcast (DVB) support IP transmission over Moving Picture Expert Group (MPEG)-2.

Figure 3. Vision of the Telecommunications World in 2015



1.3.3 Other Growth Areas

Short Range Wireless

By predicting that broadband wireless Internet will be the greatest growth area over the next ten years does not mean that this will be the only growth area. Over the next ten years, we can expect short-range wireless to be another significant growth area. There are a few opportunities in this space. The high-speed ultra-wideband (UWB) is expected to be the dominant communications platform for personal area network (PAN) and home-networking deployments within the next five years. As this technology matures, UWB may potential be used for outdoor usage and radar imaging.

Radio frequency identification (RFID) is another important area with numerous applications for logistics and supply chain management. Extensive RFID usage in supply chain infrastructure is expected to offer companies a higher level of automation and help drive lower cost through more efficient tracking, inventory management, and security.

Further down the road, short range wireless technologies like ZigBee or other similar standards are expected to feature heavily in wireless sensor networking applications. With ZigBee, highly scalable networks consisting of thousands of communicating devices can be created. Fine grained monitoring over large physical areas becomes a reality. For example, containers in cargo ship can be tagged with tamper detection sensors to increase security. These sensors can form a mesh network to exchange data, allowing relevant authorities to quickly pin-point the tampered container.

Fixed-line Broadband

Besides wireless sensors, we can still expect fixed-line to complement mobile wireless because of its inherent advantages like higher access speed and better security. Today, fixed-line broadband

remains a very attractive growth area with a healthy subscriber growth of 58% in 2003. Given that the broadband subscriber figures stand at 102 million (end 2003), there is still much room for fixed-line broadband to grow, based on the reasonable assumption that the existing fixed-line population of around 1 billion subscribers remains more or less constant for the next ten years.

Within this space, Digital Subscriber Line (DSL) is currently the most commonly deployed platform, followed by cable modems. Innovations to boost the speed and reach of DSL and cable are still ongoing. For example, the Very High-Speed DSL (VDSL)-2 standard is capable of achieving up to 100Mbps downstream, and the emerging Data Over Cable Service Interface Specification (DOCSIS)-3.0 standard is expected to achieve up to 200Mbps downstream.

Beyond DSL and cable, the next phrase of growth in the fixed-line space will be Fibre-To-The-Home (FTTH). Given that 4G is expected to provide 1Gbps for stationary users, we expect 1Gbps to be the minimum fixed-line access speed in 2015. Today, FTTH is the only fixed-line access technology that is capable of achieving 1Gbps and beyond.

1.3.4 Potential Risk Factors

The vision that we painted is naturally a rather rosy one. There are definitely risk factors that may de-rail this vision. A significant global economy downturn is definitely one of them and this can be due to factors like natural disasters, widespread terrorism, high fuel prices, or even infectious communicable disease (E.g. bird flu or severe acute respiratory disease).

Another risk factor is the potential health-risk associated with long-term exposure to radiation from mobile phones. Over the last few years, several studies have investigated whether the use of cellular phones is linked with an increased risk of brain tumours. Some lab experiments have shown that radiation from mobile phones can affect brain cells. However, it was never proven that this translates to real-life health hazard because several studies on people have found no evidence that mobile phones pose a health risk. Nevertheless, none of these studies were done over a long period. In Oct 2004, a Swedish study suggests that people who use a mobile phone for at least 10 years might increase their risk of developing a rare benign tumour along a nerve on the side of the head where they hold the phone. This result was surprising and highlights the need for more long-term research in this area.

Impact of Communications

2.1 Introduction

To give a more holistic view of things, we will discuss the impact of communications on businesses, government, society and individuals in this chapter.

For the impact of communications on business, we will focus on the three major groups of businesses – the telecommunication operators, the equipment vendors, and the application and service providers.

For the impact of communications on government, we will look at the policy and regulation issues facing the telecommunication industry that has traditionally been a highly regulated industry. Issues like government licensing, spectrum management, addressing, and numbering will be discussed.

There is little doubt that higher speed communications can bring about greater productivity gains and better quality of life. Greater bandwidth allows for greater connectivity among humans and machines, leading to better collaboration, operational efficiency, distance monitoring, information retrieval, and control. It also allows the creation and delivery of multimedia content, leading to better entertainment, learning, and decision making. For the impact of communications on society and individuals, we will focus instead on the challenges that high speed communications will have on the society and individuals.

2.2 Impact on Businesses

2.2.1 Telecommunication Operators

In the cellular space, many operators around the world have started their third generation mobile systems (3G) deployments, which are expected to be their next wave of growth. The initial adoption pace has been positive, dismissing away initial fears about its viability. Analyst firms like IDC

believe that 3G adoptions among the broad consumer base will gradually gain momentum over the next few years, and 3G mobile phone shipments should expand to approximately 25% of market shipments by 2007. However, challenges remains mainly from the lack of compelling 3G services and the threat of broadband wireless technologies, such as Wi-Fi and WiMAX or other similar technology standards.

A few fixed line broadband access service providers have started to offer WLAN routers together with a fixed line broadband connection. This offers users the convenience of mobility within their own homes and the advantage of connecting multiple PCs, laptops, PDAs, and other devices. In South Korea, Korea Telecom has provided an integrated service linking local fixed-line broadband with a nationwide WLAN hotspot access in over 10,000 areas, called the NESpot service. Such a service has the potential to compete against the cellular mobile operators.

In parallel, several WLAN extended-range wireless community networks have sprung up within urban cities, examples include the Austin Wireless City Project and the Pittsburgh Public Wireless Internet Project. However, some have encountered operational challenges and legal disputes as the providers of digital subscriber lines (DSL) and cable modem services chose to enforce their subscriber agreements, prohibiting consumer subscribers to share their bandwidth.

Over the next 3 to 5 years, we expect the WLAN technology and its associated business models to become more mature. Coupled with the emergence of mobile broadband wireless access (MBWA) technologies such as the IEEE 802.16e and IEEE 802.20 standards, we believe broadband wireless will evolve to become a strong challenger to the cellular 3G.

Over the five to ten year horizon, we expect the emergence of a converged broadband wireless Internet platform through software defined/cognitive terminals, i.e. a simple handheld terminal that can access any cellular, broadcast, and broadband wireless technologies.

For fixed-line broadband, we believe it will still complement broadband wireless Internet over the next ten years. However, the target market will be smaller because each household essentially requires only one high-speed connection as multiple-access within the household can be easily achieved using a router. Within this space, DSL is currently the most commonly deployed platform, followed by cable modems. The ongoing competition between the telecommunication operators and the cable operators is expected to push the telecommunication operators to evolve their deployments from ADSL to VDSL, to FTTH eventually.

To a certain extent, we expect broadband wireless will also substitute some fixed line broadband connections because of the convenience of no-wire mobility. However, we expect there will be sufficient cost-difference and high-bandwidth intensive applications for users to maintain a fixed line connection. This is especially true in developed countries where a well-established fibre infrastructure is already in place and users tend to be more sophisticated in their usage. For less developed regions, the highly flexible and cost-effective WLAN and WMAN platforms are expected to be more popular because providing connectivity is their top priority.

The pricing strategy adopted by the telecommunication operators will also affect the successful adoption of new technologies. There are two key issues here: affordability and flat-rate pricing.

- For any technology to attain wide-spread adoption, it has to be priced affordably. Some analyst called the correct price range the "sweet-spot" or "take-off" zone. For the mobile broadband Internet to be successful, the price has to be comparable to the fixed-line broadband. This simply means that the monthly user cost must be comparable, but does not mean that mobile broadband Internet service must have a comparable "price per kbps".
- Flat-rate pricing is another important issue. Several studies have shown that users prefer a flat rate tariff because they do not have to worry and/or control usage, and this is one of the key reasons why Internet adoption took off³. However, most mobile services today are still charged based on usage volume. On 20 May 2004, NTT DoCoMo launched the "Pake-Houdai" flat-rate plan, offering unlimited access to the 3G FOMA i-mode mobile Internet service, priced at 3,900¥ (or US\$35) per month. This plan was tremendously successful, achieving over 1 million subscribers by 1 Aug 2004, which is within a short-span of less than 3 months of its launch.

2.2.2 Equipment Manufacturers

The success of WLAN has prompted laptop, handset, chip, and even consumer electronic device manufacturers to declare that they will start to provide this functionality as a standard feature in their products. At the end of 2003, market consultancy firm Gartner estimated 9 million

worldwide WLAN users. The figure is expected to increase significantly over the next few years with the increased proliferation of devices with WLAN functionality. However, little money has been made out of WLAN subscriptions because most users are only keen to make use of the service when it is free-of-charge.

Looking ahead, a similar situation is expected to happen in the rollout of technologies, such as WiMAX and UWB, whereby the early market will be driven mainly by equipment manufacturers. Intel has started trials of its WiMAX chips, named "Rosedale", with equipment manufacturers and carriers worldwide. The final version is expected to be released in the third quarter of 2005. The technology will be built into Intel notebook chipsets and Intel's handheld chipsets for smart phones eventually. However, the lack of a proven business model will likely result in service providers delaying the rollout of infrastructure, at least until there is a sufficient installed base of potential users and/or proven business models. This situation is reflected by the existing membership of the WiMAX Forum, where the majority of the members are equipment and component manufacturers with only a handful of service providers.

Over a longer term, there is the concept of wearable computers. Examples include spectacles with embedded processor chips and Internet connectivity so that the wearer can access information in a hands-free manner. Another example is clothes with intelligent sensors and radio connectivity that can send out emergency messages if the wearer falls onto the ground. This will significantly widen the potential use of Broadband Wireless Internet technologies.

Another important market development is the all-in-one, multi-purpose, re-configurable, cognitive handset. Reconfigurable systems have caught the attention of large companies, like Intel, Motorola, NEC, Nokia, and Texas Instruments. These systems form the hardware foundation for software defined radio and cognitive radio, which uses software to control functions such as protocol, wave form, and frequency that are built into hardware in conventional radios.

2.2.3 Application and Service Providers

With a ubiquitous high speed communication platform, user communications are expected to evolve from simple calls to rich multi-party multimedia communications. Application and service providers can also make use of intelligent digital agents to stream precise and personalized multimedia information to users anytime, anywhere. Below are some examples of potential application markets:

Broadband Home. The digital home of the future will be smarter with an increasing trend towards different systems interacting with each other. For example, music or movies downloaded from the Internet using a PC with broadband connections can be transferred to a home theatre system

³ In the history of Internet pricing, the shift from per-minute to flat rate pricing came in Dec 1997 when AOL announced a flat-rate price of US\$19.99 per month.

using UWB. There is also the potential for inter-device networking. For example, a break-down in the refrigerator will lead to a message being sent to the home PC, which in turn sends a message to the handset of the home owner so that appropriate action can be taken. Down the road, we can expect to see more and more consumer electronic devices to have built-in air interfaces, like Bluetooth, ZigBee and other similar standards.

Vehicular Telematics. One potential booming market is broadband Internet access in the vehicles. One major type of application will be location-based services. For example, traffic navigation systems that combine route information (potentially stored in a hard disk) with location-specific information (potentially provided by satellite-based Global Positioning System). Real-time, location specific systems that can provide information about traffic congestion, road closures, parking availability, and many others. Beyond the benefits of location-based services, there is also the possibility of creating a moving office and entertainment centre inside the vehicle.

Healthcare. There is an increasing trend towards freeing patients from lengthy healthcare treatments in hospitals. According to Forrester research, technologies that free patients from formal institutions is expected to reach US\$34 billion by 2015. For example, companies like GE, Qualcomm, and Roche Diagnostics are already developing devices that aid the monitoring of pulse rates, insulin levels, and other health attributes, allowing individuals greater control over their own health care. These devices and home-monitoring services open up new options to consumers who wish to retain their independence as they age, face chronic illness or recover from in-patient care. More importantly, some applications in this field can benefit from radio-based communications, opening up another potential use of broadband wireless Internet technologies.

2.3 Impact on Government

2.3.1 Licensing

Traditionally, licenses are the primary means for governments to regulate the telecommunication market. The national licensing policy determines the structure of the market and the degree of competition. Complicated, restrictive, and long licensing procedures will significantly increase the cost of market entry and delay the introduction of new services into the market. Today, an increasing number of regulators worldwide are introducing more liberalized and simplified licensing regimes.

General Authorisations

To reduce the cost of procuring a licence and remove the need for lengthy licence approval process, several regulators have introduced licensing regimes based on "general authorisations". That is, operators are automatically granted

licences to provide certain telecommunication services on notification or registration. Examples of such telecommunication services include directory services and messaging services. Countries that have adopted this approach include Japan and UK. However, the explicit granting of rights still continues for the use of scarce resources like radio frequencies and numbers.

Effects of Convergence

Given the technological and market developments towards convergence, an increasing number of regulators are revamping their licensing regimes to reflect the phenomenon of convergence and the principle of technology neutrality. In 2000, Singapore was one of the earliest countries to change its licensing approach to one based on the nature of operations. Facilities-based operators (FBO) deploy their own telecommunication networks, systems and facilities to offer telecommunication services to third party. Services-based operators (SBO) lease the telecommunication network elements from any FBO to offer telecommunication services.

Going one step further, some countries are changing their licensing models towards reflecting the convergence of telecommunication and broadcasting sectors. For example, TRAI in India has begun implementing the concept of "Unified Licensing/ Authorization Regime", whereby operators only require one single licence to provide telecom and broadcast services, including basic telephony, international long distance services, radio broadcasting, cable TV and many others.

2.3.2 Radio Spectrum Management

Throughout the world, radio spectrum is deemed as a scarce resource that must be tightly regulated by all governments. From military communications that affects homeland security to media broadcast that provides entertainment to the society, spectrum inefficiently allocated will lead to chaos with huge repercussions to the whole nation. Therefore, a central command and control approach has always been adopted.

In most countries, spectrum management is a two-step process involving the allocation of specific blocks of frequencies for some particular use, and the subsequent assignment of specific frequencies within each block to different licensees. However, this approach is faced with increasing pressures from rapid technological changes and unpredictable markets. In recent years, a growing number of countries have adopted or are considering adopting other approaches that can give market forces a greater role in the determination of how spectrum resources are allocated and assigned. Key approaches that have been adopted include spectrum auctions, tradable spectrum rights, spectrum leasing, market-based spectrum licence fees, and licence-exempt spectrum use.

Spectrum Auctions

Spectrum auctions have been used by many countries for 3G spectrum assignments. This method is attractive for governments as it encourages competition, ensures equitability, and transparency.

A simple 'Beauty Contest' on the other hand, tends to favour existing operators and leaves governments open to criticism whatever the final choice. Unfortunately, market hype and overbidding resulted in serious financial difficulties for some operators in Europe. For example, the German's 3G licenses went for a staggering $\approx$ 50.8 billion in 2000.

Spectrum Trading

The unexpected auction results in certain countries and the subsequent information and communication technology (ICT) recession highlighted the weakness of the auction system. In most countries, the transfer of spectrum license ownership to another party after its initial assignment can only happen in very limited circumstances. To ensure that the assigned spectrum can be used in an economically efficient manner over time, a few countries, like Australia, Guatemala, and New Zealand, have allowed spectrum users the flexibility of trading their spectrum rights in a secondary market. This approach is aimed at transferring the spectrum utilisation decision making to market players who are in a better position to respond to changes in technology and consumer wants. For example in New Zealand, spectrum sold originally for multipoint distribution service is being used flexibly as multipoint broadband wireless local loop.

However, there are a number of important constraints that limit a government's scope and flexibility on implementing spectrum trading. Depending on the geographic isolation of the country, the freedom to change spectrum use is likely to be constrained by international obligations. For example, the ITU Radio Regulations and bilateral agreements on spectrum use seek to minimise cross-border interference by allocating specific bands for specific services and to harmonize the usage of certain frequencies in order to facilitate the provision of cross-border services such as global roaming among GSM networks.

Given these constraints, countries that have implemented spectrum trading had adopted a progressive approach so that regulators have sufficient time to facilitate spectrum reorganisation. Furthermore, it allows the market an opportunity to become familiar with the new regime.

Spectrum Leasing and Spectrum Sharing

Variants of spectrum trading, spectrum leasing or sharing typically involves a partial transfer of a licensee's rights to spectrum either for a limited period of time and/or for a portion of the spectrum encompassed in the license. Examples include the transfer of the right to transmit from one site under a multi-site license for a temporary period. The flexibility has the dual benefit of allowing the licensees to receive returns on spectrum portions that they have no present need for and is ideal for a lessee who only has a minor or temporary requirement.

License-exempt Spectrum

Compared with the earlier mentioned spectrum management schemes, there is another class of license-exempt management model consisting of the Industrial, Scientific and Medical (ISM) bands like IEEE 802.11b WLAN and the low-power transmission systems like Bluetooth. This model does not assign users exclusive privileged rights over spectrum use, but opens spectrum access to all users under certain conditions.

Over the last few years, the phenomenal growth of the IEEE 802.11b WLAN standard has generated considerable attention in the 2.4 GHz ISM bands. Subsequently, the 5 GHz bands are used by the newer IEEE 802.11a and IEEE 802.16 standards to achieve higher data rates and coverage. Most regulators set few restrictions for these usages, although users are not guaranteed any non-interference. This lack of restrictions, however, has lowered market entry barriers and spurred competition. Users can also deploy innovative systems that offer dynamic traffic-channel monitoring and selection and fast frequency hopping spread spectrum waveforms.

There has been some discussion surrounding the long-term viability of an open access regime given the huge success of Wi-Fi systems. Over time, an increasing use of such bands will result in congestion and interference, causing an overall degradation of service quality. A commonly cited example is the drastic fall in popularity of citizen band radio of the US in the mid-1970s. However, it is still debatable whether technological advancements in mesh/ad-hoc networking and smart antennas can resolve these issues.

2.3.3 Advanced Wireless Technologies

Several advanced wireless technologies can be expected in the future. In line with these developments, new approaches to spectrum management need to be explored to better exploit the benefits of these advanced technologies.

Spectrum Underlays

Underlay refers to spectrum spreading technologies like UWB where signals are spread across almost the entire frequency spectrum at very low power, below the noise level. If the operating power is kept sufficiently low, then existing users of the same frequency bands will not even know that there are UWB transmissions taking place.

Today, regulators of countries like US and Singapore have approved limited usage of UWB. The FCC of US has approved a low-powered version of the technology in February 2002. They have taken a cautious approach, limiting the range of the technology to roughly 30 feet, close enough for home networking indoors. If systems under development work as planned, the FCC had stated that it would be willing to increase the power limits in the initial ruling. IDA of Singapore has also introduced trial regulations to permit controlled

UWB emissions within a specific area in Feb 2003. Within the designated "UWB-Friendly Zone", developers are given substantial latitude in experimenting with newer and more innovative UWB designs. At the same time, IDA has ensured that existing wireless services are well safeguarded and a series of risk control measures have been put in place to allow IDA to resolve any complaints of interference promptly, in the event that they arise. More information on Singapore's UWB Programme can be found at <http://www.ida.gov.sg/idaweb/techdev/index.jsp> -> Ultra-Wideband (UWB).

Over the long run, it will be interesting to see if UWB can move beyond its existing indoor limitations to become a LAN-based or even WAN-based wireless communication technology.

Noise temperature measurements

One of the key prerequisites for a spectrum underlay system is the regulatory definition of the noise floor, which defines the permitted level of interference for existing communication systems. Currently, there is no standard system for measuring the amount of inference in an area, also known as the noise temperature. Several regulators like FCC are looking into ways to improve spectrum efficiency by using noise temperature measurements. The FCC has requested comments on how such a system might work.

Co-existence models

Another means that will significantly increase the efficiency of spectrum usage is the creation of co-existence models that allows users with frequency hopping radios to transmit on frequencies licensed to other users when those frequencies are not in use. As transmissions cannot effectively exist in the same exact time and space as another, the technology of frequency hopping radios must be robust enough to immediately detect a licensed transmission and vacate the frequency before causing interference. Therefore, it is prudent to initially limit the licensing of frequency hopping technologies to certain frequency bands with low existing usage and minimal risk of interference, before opening up to other bands when the technology matures.

Permitting Software Defined/Cognitive Radios

Software defined radio technologies will allow a device to "morph" into different devices based on the internal software. It can take on a mobile phone, cordless phone, or GPS, which traditionally fall under different regulatory requirements. However, if the generic device must take on all the requirements that it can potentially "morph" into, then it may be overly constrained. Therefore, the regulator must decide on the device categorisation and its approval process.

2.3.4 Names and Addressing

Top Level Domain Names

The Internet Corporation for Assigned Names and Numbers (ICANN) has requested for a proposal process for new top level domain (TLD) specifically targeted at the mobile user

community, which would include 3G users. This request has attracted the attention of several organisations that have filed proposals for new TLDs. An example of new TLD proposed is the .mail TLD that is backed by the Anti-Spam Community Registry, based in London. The .mail TLD is intended to better identify the authenticity of online marketers in an effort to combat spam e-mails. Another significant proposal is the .mobi TLD, which is supported by the Mobi JV consortium, formed by nine leading mobile device manufactures, telecoms and IT companies, including Nokia, Microsoft and Samsung. The .mobi TLD domain is intended for websites created specifically for viewing on mobile phone and PDA screens.

ICANN considers the addition of new TLDs to meet the needs of the growing Internet user base among its top priorities. It expects these new TLDs to be approved and be operational in 2005.

Electronic Numbering

Electronic Numbering (ENUM) is a suite of protocol to unify the telephone system with the Internet by using the E.164 addresses with the Domain Name System (DNS). It is the result of IETF's Telephone Number Mapping working group, which defined a DNS-based architecture for mapping a telephone number to a Uniform Resource Identifier (URI) that can be used to access a resource associated with that number. ENUM promises to deliver a greater level of convergence between IP and PSTN networks, allowing users to communicate regardless of the technology services involved: mobile wireless, Internet or fixed line PSTN.

ENUM has generated international interest. Austria's Broadcasting & Telecom Regulatory Authority (RTR) is the first in the world to launch a commercial ENUM service in 2004. The Australian Communications Authority (ACA) has held a Call for Expressions of Interest for a Tier-1 registry operator for their ENUM Trial. In the Asia Pacific region, CNNIC (China Network Information Center), JPRS (Japan Registry Service), KRNIC (Korea Network Information Center), SGNIC (Singapore Network Information Center) and TWNIC (Taiwan Network Information Center) have formed the Asia Pacific ENUM Engineering Team (APEET), an informal technical project team formed to coordinate and synergise ENUM activities in the Asia Pacific region.

However, ENUM also highlighted several complex policy issues. For example, there is the politically charged question of the administration of the ENUM root zone (e164.arpa) that is closely intertwined with a number of issues related to Internet governance, including sovereignty over national numbering plan administration, privacy and protection of personal data. Furthermore, there are security and trust issues concerning ENUM directories, which may result in identity theft, number hijacking, and spamming.

In Singapore, IDA has sought industry feedback on the policy framework to facilitate the introduction of Internet Protocol (IP) Telephony and Electronic Numbering (ENUM). Additional details and updates on ENUM related policy can be found at <http://www.ida.gov.sg/idaweb/pnr/index.jsp>

Internet Protocol version 6 (IPv6)

Currently, the number of remaining Internet Protocol version 4 (IPv4) addresses is not sufficient for all the existing GSM handsets to have IP addresses. The deployment of 3G services is expected to lead to a proliferation of Internet access capable mobile devices and this has attracted the concern of mobile operators because 3G is based on an underlying IP platform, and the inability to assign a permanent IP address to every device will result in complications. The next generation IPv6 will be able to resolve this address shortage issue because of its 128 bits address space, compared to IPv4's 32 bits address space. Furthermore, mobility management of terminals using IPv6 will be much simpler because of its auto-configuration and auto-renumbering functionality. The trend towards IPv6 migration is therefore, only a question of time.

2.4 Impact on Society and Individuals

2.4.1 Protection of Minors

Research firm, Research and Markets, predicted that wireless adult content will be worth US\$1 billion by 2008. Concerns over children's exposure to undesirable content like pornography, gambling, and hate material, on fixed line Internet remain the same for wireless Internet. In fact, mobile handsets provide greater privacy for the viewer, making effective supervision almost impossible.

Among the youths, instant messaging and chat rooms are popular means of keeping in contact with their peers. The widespread availability of interactive services, like chat rooms, to children has raised concerns among parents and policy makers because these services provide an easy means for predatory individuals to deceive children about their identity and lure them into meetings without the knowledge of parents. The advent of mobile devices will provide minors with a greater level of privacy than the family PC. However, location based services may potentially provide parents with the ability to locate the whereabouts of their children. Nevertheless, this raises further security and privacy concerns.

In most countries, law enforcers are already monitoring online chat services to pre-empt such dangers. However, the expansion of interactive services to mobile devices will certainly require more resources on such monitoring. On the

industry front, several mobile operators have established self-regulatory initiatives. For example, Vodafone in anticipating consumer concerns has set in place a combination of technical measures, like filtering and blocking, and age verification mechanisms to combat this issue.

2.4.2 Spam

In just a few years, spam has grown from a minor annoyance to a significant global economic and social problem. According to industry estimates, over 60% of global e-mail traffic today is now spam, up from 8% in mid-2001. Many feel that spamming is rude, intrusive and lacking in e-mail etiquette. Spam is also a drain on the global economy. It has been estimated that spam could be costing more than US\$20 billion in wasted technical resources. As a result of the growing magnitude of the problem over the past few years, policy and regulatory efforts have stepped up to combat spam, with approaches ranging from legislation and direct regulation to government support of self-regulation efforts by the private sector.

Different approaches have been taken in different countries in the fight against spam. In Japan, one of the first countries to experience mobile spam, legislation was passed that requires the flagging of e-mail advertisement and the prohibition of sending unsolicited e-mails to randomly generated addresses. In UK, content providers offering new or existing premium text services must implement an opt-out option by Aug 2004 under the Mobile Content Code.

In Singapore, IDA has taken a multi-pronged approach to curb e-mail spam. This approach includes public education (including the use of appropriate technology measures), industry self-regulation, anti-spam legislation and international cooperation. The multi-pronged approach serves as a concerted effort by the public and private sectors⁴ to address the issues and curb spam in Singapore.

2.4.3 Intellectual Property Protection

The digital age has created huge opportunities for people to create innovative content and services. At the same time however, there is a need to protect these creators as digital content makes copying a lot easier. The challenge for the legislator is to give protection to the works of these authors, artists, and producers, thus providing a conducive environment for them to create so that society as a whole can benefit from their works. Therefore, much thought is needed to achieve this delicate balance between content creation and distribution.

⁴ Besides IDA, other parties involved in this effort include the three major Internet Service Providers in Singapore, Consumer Association of Singapore (CASE), Direct Marketing Association of Singapore (DMAS), Singapore Business Federation, and Singapore infocomm Technology Federation (SiTF).

Currently, P2P technology is infamous throughout the music and entertainment industry. From Napster to KaZaA, digitisation of media content and p2p file sharing has threatened the traditional ways of distributing music and movies, raising many copyright and legal concerns. At the policy level, the US had taken a strong reactive approach to P2P file sharing, prohibiting the circumvention of Digital Rights Managements systems through legislation. Intermediaries such as ISPs must also ensure copyright compliance by their users before they can qualify for exemption from liability for copyright infringement of materials that may be accessed from or through their network. However, this strategy has been criticised for alienating both the consumer and ISPs, potentially hindering the adoption of technology. Over the long run, it seems that legal online commercial offerings such as Apple's iTunes present the most viable alternative.

2.4.4 Data Protection and Privacy

Today, commercial exploitation of personal data and information via electronic communications on fixed line communication on the Internet have become public concern. These concerns are expected to be magnified in future with more widespread use of broadband wireless Internet because mobile devices are personal devices, while existing fixed broadband Internet connection are usually shared among the whole family. Detailed tracking of an individual's day-to-day activities becomes possible because "location" and "usage" information can easily be collected by the service provider.

In most countries, the monitoring and regulation of personal data gathering activities remain vague. Governments do not explicitly ban such activities because they want to have the power to access such information for purposes of crime prevention, anti-terrorism, and other security related concerns.

Technology and Standards Development

3.1 Introduction

In this chapter, we will highlight eight technology trends that will drive the communication landscape over the next ten years. They are:

1. Cellular wireless paradigm;
2. Broadband wireless paradigm;
3. Short range wireless paradigm;
4. Wireless capacity;
5. Universal access platform;
6. Fixed line access technologies;
7. Backbone core; and
8. Future Internet architecture.

The first three trends focus on the wireless networking technologies. The fourth trend on wireless capacity discusses the fundamental research that is driving capacity gains in future wireless systems, like advanced modulation techniques, capacity approaching codes, and multiple-input multiple output antenna systems. The fifth trend is on the eventual creation of a single universal access device that is software definable. Broadband fixed line access technologies are covered in the sixth trend, followed by trends in the backbone core communication infrastructure. Finally, we discussed potential architecture changes on the Internet platform.

3.2 Cellular Wireless Paradigm

The cellular wireless paradigm will be characterised by a natural progression towards 3G and subsequently 4G.

3.2.1 3G Mobile Systems

Paradigms shift for the mobile systems have normally undergone a 10 year cycle. First Generation (1G) analogue systems were introduced in the early eighties. This was followed by the Second Generation (2G) narrow-band digital Global System for Mobile Communications (GSM) systems in the early nineties. 3G wide-band digital Universal Mobile Telecommunications System (UMTS) was first introduced at the start of the new millennium.

Today, the three main International Mobile Telecommunications-2000 (IMT-2000) standards are:

1. Wideband Code Division Multiple Access (WCDMA)

The 3G standard that Europe and Japan have agreed to adopt is known as UMTS. UMTS is an upgrade from GSM. The standardisation work for UMTS is being carried-out by the 3GPP. The terrestrial part of UMTS is known as UTRA (UMTS Terrestrial Radio Access). The FDD (Frequency Division Duplex) component of UTRA (UTRA-FDD) is based on the WCDMA standard that can offer average data rates of around 100–200kbps with peak rates of up to 2Mbps. The Time Division Duplex (TDD) component of UTRA is called the Time Division-CDMA (or UTRA-TDD).

2. Code Division Multiple Access 2000 (CDMA2000)

The chief competitor to WCDMA is CDMA2000. The standardisation work for the CDMA2000 is carried out by the Third Generation Partnership Project 2 (3GPP2). Under the CDMA2000 family of technologies are CDMA2000 1x, CDMA2000 1xEV-DO, and CDMA2000 1xEV-DV. CDMA2000 requires only 1.25MHz of spectrum per channel and is backward compatible with the 2G CDMAOne IS-95A/B systems. CDMA2000 1x offers packet data speeds of 153 kbps (Release 0) and 307kbps (Release 1), making it capable to support advanced applications such as e-mail, games, picture and music downloads. CDMA2000 1x has been commercially available since Oct 2000, launched by South Korea's SK Telecom, followed by LG Telecom and KT Freetel. CDMA2000 1xEV-DO is a solution for bursty data application. Optimised for packet data services, CDMA2000 1xEV-DO provides a peak data rate of 2.4Mbps and leverages on the existing suite of IPs. CDMA2000 1xEV-DO was first commercially deployed by SK Telecom in Jan 2002. KT Freetel followed four months later in time for the World Cup Games. Monet Mobile Networks was the first to launch this service in North America, in Oct 2002. Building on top of the CDMA 1x architecture is CDMA2000 1xEV-DV, which was submitted to ITU for approval in Jul 2002. CDMA2000 1xEV-DV is still in development stage.

3. Time Division Synchronous Code Division Multiple Access (TD-SCDMA)

Since 2001, China has more mobile phone users than any other country in the world. A TDD standard namely TD-SCDMA was developed by the China Academy of Telecommunications Technology in collaboration with Siemens. Together with local vendors like Datang, the technology was tested since Oct 2001 and can deliver data rates up to 384 kbps. TD-SCDMA stands alongside WCDMA and CDMA2000 as an official IMT-2000 standard. TD-SCDMA uses a spectrum bandwidth of 1.6MHz and is relevant for migration to 3G for GSM/ General Packet Radio Service (GPRS) networks, without the need to build a new infrastructure. Chinese officials have announced the successful testing of chipsets based on TD-SCDMA and expect cell phones models based on TD-SCDMA with homegrown chips to be launched by Jun 2005.

The initial deployment of 3G had been slow due to the downturn in the communications and Information Technology (IT) industry in the last few years. The initial hype surrounding 3G had more or less died down, replaced by practical considerations of whether rolling out 3G services early makes good business sense. With the global economy picking up, we are beginning to see deployment and adoption of 3G picking up. NTT Docomo has seen its Freedom of Mobile Multimedia Access (FOMA) subscription shoot up from 152K in Jan 2003, to 1.8 million in Dec 2003, to 7.5 million in Nov 2004. Other commercial 3G networks can also be found in Australia, Austria, Italy, Sweden, and UK. By the end of 2003, there are about two million WCDMA customers worldwide, of which 72% is from Japan. According to the UMTS Forum, there are 62 3G networks in service as of Jul 2004. Singapore is also expected to become the first country to have all its mobile operators roll-out 3G.

Another 3G alternative is Enhanced Data Rates for GSM Evolution (EDGE). There are over 10 EDGE live networks; mostly deployed Latin American operators. In Europe, Italian operator TIM has also announced its commitment to EDGE and plans to introduce services in all principal Italian cities by mid-2004. An average of 110-130kbps data can be delivered to the user.

3.2.2 Path Towards 4G Systems

First steps toward the Beyond 3G (B3G) and Fourth Generation (4G) have started. Today, there are several groups promoting 4G, such as the Wireless World Research Forum (WWRF), 4G Mobile Forum (4GMF), Mobile IT Forum (mITF), and others. For example, Wireless World Research Forum (WWRF) has published a "Book of Visions 2001" on 4G, although some of the concepts may need to be refined due to new technology developments.

ITU has not given a clear definition on the 4G yet. Currently, there are two possible ways to describe the 4G paradigm:

1. one based on data rates, where the targeted speed is **100 Mbps for high mobility and 1 Gbps for stationary**;

2. the other based on open architecture, also known as **converged broadband wireless platform or open wireless architecture**.

The most fundamental way to describe 4G is based on the potential data rate that it can expect to achieve. From Figure 4, we can see that existing wireless solutions like the CDMA2000 1xEV-DO can achieve over 2Mbps. New efforts, like the WCDMA Release 5 is expected to achieve 10Mbps or more. As 4G systems are expected to be a quantum leap over 3G systems, forums like WWRF, have set the 4G research targets at 100Mbps/1Gbps (high mobility/stationary).

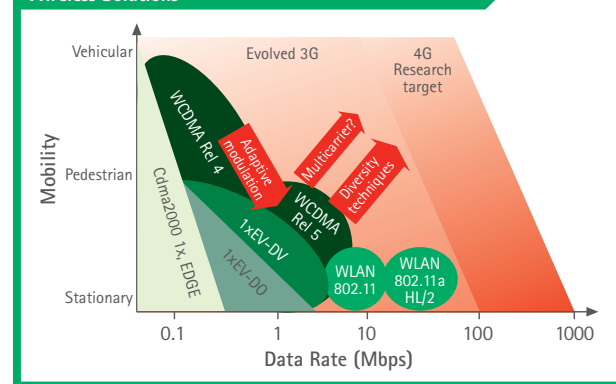
Another way to describe 4G is based on its architecture, which targets to be an open wireless architecture based on the principle of a converged broadband wireless platform. As there will be many predecessor cellular systems before 4G's introduction, the issue of backward compatibility of the 4G systems with all these existing cellular systems becomes important. Inter-working of all systems must occur in terms of horizontal and vertical handover, and seamless services with service negotiation, including mobility, security, and quality of service (QoS).

The International Telecommunication Union – Radio-communication Standardization Sector (ITU-R) has defined the developmental timeline for 4G in Figure 5. The requirements definition for the radio-based telecommunications is expected to be standardized from 2007 onwards. The 4G networks are expected to be deployed from around 2010 onwards.

According to the ITU-R visions, B3G systems will be a natural evolution of existing cellular networks and will include:

- Higher data rates with adaptive interfaces;
- Co-existence of existing 3G systems with any future enhanced or newly developed systems;
- Nomadic wireless access systems; and
- Seamless inter-working with other cellular systems.

Figure 4. Data Rate Versus Mobility Performance of Existing Wireless Solutions



Source: Wireless World Research Forum

Beyond 3G (B3G) Solutions

Even though 3G deployments are still in their early stage, a few B3G or 3.5G solutions have already been proposed. The most prominent of them is the High-Speed Downlink Packet Access (HSDPA). HSDPA was part of the 3GPP WCDMA/UMTS standard Release 5, approved in 1999 when the global economic landscape was still rosy. It is a natural evolution of the 3G UMTS standard with advantage of being backward compatible to deployed 3G systems.

Today, HSDPA is still in the lab testing stage of most mobile operators, with a few field trials expected in the later part of 2004. Commercial deployments and handset availability will likely happen in late 2005. So far most network operators are silent on their plans for HSDPA, only Japan's NTT DoCoMo has committed to eventually deploy HSDPA in 2005.

HSDPA is only about enhancing the downlink portion of mobile data transmissions, to enhance the uplink portion, the High Speed Uplink Packet Access (HSUPA), also known as the Enhanced Uplink Data Channel (EUDCH) technology has been proposed. Work on HSUPA/EUDCH standard is expected to be approved by the end of 2004.

Super 3G Standards

NTT DoCoMo and 25 firms within the 3GPP consortium, including Alcatel, Cingular Wireless, Ericsson, Lucent, Motorola, Nokia, Nortel, Qualcomm, Siemens, T-Mobile, and Vodafone, have proposed a study to determine the feasibility of defining a standard that will support data rates of 100Mbps downlink and 50Mbps uplink.

The study will be conducted by the 3GPP's Radio Access Network working group, which expects to complete its investigation in June 2006. The specifications for the "Super 3G standard" are expected by Jun 2007.

This standard is an intermediary between HSDPA (14Mbps) and 4G (1Gbps), and will be a low-cost upgrade on the current WCDMA networks. DoCoMo has announced that Super 3G will be rollout in metropolitan areas initially and be operational by 2008.

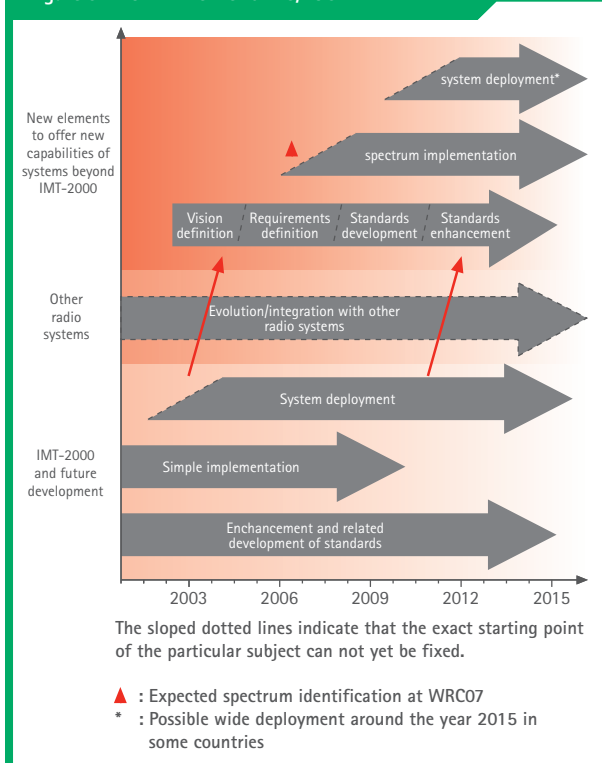
4G Prototypes

Since Apr 1998, NTT DoCoMo has been conducting research on 4G mobile communications. In Jun 2004, DoCoMo announced that it had achieved average data rates of 135Mbps downlink and more than 20Mbps uplink transmission at a bandwidth of 100MHz, involving a car moving at 30km/h in an environment where the wireless base station was not visible from the car because of surrounding buildings. The moving car test recorded a downstream data rate of 300Mbps even at the speed of 30km/h when the wireless base stations were visible from the car. DoCoMo's experimental 4G mobile communications system employed variable spreading factor (VSF) and orthogonal frequency code division multiplexing (OFCDM) technologies which were developed by DoCoMo to mitigate the impact of severe multi-path interference, and to allow

flexible and fast packet transmission in compliance with area and other communications conditions, thereby achieving a broad-bandwidth, large-capacity wireless system.

In Dec 2004, DoCoMo further increased the data rates of its prototype with multiple-input multiple-output (MIMO) antenna technology, achieving downlink data rates of 1Gbps. DoCoMo has announced that it plans to roll-out 4G services capable of 1Gbps downlink speeds from 2010.

Figure 5. ITU-R Timeline for 4G/B3G



Source: IEEE

3.3 Broadband Wireless Paradigm

Technologies in the broadband wireless space have the potential to create an alternative low-cost wireless infrastructure that may potentially disrupt the cellular technologies.

3.3.1 Wireless Local Area Network (WLAN)

The success of WLAN technology back in 2001 surprised many people, partly because it happened amid a global economy downturn. One of the key advantages that WLAN offers to users is the "no-wire" convenience as it extends the reach of a fixed line broadband by approximately 100m in range. At home, each member of a household can have access to the Internet simultaneously through a single Internet connection. In the office, computers and printers can share files and printers as if they were connected via a wired Ethernet backbone.

WLAN is also ideal for temporary use like for exhibitions and conferences, and places where installing wires may be difficult like factories with heavy machineries. Furthermore, several WLAN hotspots can combine to create one large WLAN hotzone providing users with greater wireless coverage.

Today, the prevalent standard is the Institute of Electrical and Electronics Engineers (IEEE) 802.11⁵. Data rate specifications are defined in versions b, a, and g. The next generation version of IEEE 802.11n, which is required to be above 100Mbps from the existing 54 Mbps (defined in 802.11a and g), is currently being defined with final approval expected in 2007. So far, Agere Systems and WWiSE (World Wide Spectrum Efficiency) group consisting of Airgo Networks, Bermai, Broadcom, Conexant, STMicroelectronics, and Texas Instruments, have proposed solutions that can achieve 500 Mbps and beyond.

On the research front, Siemens has developed a prototype that achieved a wireless transmission speed of 1Gbps using an intelligent multi-antenna system in Dec 2004. This experimental system operates in the 5GHz band and utilises a bandwidth of 100MHz.

An overview of similar WLAN technologies is shown in Table 1. Similar to its highly successful wire-line cousin, the IEEE 802.3 Ethernet standard that has become the de-facto wire-line local area network (LAN) technology replacing other technologies like Token Ring and Fibre Distributed Data Interface (FDDI) over the last 20 years, we expect the IEEE 802.11 WLAN standard to replace other WLAN networking technologies and evolve to higher speed over the next ten years to come.

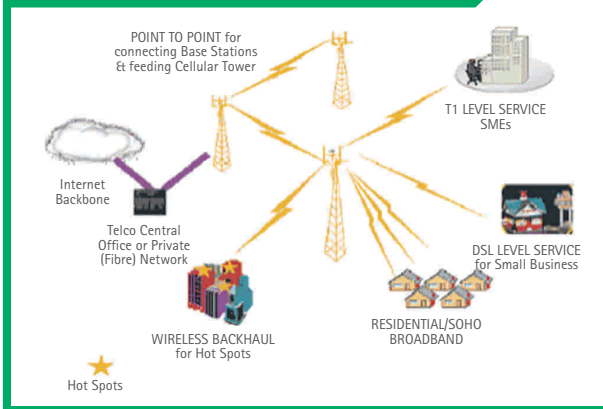
Beyond efforts on increasing data rate, there are numerous efforts on improving WLAN's service functionality, such as QoS (802.11e) and security (802.11i).

3.3.2 Wireless Metropolitan Area Network (WMAN)

A WMAN offers a wireless backhaul solution that is an alternative to wire-line access networks, such as DSL, coaxial

cable, and fibre optics (see figure 6). It has the capacity to address broad geographic areas without the costly infrastructure development required in deploying cables to individual sites. Compared to WLAN, WMAN technologies offer higher speed over a longer range.

Figure 6. Wireless Metropolitan Area Network as a Wireless Backhaul Solution



IEEE 802.16 or WiMAX

WiMAX or "Worldwide Interoperability for Microwave Access" was originally developed to meet the requirements of broadband wireless access systems operating between 10-66GHz. Operating at this frequency range, however, requires line-of-sight that becomes a significant limitation. This was subsequently amended to become IEEE 802.16a⁶, ratified in Mar 2003, which operates in the lower 2-11GHz range and does not require line-of-sight to operate. Speeds of up to 75Mbps in 20MHz channels are possible over a range of less than 6.4km, although the maximum projected range (at lower speed) is expected to be 50km. Both these standards have been revised recently and replaced by the new IEEE 802.16-2004 standard.

A further extension, IEEE 802.16e, has been developed to enable a single base station to support both fixed and mobile broadband wireless access (BWA). This standard is aimed at the slow-speed, lightly mobile user who wants to maintain some level of roaming within metro access points,

Table 1. Overview of Wireless Local Area Networking Technologies

Name	Speed	Frequency	Remarks
802.11	2 Mbps	2.4 GHz	The original standard, extended to become 802.11b
802.11b (Wi-Fi)	11 Mbps	2.4 GHz	Most widely adopted. Also known as Wireless Fidelity
802.11a (Wi-Fi5)	54 Mbps	5 GHz	Higher speed at higher frequency
802.11g	54 Mbps	2.4 GHz	Higher speed at same frequency as Wi-Fi, backward compatible
802.11n	>100 Mbps	N.A.	Next generation standard using MIMO technology
RadioLAN	10 Mbps	5.8 GHz	Specialises in wireless bridges
HomeRF	1 Mbps	2.4 GHz	Intended for home use. No longer supported by vendors, replaced by HomeRF2.
HomeRF2	10 Mbps	2.4 GHz	Higher speed, QoS, better encryption than HomeRF
HiperLAN	20 Mbps	5 GHz	European standard similar to 802.11b
HiperLAN2	54 Mbps	5 GHz	European standard, QoS

⁵ A similar set of standards in Europe are defined in the ETSI HIPERLAN/2, although the momentum of 802.11 adoption may have already left HiperLAN adoption far behind.

⁶ A similar set of standards in Europe is defined in the ETSI HIPERMAN.

although the Working Group has achieved speeds of 120–150km/h in simulations. This standard will operate in the 2–6GHz range, and is expected to be approved in Mar 2005.

IEEE 802.20 or Mobile Broadband Wireless Access (MBWA)

Unlike the 802.16e, this specification is aimed at the highly mobile user. It targets to achieve peak data rates per user in excess of 1Mbps at mobility speed up to 250km/h in a Metropolitan Area Network (MAN) environment, operating in the licensed bands below 3.5GHz. The 802.20 is seen by some people as an alternative "Beyond 3G" solution by some people. Currently, the IEEE 802.20 is in the proposal selection phase with standards approval targeted at Dec 2006.

IEEE 802.22 or Standards for Wireless Regional Area Networks (WRAN)

The most recent effort (announced in Oct 2004) by IEEE is to specify a cognitive air interface for fixed, point-to-multipoint, wireless regional area networks that operate on unused channels in the Very High Frequency (VHF)/ Ultra High Frequency (UHF) TV bands between 54MHz and 862MHz. In many parts of the United States (US), the broadcast TV spectrum is often not well-utilised. To tap into these under-utilised TV channels and put them into better usage, IEEE is defining this standard to enable the deployment of wireless regional area networks using these under-utilised spectrum, while not interfering with the licensed services now operating in the TV bands. This effort has the blessings of the Federal Communications Commission (FCC) but is expected to face strong resistance from the broadcasting industry.

Most approved standards in the WMAN area can be classified as fixed BWA solutions. The existing focus is towards creating mobile BWA solutions, such as the 802.16e and 802.20. These mobile BWA solutions provide users the extra mobility (compared with WLAN) making them strong challengers to the existing cellular 3G solutions. ITU used the term "Portable Internet" to describe this new group of technologies and highlighted it as a potential disruptive technology that may upstage the cellular 3G technologies.

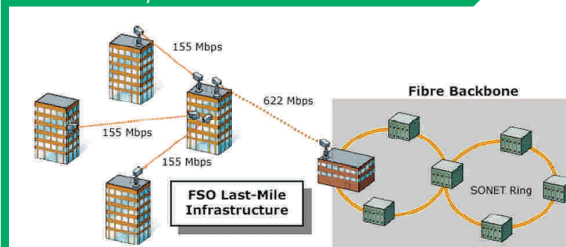
In Feb 2004, IDA allocated the 2.3GHz and 2.5GHz spectrum bands for trials and commercial deployment of wireless broadband. Examples of such wireless broadband systems include those based on the IEEE 802.16 and IEEE 802.20

standards. This move is timely as various wireless broadband technologies are now ready for trial or deployment. When deployed, these new technologies could provide Singapore with an additional broadband infrastructure, thus giving consumers more choices and options when going "broadband". Companies interested to conduct trials for wireless broadband technologies in Singapore can approach IDA for details.

3.3.3 Free Space Optics (FSO)

Not all locations are suitable for laying cables; there are difficult terrains, such as over highways, across rivers and marshland, where a wireless solution is significantly cheaper and easier to deploy. FSO is one such solution. FSO enables high-speed wireless communication between two locations, delivering fibre-like performance without the fibre (see Figure 7). FSO is often regarded as a fixed-wireless technology, although the latter term is more frequently used to describe systems that rely on radio waves (not light) to transport information wirelessly between two stationary points. Other wireless transmission technologies, such as WLAN and Bluetooth, allow for a certain range of motion within which communication is still possible. In the case of FSO, both ends of the link must be stationary; otherwise, the communication could fail.

Figure 7. Free Space Optics Being Used to Provide Last Mile Connectivity



FSO systems transmit data from one end to another using a narrow laser beam. A single link consists of two FSO transceivers pointed at each other. FSO systems rely on virtually the same technology that has been used for years to transmit data through fibre optic cables.

Table 2. Overview of Wireless Metropolitan Area Networking Technologies

Name	Speed	Frequency	Remarks
802.16 (WiMAX)	75 Mbps	10–66 GHz	QoS, very long distance, line of sight requirement
802.16a	75 Mbps	2–11 GHz	QoS, very long distance, robust transmission
802.16–2004	75 Mbps	2–66 GHz	Compilation of 802.16 and 802.16a
802.16e	N.A.	2–6 GHz	Extension of 802.16a to include mobility
802.20 (MBWA)	>1 Mbps	<3.5 GHz	>1 Mbps at mobility up to 250 km/h
802.22 (WRAN)	N.A.	54–862 MHz	Cognitive air interface, allows unused spectrum in that space to be tapped
HiperMAN	75 Mbps	2–11 GHz	European standard compatible with 802.16a
WiBro	50 Mbps	2.3 GHz	Korean standard that is compatible with 802.16

However, instead of bouncing a weak laser beam within a glass core to transport the light signal from point A to point B, an FSO transceiver transmits a laser beam powerful enough to penetrate the atmosphere ("free-space") and arrive at the intended receiver up to several kilometres away. However, for the communication link to function properly, the receiver must be able to see the narrow beam of light arriving from the transmitter at the other end. This is reason that the transceivers have to be fixed in position; even small movements could swing the laser beam out of the receiver's view and break the link.

FSO can be used to form a wireless backbone infrastructure between buildings or serve as a high-speed link between mobile switching centres and its base station controllers, as long as line-of-sight is available. It is cost effective to set up compared to laying cable and offers speeds of up to 2.5 Gbps. When it is no longer required, it can be taken down to be re-deployed to another location easily.

Most people perceive free-space as a hostile and unpredictable medium for data transport because no conduit is used to contain and guide the laser beam. Therefore, rain, fog and other weather phenomena can cause severe and sometimes unpredictable degradation to the link. In 2002, IDA completed a trial to study the challenges and evaluate the performance and reliability of the FSO technology. The trial results showed that FSO can be used for high-speed data communications between buildings. More details of this study and the trial assessment report can be found at <http://www.ida.gov.sg/idaweb/techdev/index.jsp> -> Free Space Optics (FSO).

Most of the research and development efforts in the FSO industry are directed towards increasing data throughput, moving beyond the point-to-point architecture, and improving transmission reliability. Although the atmosphere is considered to be highly transparent in the visible and near infra-red wavelengths, certain wavelengths are more susceptible to atmospheric absorption. Currently, most if not all of today's commercially available FSO systems operate in the windows of 780-850nm or 1520-1600nm because of low attenuation (around <0.2dB/km). Recently, there is research into FSO systems that operate in the range of 10,000nm (10µm) because of claims of better fog transmission characteristics. 10µm energy does not penetrate glass, so it is ill-suited for deployment behind windows, but it allows for high-powered operation in unrestricted environment. 10µm is normally not used in telecommunication equipment and there are few components available.

3.3.4 Creating a Low Cost Wireless Internet Infrastructure

One of the biggest disruptive impacts of the class of broadband wireless technologies is the ability to create an alternative wireless Internet infrastructure that is considerably cheaper than a 3G cellular infrastructure. In

Sep 2004, Philadelphia city officials announced that they are turning all 135 square miles (350 sq. km.) of the city into one of the world's largest wireless Internet hot spots using Wi-Fi technology. The project is estimated to cost from US\$7 million to US\$10 million and is expected to be ready by early 2006.

The benefits to the society are even greater in the developing countries. For example in Feb 2002, Telkom South Africa deployed a broadband wireless access technology that operates in the 1.9GHz frequency band to provide telecommunication services throughout the South Africa. Elsewhere in India, a partnership between the Department of Tourism and private companies Wi-Fi enabled the Dal Lake, the second largest lake in the state of Jammu and Kashmir. Local boats, shikaras, which move within the lake, are connected to the houseboats, which lie stationary within Dal Lake. The houseboat equipped to provide the lake's Wi-Fi connectivity so that tourists and residents can have Internet connectivity when travelling on the lake.

It is however, unlikely that a wireless infrastructure based on broadband wireless technology will completely supplant the cellular infrastructure in the near future, because there still remain some interesting problems to solve. One of key problems is security and management. Broadband wireless technology essentially creates a mesh network architecture that is difficult to do network monitoring, management, and security, because it lacks a central controller. This makes it difficult for the network to prevent rogue nodes from hoarding network resources and ensure that new nodes are connected securely. Efforts that are working to resolve security include the IEEE 802.11i. This new solution will require changes to the existing Wi-Fi implementations and technology diffusion may take some time.

Another important issue is roaming, which currently faces roadblocks that include substantially different interfaces, security provisions, and authentication methods between home, work and public WLANs. There are two key developments required to resolve this issue:

1. the industry needs to adopt an end-to-end framework and customer interfaces for simple wireless connectivity; and
2. the service operators need to develop roaming agreements similar to that of the cellular industry.

Existing efforts to resolve the seamless roaming issue include the Wireless Hotspots and Networking Interworking Initiative, a joint collaboration between Intel and IDA to work on the technical challenges towards achieving seamless connectivity in the wireless world. This collaboration is significant for Singapore and Asia as a whole, in that it is the first of its kind to involve the participation of operators and vendors from across the Asia-Pacific region and beyond. More details on this initiative can be found at <http://www.ida.gov.sg/idaweb/techdev/index.jsp> -> Intel-IDA Wireless interworking Initiative.

Cost is the single biggest reason behind the popularity of broadband wireless technologies. Compared to their cellular counterparts, they may not be able to provide the level of security, manageability, accountability, and QoS. However, existing experience showed that the popularity of Wi-Fi adoption has not been hindered by its lack of security and QoS. Most users of Wi-Fi today are not tech-savvy because Wi-Fi devices are easily available off the shelves and Wi-Fi hardware makers have made the initial setup easy, although enabling Wi-Fi security is not. Therefore, the majority of home users do not even bother to enable basic encryption or other protections against connection theft, eavesdropping and network invasion. Furthermore, lessons from the history of Internet, where the best-effort IP defeated the guaranteed services Asynchronous Transfer Mode (ATM), suggest that low-cost, no-frills connectivity is valued more by users.

Over the next 3 to 5 years, we believe that broadband wireless technologies and cellular technologies will address different markets segments; broadband wireless will provide no-frills wireless connectivity for leisure and entertainment surfing, while cellular will provide secure and guaranteed service wireless connectivity for business usage.

Beyond 2010, it remains interesting to see if broadband wireless will actually overtake cellular to become the dominant wireless Internet platform. Based on today's analysis, this outcome seems very likely to happen in 2015. There is little doubt that new mobile BWA standards will threaten the existing cellular technologies. Furthermore, efforts to improve the service functionality of broadband wireless technologies, such as QoS, security and manageability, can be expected. On the other hand, there is a possibility that cellular technologies will evolve to become more cost-effective, adopting features of broadband wireless technologies.

3.4 Short Range Wireless Paradigm

Today, short range wireless technologies are predominately used in Personal Area Network (PAN) applications. Over the next ten years, this cluster is expected to move beyond PAN communications towards wireless sensor network applications for remote monitoring and control.

3.4.1 Bluetooth

Bluetooth was designed to replace proprietary cables between a wide range of computing and communication devices. It operates in the unlicensed 2.4GHz range and can transmit at 1Mbps over a distance of 10m. Bluetooth connections are established through the detection of other nearby Bluetooth enabled devices.

Bluetooth has come a long way since 1998 when it was first unveiled. The technology is fairly mature now, interoperability between devices is seldom an issue and interference with other radio technologies is also limited. In 2003, the number of Bluetooth shipments reached around 70 million. According to more recent market figures (10 Sep 2004), IMS Research

announced that Bluetooth shipment figures has exceeded 3 million per week, just 3 months after the technology met the 2 million units per week milestone.

Bluetooth wireless technology is supported and used in products by over 3000 companies including BMW, IBM, HP, Logitech, Microsoft, Motorola, Nokia, Palm One, Sony Ericsson and Toyota. The short-range wireless technology has made its way into products with strong household brands such as the wireless photo kiosk by Kodak, available in Eckerd and CVS stores across the globe, and the wireless MP3/pedometer by Nike and Philips. Ford Motor Company has also selected the US carrier Sprint to provide Bluetooth enabled phones to work with hands-free systems in its North American automobiles. Figure 8 shows some existing examples of devices with Bluetooth connectivity.

Bluetooth is the most popular and mature wireless technology in the wireless personal area network (WPAN) space. The commitment of the Bluetooth community to the ongoing development of standards is expected to make it an important technology for at least the next 3 years. Further down the road, it remains to be seen whether alternative WPAN technologies like Ultra-Wideband (UWB) and ZigBee can steal the attention of electronic companies from Bluetooth.

Figure 8. Examples of Devices with Bluetooth Connectivity



Source: Wireless Academy

3.4.2 Ultra-Wideband (UWB)

One of the most innovative use of the radio frequency spectrum, UWB leverages off the computational powers of today's devices to allow multiple systems to share the same spectrum. Unlike most existing technologies that transmit a powerful signal over a small range of frequencies, UWB transmits signals at very low power levels over a very wide range of frequencies. The UWB power levels are so low that it can transmit in the licensed frequency ranges used by other devices. Therefore, UWB is also known as a spectrum underlay technology because its transmissions are seen as low-level noise.

UWB promises to transmit digital data at extremely high-speed (up to 1Gbps and above) at low power levels (less than 0.5mW) for a short distance (up to 10m). It is expected to be a dominant communications platform for PAN and home-networking deployments. Today, companies like Pulse~LINK has demonstrated the transmission of High Definition Television (HDTV) content using UWB to all televisions and computers in an indoor residential environment. UWB may also be used as a wire replacement between Digital Versatile Disk (DVD) players and television sets because of its high speeds and robust connectivity. Further down the road, once the technology becomes more matured, it is expected that higher UWB power transmission levels will be allowed, opening up the possibility of outdoor usage.

Beyond high speed transmission, UWB can also be used as an open-air, through walls, or ground penetrating radar imager, with many applications for tracking and monitoring. Examples include devices that can help rescue workers locate victims trapped in collapsed buildings, real time tracking of equipment and people in hospitals, and systems for finding structural problems in buildings, bridges and dams. More ground breaking is the potential to create UWB wireless sensor networks that can do health monitoring of life-threatening conditions.

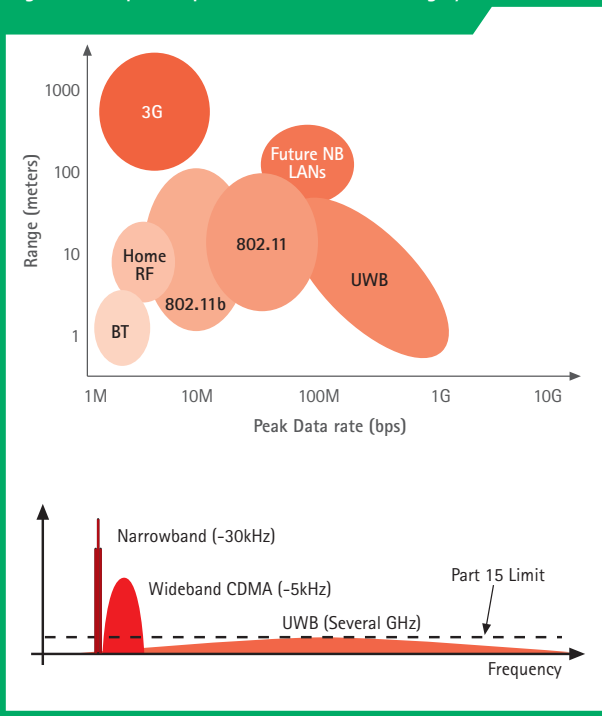
Today, standard is the key stumbling block for UWB adoption. The IEEE 802.15.3 SG3a working group has been working towards defining a high-speed physical layer (PHY) enhancement amendment to the existing IEEE 802.15.3 PAN standard for UWB. Unfortunately, there are two opposing camps, the UWB Forum that supports the use of Direct Sequence Spread Spectrum modulation and the Multi-band Orthogonal Frequency Division Multiplexing (OFDM) Alliance that supports the use of OFDM modulation. This means that UWB devices in the market may not be interoperable with one another and this may hinder its adoption.

3.4.3 Radio Frequency Identification (RFID)

RFID is seen as the most exciting thing that has happened to supply chains in the last 30 years with numerous opportunities across the whole chain (see Figure 10).

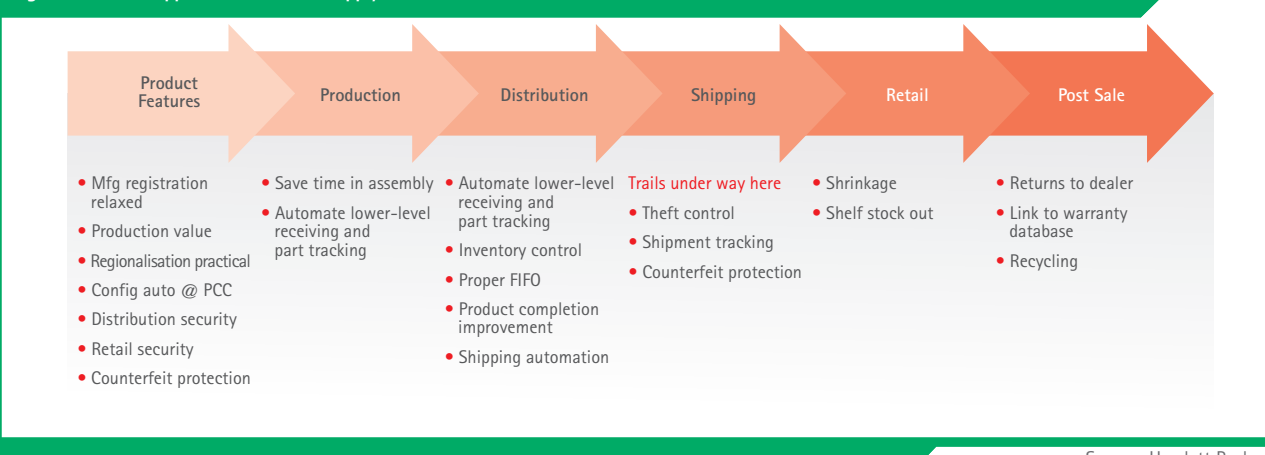
A basic RFID system consists of an antenna, a transceiver, and a RF tag electronically programmed with unique information. RFID tags are categorised as either active or passive. Active RFID tags are powered by a separate power source like an internal battery and its data can typically be rewritten and/or modified. Passive RFID tags operate without a separate power source and obtain operating power generated from the reader. Passive tags are typically much lighter than active tags, less expensive, and have a significantly longer operational lifetime.

Figure 9. Simple Comparison of UWB with Existing Systems



Source: Swiss Federal Institute of Technology Zurich

Figure 10. RFID Opportunities in the Supply Chain



Source: Hewlett Packard

RFID systems are also distinguished by their frequency ranges. Low-frequency (30kHz to 500kHz) systems, commonly used in security access and asset tracking, have short reading ranges and low system costs. High-frequency (850MHz to 950MHz and 2.4GHz to 2.5GHz) systems, commonly used in railroad car tracking and automated toll collection, have longer reading ranges and higher reading speeds, but higher system costs.

The significant advantage of all types of RFID systems is the non-contact, non-line-of-sight nature of the technology. Compared to barcodes and other optically read technologies, RFID tags can be read through a greater variety of substances and under more environmentally challenging conditions.

Today, the RFID market is still in a state of flux with many vendors and standards groups vying for dominance. For example, Matrics and Alien, the main Electronic Product Code (EPC) tag and reader provider today will have to retool its existing passive tags and readers once the EPC standards body, EPCGlobal completes its definition of the tag. On another front, the International Standards Organization (ISO) is also working on its own RFID standards, the ISO 18000-6. Furthermore, the potential entry of major chip providers such as Phillips and Texas Instruments into this market is also expected to have significant impact on the cost and availability of RFIDs.

There are also issues related to the RFID frequency band. The EPC applications use the UHF frequency band of 868MHz to 956MHz. However, there are regional differences in using this band: Europe is using the lower end, North America is using the 915MHz, and Japan is using the higher end. Furthermore, there are interference issues because there are many existing radio frequency systems using the UHF range, cordless phones being one such example.

Despite the above mentioned challenges, the long term potential of the RFID market remains huge because of its potential to offer companies a new level of automation that will drive cost out of the supply chain through more efficient tracking, inventory management, and security. AMR Research estimated that this market will surpass the US\$20 billion market by 2013 (see Figure 11).

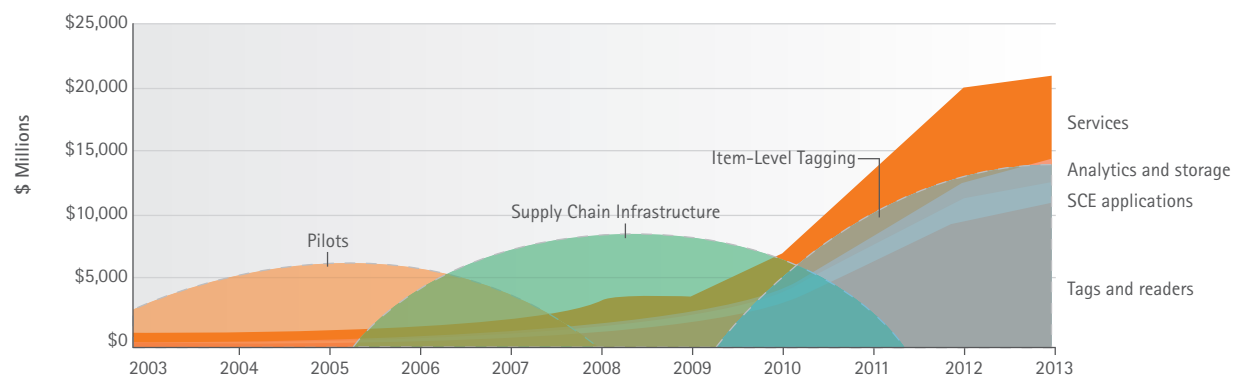
In May 2004, IDA announced a three-year S\$10 million plan to support the development of five RFID-enabled supply chain clusters in Singapore by 2006. To date, the industry has responded with commitments to invest more than S\$12 million towards RFID projects. To encourage RFID adoption and interoperability in Singapore, IDA also expanded the frequency bands for RFID applications to 866-869MHz and 923-925MHz in the UHF bands. The power limit for both bands was increased from 0.01W to 0.5W. In addition, the power limit for the 923-925MHz band will be increased to 2W for RFID devices only. These moves are important as they allow RFID systems developed in Singapore to interoperate with those developed in Europe or the US. Goods tagged in Singapore can also be easily read by RFID readers in these countries. More details on this initiative can be found in <http://www.ida.gov.sg> -> IDA Programmes -> RFID (Radio Frequency Identification)

3.4.4 ZigBee

ZigBee is an emerging wireless technology that addresses the unique needs of wireless sensor network applications for remote monitoring and control. It is highly scalable and can support up to 65,536 network nodes, which is many times greater than Bluetooth's 7 nodes. It is designed for broad-based deployment of wireless sensors at low cost and low power, enabling a typical sensor to run for years on inexpensive primary batteries. Compared to RFID, ZigBee can provide greater functionality because it allows sensor data to be exchanged. For example, containers in cargo ships can be tagged with tamper detection sensors to increase security. These sensors can form a mesh network to exchange data, allowing relevant authorities to quickly pin-point the tampered container. Container information of the entire cargo can also be communicated through the sensor network allowing for faster container processing.

In the future world filled with wireless monitoring sensors, ZigBee may potentially be the wireless protocol that enables all these sensors to communicate with each other. Today, the hype surrounding ZigBee is growing bigger and bigger.

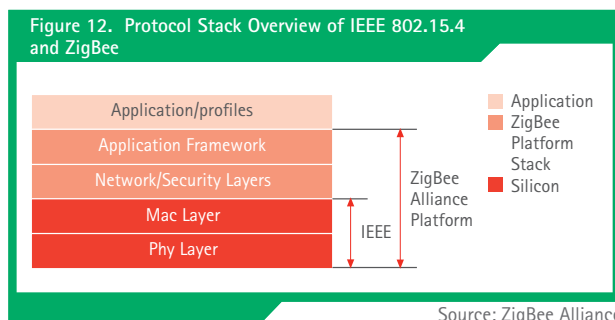
Figure 11. RFID Market Evolution



Source: AMR Research, 2003

According to a study conducted by West Technology Research Solutions LLC, the size of the market of appliances that will be produced under ZigBee protocol will be over US\$8 billion by the year 2008. It was also predicted that by end 2005, many domestic appliances, such as refrigerators, DVD players or washing machines, will carry a small label saying 'ZigBee-compliant'. Another study by ABI Research predicted that 1 million ZigBee compliant devices will be shipped worldwide in 2005, and this total is likely to zoom to 80 million units by the end of 2006.

ZigBee is often confused with IEEE 802.15.4. Strictly speaking, the IEEE 802.15.4 standard, which was formally ratified in May 2003, defines the physical radio specifications. ZigBee leverages on this physical radio specification by adding the logical network, security, and application software (see Figure 12).



The IEEE 802.15.4 operates in the unlicensed bands of 2.4GHz (global), 915MHz (US), and 868MHz (Europe). Data speeds ranges from 20kbps (at 868MHz) to 250kbps (at 2.4GHz). Depending on the power output and environmental characteristics, transmission distance ranges from 10-100m.

3.4.5 Wireless Sensor Networks

The future of these short range wireless technologies is closely tied to the future landscape of wireless sensor networks. Today, sensors are already everywhere, but most sensors lack the intelligence to analyse or act on their measurements. Technology advancements in sensor network protocols and miniaturisation of sensor devices are expected to bring smart, networked sensors into reality. These smart sensor networks will collectively monitor and process vast amounts of data to help run factories, optimise supply chain management, monitor our health and even predict coming earthquakes.

Wireless sensor networks may eventually be as important as the Internet in the long run. Imagine smart sensors permeating the entire physical environment, forming intelligent networks that spread over wide areas, providing us the platform to remotely interact with the physical world. In fact, wireless sensor networks form the technology foundations behind concepts like "Pervasive Computing", "Ubiquitous Internet", and "Ambient Intelligence".

3.5 Wireless Capacity

There is little doubt that wireless data rates will evolve higher over the next ten years. Currently, most of the fundamental

technology research that are driving capacity gains in future mobile wireless systems can be broadly categorised into the four areas of:

1. Advanced modulation techniques;
2. Capacity-approaching codes;
3. Multiple-Input Multiple-Output (MIMO) antennas systems; and
4. Mesh communication architectures.

3.5.1 Advance Modulation Techniques

The earlier mobile wireless communication technologies have been frequency-division and time-division based. In recent years, significant improvements in spectrum usage have been achieved from a family of technologies that leverage off the computational powers of today's devices to allow multiple systems to share the same spectrum.

Spread Spectrum (SS) and Orthogonal Frequency Division Multiplexing (OFDM)

SS is the earliest technique to do so. First used during the World War II by the military, SS technology is currently used in many cellular phone networks and in WLAN hotspots. Unlike the older systems that do high-power transmission of signals over a narrowband of frequency, spread spectrum uses special codes to spread the signals over a wider band of frequencies allowing systems to do low-power transmission of signals.

There are three main techniques:

1. **Direct Sequence Spread Spectrum (DSSS)** achieves the spreading of signal by modulating the data with a key sequence known as the chipping code. The result of this operation is a signal spread across the desired frequency band.
2. **Frequency Hopping Spread Spectrum (FHSS)** modulates signal with a narrowband carrier signal that hops from frequency to frequency in a random but predictable sequence determined by a spreading, or hopping, code. Signal is spread across the time domain, unlike DSSS where the signal is spread across the frequency domain.
3. **Orthogonal Frequency Division Multiplexing (OFDM)** is a multi-carrier modulation that splits the input signal into several parallel streams. At the transmitter, each stream is modulated onto a separate carrier frequency; at the receiver, signals from all carriers are demodulated and recombine to form the original signal. OFDM is inherently resistant to multi-path and is ideal for cluttered environments with high signal reflection.

Currently, OFDM is the technology of choice, being adopted in standards like Digital Audio Broadcasting (DAB), IEEE 802.11a, IEEE 802.11g, and IEEE 802.16a. Many alternative forms of OFDM have also been proposed. Examples include Vector-OFDM proposed by Cisco, Wideband-OFDM proposed by Wi-LAN and Flash-OFDM proposed by Flarion. Other companies like Intel are looking into adaptive OFDM techniques to optimise the data-carrying capacity of the system based on the channel conditions.

Ultra Wideband (UWB)

Taking spread spectrum to a new level, beyond existing wideband systems like WCDMA, is UWB. Compared to WCDMA, UWB signals are spread across several GHz of the frequency spectrum so that transmission at extremely low power of less than 0.5mW is possible. As discussed in Section 3.4.2, UWB is currently restricted for PAN communication usage. Technology advancements further down the road may extend its usage into the outdoor space.

3.5.2 Capacity Approaching Codes

In 1948, Shannon showed that with the right error correction codes, data could be transmitted at speeds close to the channel capacity, almost error-free, and with low transmitting power. His landmark paper launched the field of coding theory. However, for more than four decades, the best codes that were used in practice still required more than twice the transmitting power that Shannon's law said was necessary.

In 1993, two French scientists, Berrou and Glavieux, introduced the turbo codes, and showed that this new coding system can increase performance with respect to older code systems by as much as a factor of two. This translates to improvements for longer battery life, or longer transmission range, or higher data rate, just by using the codes.

Turbo codes are parallel concatenated codes that make use of iterative decoding. As several iterations are required for decoding, the associated decoding delay becomes the biggest drawback for this code. However, advancements in processor speeds have changed the entire landscape, making it more practical to apply these codes into existing communication systems.

Applications

Turbo codes have become a very attractive option for transmissions that can tolerate decoding delays, such as deep-space communications. In Sep 2003, the European Space Agency (ESA) launched SMART-1, the first space probe to use turbo codes for its data transmission. ESA will continue to use these codes on other missions, such as Rosetta that will be launched this year. The United States National Aeronautics and Space Administration (NASA) are also planning missions that will depend on turbo codes to boost reliable communications. The first missions that will be using these codes will be Mars Reconnaissance Orbiter and Messenger.

For cellular systems, turbo codes are already in use in Japan's 3G systems. These codes are used for pictures, video, and mail transmissions. However, it is still not used for voice transmission because of its decoding delays. Nevertheless, this may also change in the near future with faster processors. Other implementations of turbo codes in communication systems include digital audio broadcasting and satellite links transmission.

Other Similar Codes

The discovery of turbo codes has led to the "discovery" of

other codes that make use of a similar iterative decoding process. In fact in 1960s, Robert Gallager at MIT had invented a low-density parity-check (LDPC) code. This code did not receive any attention then because it was too complicated for any practical use.

Today, researchers are finding LDPC to be a good alternative to turbo codes. For certain implementations, they are found to be easier to implement and can have better performance over turbo codes. Most importantly, the LDPC patents have expired so companies can make use of them without having to pay for intellectual-property rights. Currently, LDPC is also being considered for next generation wireless network standards, like IEEE 802.11 and IEEE 802.16.

Besides the parallel concatenated (turbo) codes and the LDPC, other recently proposed codes that make use of iterative decoding include the class of serially concatenated codes and the repeat-accumulate codes. Some of these codes have been shown to have better performance and lower complexity than turbo codes.

3.5.3 Multiple-Input Multiple-Output (MIMO) Smart Antennas Systems

The concept of smart antennas started in the area of military communications, where large antenna structures are used to create directed beams to hide transmissions from the enemy. The earliest implementations usually require large antennas structures, with time intensive processing and calculation.

With the emergence of personal wireless communications and the steady growth of wireless subscribers, wireless operators face ever-increasing demands on their finite spectrum and infrastructure resources. As deploying new cell sites is not always the most economical or efficient means of increasing capacity, these operators started to explore new ways to maximise the spectral efficiency of their networks.

Traditionally, users communicating via the same base station have leveraged on the dimensions of frequency (Frequency Division Multiple Access, FDMA), time (Time Division Multiple Access, TDMA), and code (Code Division Multiple Access, CDMA), for maximising channel capacity. The introduction of smart antennas provides the additional dimension of space, through spatial division multiple access (SDMA), for achieving advanced channel utilisation.

Differences between Smart Antennas and MIMO Systems

In conventional terms, smart antennas refer to signal processing techniques used to process the data captured by **multiple antenna elements located at only one end of the link** in order to mitigate adverse propagation conditions such as multi-path fading and interference. Due to space and complexity constraints, the array of antenna elements is normally deployed at the base station.

A few years ago, Bell Labs researchers proposed the Layered Space Time architecture. This proposal extended the concept of smart antennas to include multiple antennas at both the transmitter and receiver end, leading to the formation of a MIMO matrix channel.

Beyond retaining the original benefits of smart antennas, which is the ability to do optimisation of the transmitting and receiving antenna elements over a larger space, MIMO systems opened up the possibility of transmitting over several spatial modes of the matrix channel within the same time-frequency slot resulting in a significant increase in spectral efficiency. For example, a simple spatial multiplexing involving three transmitting and three receiving antennas can lead to a three-fold improvement in spectral efficiency (see Figure 13).

Applications and Challenges

There are little commercial implementations of MIMO in cellular systems as yet and none is currently being deployed for 3G. There are, however, demonstrated examples that include Lucent's BLAST chip and proprietary systems intended for specific markets such as Iospan Wireless's AirBurst system.

On the standards front, MIMO channel models have been standardised in IEEE 802.16 for fixed broadband wireless access. Proposed solutions for next generation IEEE 802.11n and 3G HSDPA are also based on MIMO technology.

The full scale commercialisation of MIMO systems is around two years away. Several open issues and hurdles remain. One of the key issues is the antenna inter-element spacing, which in turn limits the number of antenna elements that a practical system can have. Antenna element numbers and inter-element spacing are key parameters for high spectral efficiencies of MIMO systems.

Currently, antenna inter-element spacing actually limits the size of antenna arrays. At the base stations, an inter-element spacing of 10λ is usually required to ensure a fair amount of uncorrelated fading of the signals. This has limited existing deployment to only four antennas. While at the terminal ends, 0.5λ spacing is usually sufficient. This may not pose a problem for laptop computers, where multiple antennas can be embedded into the casings. However, for handsets, fitting even two elements may be problematic because of the current handset design trend to imbed the antennas inside the case to improve the look and appeal factor.

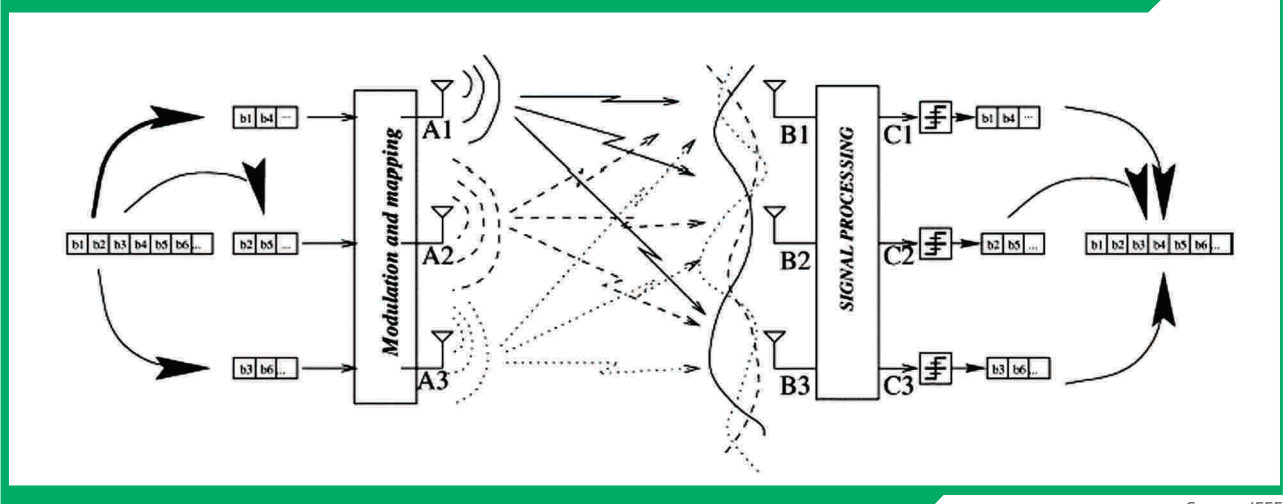
Receiver complexity is another issue. MIMO channel estimation results in increased complexity because a full matrix needs to be tracked per path delay instead of a single coefficient. Depending on the number of antennas in the system, the processing power required may become a bottleneck.

3.5.4 Mesh Communication Architecture

The technology innovations mentioned in the subsections 3.5.1 to 3.4.3 will all lead to greater wireless capacity, however, the greatest technological gain in wireless capacity will actually come from systems that work cooperatively. This is based on a new network architecture called mesh, also known as ad-hoc networking (see Figure 14). Similar to smart antennas, this is another technology innovation with roots in military communications.

In mesh networks, each device can function as a receiver and transponder, retransmitting data sent by other devices in the network. The devices, therefore, act as peers that cooperate with each other, eliminating the need for a central controller (or base station).

Figure 13. Basic Spatial Multiplexing Scheme with Three Transmitter and Three Receiver Antennas.



Source: IEEE

This distributed architecture of mesh leads to the following advantages:

1. Robustness and efficiency. With a dense mesh of devices, failure of one device merely means that packets moving across the network have to take an alternate route. Furthermore, each device can select routes according to the traffic congestion conditions, allowing the best use of spectrum bandwidth and allowing quality of service considerations to be part of the routing process.

2. Almost limitless capacity. As the transmission of data from source to destination is by means of multiple hops instead of a single hop, each device only needs enough transmission power to communicate with its nearest peers, leading to significant reduction in power. The network can therefore, accommodate more devices without any noticeable increase in interference. Furthermore, if multiple parallel paths are available between the source and destination nodes, then parallel transmission becomes another possibility to increase transmission capacity.

3. Non line of sight communications. Through the help of intermediate peers, devices can transmit data to destinations that do not have line-of-sight with each other and/or are limited by transmission power.

Existing Landscape

Most if not all implementations of mesh networks consist of fixed stations. Companies that have successfully implemented mesh networks include MeshNetworks Inc., Aerie Network, and BroadBand Solutions. MeshNetworks, for example, have implemented its technology in cities like Medford, Oregon and Garland, Texas. Its implementation in Garland, Texas provides coverage of over 57 square miles and will be used by the city's police and fire fighters. Initial test has reported that throughput rates of up to 1.5Mbps can be achieved even for vehicles travelling at 60mph.

On the standards front, mesh networking is increasingly being adopted. For example, the IEEE 802.16 and IEEE 802.11 have included mesh networking as an option.

Future directions

Some future developments in the area of mesh networking are discussed here.

1. Progress to mobile mesh networks. Today, deployed mesh networks are formed between fixed nodes. The ideal stage is to have a mesh network consisting of only mobile devices. This is far more complicated to implement, as each device can appear, disappear, and move in and out of range of each other all the time.

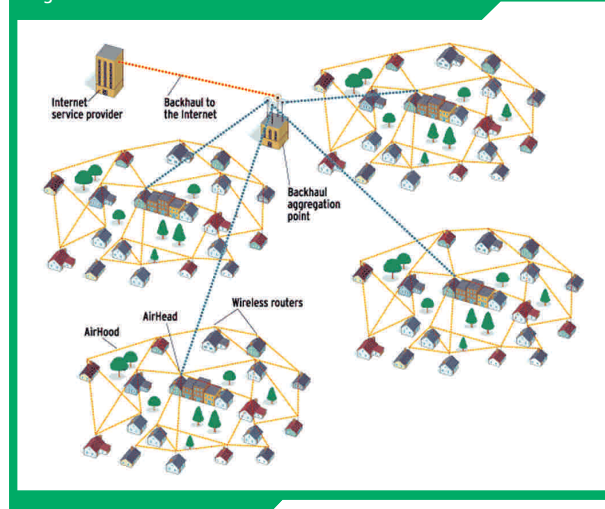
2. Combining UWB with mesh. UWB is currently limited to the PAN. A possible means of extending UWB's reach into the LAN space without increasing its transmission

power is through mesh networking. Combining UWB with mesh therefore, offers end-users a high data-rate cum mobility scenario.

3. Embedded Computing Applications. We live in the world of machines. In the future, devices will be increasing embedded with processors and computer applications to become intelligent machines. These machines will be able to process more information about the environment in which they operate, and react to its changing environment. As we move through these environments, we are able to communicate with the surrounding machines to use any important information.

4. Sensor Networks and Dust. Recent research has shown the possibilities of co-ordinating the activities of a large number of sensor devices. These devices, when deployed over a terrain, can be used to capture detailed information about the environments, weather or structures of buildings.

Figure 14. A Wireless Mesh Network

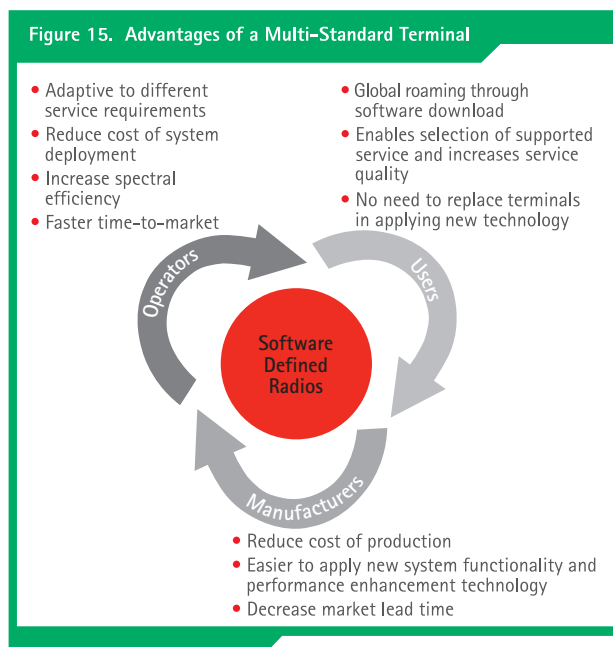


Source: IEEE

3.6 Universal Access Platform

Today, an increasing number of devices are equipped with multiple air interfaces or network connectivity. For example, most mobile phones today are tri-band, and an increasing number of them are also equipped with Bluetooth connectivity. In the near future, we can also expect to see multi-network phones that are compatible with fixed-line networks, cellular networks, and broadband wireless networks. One example is BT's BluePhone project, which is expected to be commercially launched in 2005. BluePhone will be compatible with 3G, GSM, Wi-Fi and fixed-line networks. As technologies, like WiMAX, UWB, and ZigBee, become more mature, it is likely that future devices will also be enabled with them.

Further down the road, the trend is towards a single universal access device that is software definable to take on different wireless standards. Figure 15 illustrates some advantages of such a system. To deliver upon this vision, we need to have devices that can re-configure automatically depending on the user's needs.



3.6.1 Software-Defined Radios (SDRs)/Cognitive Radios (CRs)

A SDR is a system that processes signals using software instead of hardware, making it re-configurable and more flexible than a traditional radio. Theoretically, a SDR can address any advances in wireless standards, changes in protocols, upgrades in service and features through a simple program download. For example, a person travelling to a neighbouring country with a different wireless standard can access its network by downloading the software needed to process signals using this different wireless standard.

In a nutshell, SDR refers to the technology, where software modules running on a generic hardware platform consisting of digital signal processors and general purpose microprocessors, can be used to implement radio functions such as modulation of transmitted signal and, for detection of the received signal.

SDR has its roots in military communications dating back to the early 1990s. Today, there are several available SDRs. In 2000, the US Navy selected General Dynamics to develop the Digital Modular Radio (DMR), considered by some as the first true SDR. The DMR has a four-channel, full-duplex design that is essentially a four radios in one system.

Commercial interests in SDR, however, only began recently. Today, there have been successful field trial applications of SDR technology for cellular based stations. For example, Vanu Inc, has helped Mid-Tex Cellular Ltd. to deploy SDR

technology on its base stations in Comanche Country, Texas. Their solution is unique in that the software is not tightly coupled to the hardware, and can be used for systems based on Intel processors. This solution became the first SDR base station technology to receive FCC's certification, paving the way for commercial sales of this technology in United States.

The logical next step is to apply this technology to handheld devices. Existing SDR handheld implementations are limited to control functions. From a technical perspective, this typically extends to inter-connects and power levels but not to frequency bands and/or modulation types. This may not be considered the true SDR to some as SDR is suppose to provide control of a variety of modulation techniques, for wide-band or narrow-band operation, communications security functions (such as hopping), and waveform requirements of current and evolving standards over a broad frequency range.

The clear limitations here are the processing power and size of handheld devices. Besides the need for a smaller but more powerful processor, there are also functionality differences between base stations and handheld devices. For base stations, SDR will be used to support bug fixes and assist in system upgrades as new air interface standards are introduced. Reconfiguration is therefore, relatively infrequent. For handheld devices, SDR will be used to support bug fixes and switches between air interfaces as the user moves across different networks involving different air-interface standards. Reconfiguration can therefore, be relatively frequent. Therefore, the complexity involved to create a SDR handheld device is a lot more significant compared to a SDR base station.

Currently, Vanu has developed a prototype that runs on an HP iPAQ with a custom expansion sleeve. This prototype is part of a project to enable public safety users to use their existing radios to communicate with users of incompatible radio systems. This system is a critical tool in mutual aid situations, where multiple agencies must work together without prior planning. Implementations include fixed rack systems, vehicle-mounted systems, or Personal Digital Assistant (PDA) units, depending on need and functionality.

The successful commercial deployment of SDR will depend heavily on the cost considerations between having a single hardware device with multiple air interfaces versus having a SDR. Today, incorporating up to four air interfaces into a single device is still the cheaper solution. We therefore, believe that it will take at least three years for SDR to mature sufficiently for mass market deployment.

On the standards front, the Software Defined Radio Forum (<http://www.sdrforum.org>) is an open, non-profit cooperation dedicated to support the development, deployment, and use of open architectures for advanced SDR wireless systems. The SDR Forum has adopted the Software Communications Architecture (SCA) developed by the Modular Software-Programmable Radio Consortium (MSRC) under contract

to the Joint Tactical Radio System (JTRS) Program Office as the standard software structure of SDR systems. This architecture describes the radio structure in modules, and defines a standard application framework for instantiating and connecting the waveform objects associated with each radio channel. An open source reference implementation for SCA version 2.2 is scheduled for completion by Nov 2004.

The SDR concept has also been extended to include cognitive functionality. CR technology represents an SDR that not only can adapt to spectrum availability, protocols, and waveforms, but also has the ability to learn protocols and waveforms so as to adapt to local spectral activity and learn the current needs of its user.

A CR is able to self-learn, making it possible to perform cognitive functions such as identifying and using under-utilised spectrum to communicate more efficiently. CRs will sense and adapt their behaviour according to the environment that they operate in. This may also include negotiating with the different mobile systems in its environment. For example, a CR can be aware of a WLAN network and what is available and of interest to its user within this WLAN service zone. It can also be aware of what is cheapest network available for him or her to make a phone call. A cognitive radio can also learn about the various services that its user is interested in through the user's usage patterns. For example, a cognitive radio can notify its user that a bookstore down the street has a rare book the user wants and tells the user how to find the store.

The CR's decision making process mimics that of a human when he or she goes about deciding what to do in a particular situation. This process is called the Observe, Orient, Decide, and Act loop. These concepts can be further extended to include planning and learning in the cognition cycle.

Demonstrations of CR techniques are expected to appear in both the commercial and research areas within the next three to five years. Spectrum rental transaction could be one such experiment that will prove the technology's value. Standardisation of this technology may happen within the next five to seven years

3.6.2 Re-configurable Equipment and Devices

Another important factor that will determine the success of a SDR is the hardware feasibility of developing a reconfigurable access device. To answer this question, we need to examine the state of electronic design.

Microprocessors and application-specific integrated circuits (ASICs) are the two most popular processors used today. The general purpose microprocessor is the more ubiquitous of the two and can be found in almost everything from personal computers, washing machines, digital cameras, to toasters. General purpose microprocessors are extremely flexible because functions are executed using software.

Over the years, microprocessors have become tremendously fast, achieving speed above 3GHz, making it feasible to incorporate them into various electronic devices.

The microprocessor's flexibility comes at the price of lower efficiency and higher power dissipation than ASICs. ASICs are special-purpose chips designed usually for a single specific purpose. It is used by companies such as Nokia and Ericsson for core digital baseband processing in their cell phones, which includes vocoders, codecs, user interface functions, peripheral controllers, and protocol processors. Another form of ASICs is the Application-Specific Standard Product (ASSP), which is a special-purpose chip for a particular application. Companies that make ASSP chips include Analog Devices, Infineon, Motorola, Qualcomm, and Texas Instruments. Compared to ASICs, ASSP chips are less specialised and can be used by different system makers to build cellphones. However, ASSPs cannot incorporate unique features into their chipset.

Although ASICs and ASSPs are more efficient, they are still not versatile enough, and can only be used to create single-purpose devices. To achieve the final stage of a single universal digital assistant, we need a programmable logic device (PLD), where the logic function of the device can be modified after the device is manufactured, enabling gadgets that combine the performance and efficiency of special-purpose hardware with the versatility of a microprocessor.

PLDs are commonly known as field-programmable gate arrays (FPGAs). They fill the gap between the custom, high-speed, and low power ASICs and flexible, low-speed, and higher-power microprocessors. A PLD is typically an IC that contains one layer of configurable wiring and logic elements, and another layer of personalisation memory. Personalisation memory is implemented using static random-access memory (SRAM) and SRAM is what makes PLDs reconfigurable. Bits in the SRAM can be programmed to configure each logic element, like AND gates and OR gates, and specify how these elements interconnect to build a custom circuit that carries out the desired function.

Currently, most PLDs load their personalisation bits upon initialisation only. Some can do partial reconfiguration, which is to change part of their logic elements and their connections while others remain fixed. A few PLDs are dynamically reconfigurable, allowing the configuration of any of the logic elements and their connections to be modified while on-chip circuits are still operating.

Compared to an ASIC with a customised interconnect structure, the setup overhead of PLDs is significant. Majority of the transistors in the PLD's personalisation memory are not utilised once the programmed interconnection circuit is finalised. Furthermore, transistor connections at the wire intersections in the PLD slow circuit operation.

Compared to microprocessors, they still deliver higher performance but are more expensive.

To summarise, PLDs are considered big, slow, power hungry, and expensive to be implemented for complex functions. Therefore, PLDs are mainly used in low-volume prototyping applications, although they are slowly moving into consumer markets. Altera Corp. and Xilinx Inc., the current market leaders, are offering low end SRAM PLD products, Cyclone and Spartan respectively. These companies are extending the features of their products to compete with microprocessors and digital signal processors.

Reconfigurable systems have caught the attention of large companies, like Intel, Motorola, NEC, Nokia, and Texas Instruments. Some of them have greater interest in the closely related software defined radio, which uses software to control functions such as protocol, wave form, and frequency that are built into hardware in conventional radios.

In the next three to five years, performance improvement of PLDs can be expected on several fronts: reduction in input/output overhead, reduction in wiring overhead, boost in speed configuration, and addition of partial or dynamic reconfiguration features.

Several companies, like Elm Technology, IBM and Matrix Semiconductor are working on multiple layered silicon chips, where each layer is connected internally by vertical wires. This shrinks the size of the transistors, amplifies digital outputs as signals reach distant inputs more quickly through short vertical wires. Furthermore, shorter wires and smaller drive transistors reduce power draw and speed circuits.

Another improvement will come from the replacement of power hungry SRAM with the more efficient non-volatile memory. Three leading candidates in this area are magneto-resistive memory, ferroelectric memory, and ovonic unified memory. Each of these uses exotic materials with special magnetic, electrical, or phase-change properties to store bits compactly and without volatility. These fast non-volatile memories are expected to improve PLDs' circuit capacity, ease of use, and security. Security is improved because SRAM PLDs load the personalisation memory from off-chip storage, while non-volatile memory keeps personalisation bits inside the chip.

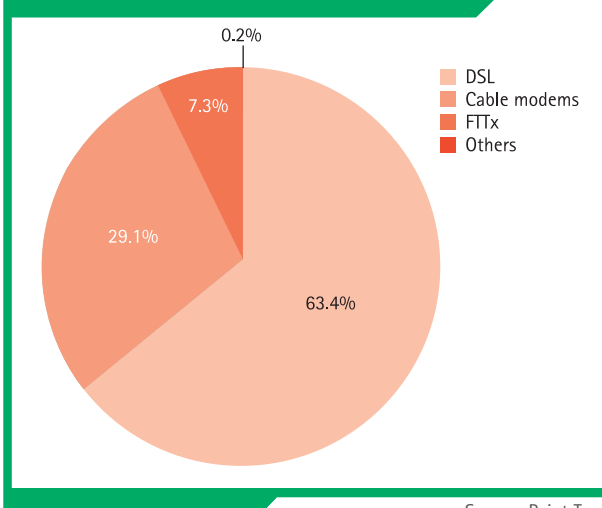
A single reconfigurable hardware alone may not be able to provide the optimal solution under most circumstances. Today, research labs at institutes at the University of California at Berkeley, the Imperial College of Science, Technology and Medicine in London, and the Massachusetts Institute of Technology, are working on reconfigurable systems consisting of multiple FPGAs, ASICs, and microprocessors. The FPGAs can be re-configured one by one while the rest of the processors are running. All the processors can communicate over an interconnect network that supports both compile-time and run-time routing. Commercial products based on such systems are expected in 5 years or beyond timeframe.

3.7 Fixed Line Broadband Access Technologies

Currently, broadband is viewed very much as a fixed line phenomenon. Although, we believe that over the next ten years, this broadband landscape will be slanted towards the wireless side with the increased adoption of 3G cellular services, Wi-Fi, WiMAX, and other high-speed wireless access technologies, there is little doubt that fixed line broadband access technologies will continue to play an important role.

The existing broadband landscape is dominated by DSL and cable, although broadband over fibre has grown significantly over the last 12 months to become the third most popular broadband wireline technology. According to Point Topic (see Figure 16), as at 30 Jun 2004, worldwide broadband lines passed the 123 million mark, with DSL accounting for 63.4% of the total broadband market. Cable and FTTx accounts for 29.1% and 7.3% of the remaining market share respectively. Other technologies, mainly fixed wireless access and satellite, accounted for less than 0.3% of the total. Note that these figures did not account for the subscribers of 3G technologies, like CDMA2000 1xEV-DO and WCDMA.

Figure 16. Global Broadband Market Share at 30 Jun 2004



Source: Point Topic

Out of these three technologies, we believe fibre will become the fixed line broadband access technology of choice in 2015.

3.7.1 Digital Subscribers Lines (DSL)

The popularity of DSL as a broadband access technology started with the introduction of Asymmetric Digital Subscriber Line (ADSL) in 1992 as an access technology capable of delivering Video-On-Demand service over telephone networks. Subsequently, different DSL implementations, like Rate Adaptive DSL, Symmetric DSL, High bit-rate DSL, ISDN DSL, and others, entered the market to support a variety of market needs.

Today, however, most of these deployments have converged to the three technologies of Asymmetric Digital Subscriber Line (ADSL), Single-Pair High-Speed Digital Subscriber Line (SHDSL), and Very High-Speed Digital Subscriber Line (VDSL).

ADSL. Today, ADSL technologies are the most popular DSL technology in business and residential use. There are several flavours of ADSL, all specified in ITU-T Recommendations G.992.x. The original two standards G.dmt ADSL and G.lite ADSL are specified in G.992.1 and G.992.2 respectively. The second generation of ADSL technologies, also known as ADSL2, like G.dmt.bis, G.lite.bis, and ADSL Plus, are specified in G.992.3 to G.992.5. The ADSL2 standards have better transmission rate and reach than the original ADSL standards. Furthermore, ADSL2 includes advanced features like power management modes, rate adaptation, extensive diagnostic tools, and performance monitoring.

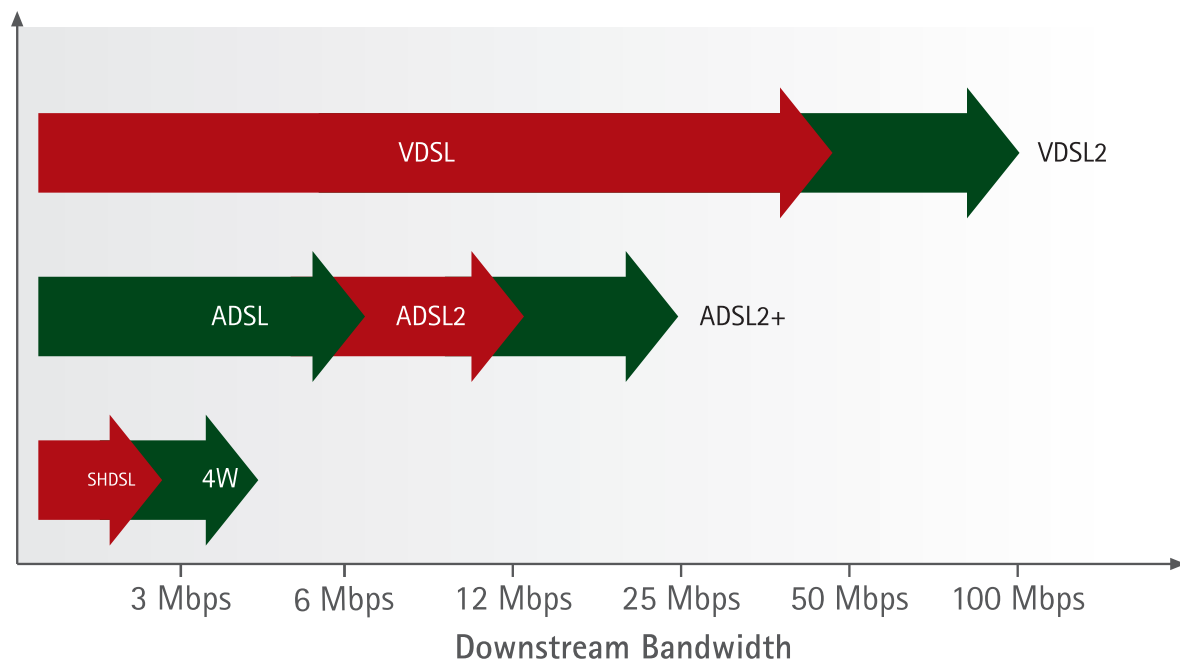
SHDSL. Single-Pair High-Speed Digital Subscriber Line (SHDSL) is the industry standard symmetric DSL (SDSL), approved under ITU-T Recommendation G.991.2 in Nov 2001. G.991.2 is also known as G.shdsl. It is targeted at the business market,

unlike ADSL that targets the consumer market. This standard is an improvement over earlier HDSL, HDSL2 and other propriety SDSL systems. SHDSL transceivers are designed primarily for duplex operation over mixed gauge two-wire twisted metallic pairs, but optional four-wire operation is supported for extended reach applications. It supports selected symmetric user data rates ranging from 192kbps to 2,312kbps.

VDSL. Very High-Speed Digital Subscriber Line (VDSL) is the next generation DSL technology that can deliver up to 52 Mbps downstream and 2.3Mbps upstream, depending on the wireline distance.

Recent innovations have improved the transmission rates and reach of ADSL and SHDSL significantly, making their performance closer to that of VDSL, thus extending their life-cycle. At the same time, work has begun on a new VDSL2 standard, based on ADSL2 and T1.424 to facilitate multi-mode ADSL2/VDSL2 implementations. VDSL2 is expected to deliver up to 100Mbps downstream.

Figure 17. Evolution of Downstream Bandwidth of xDSL Technologies



3.7.2 Cable

Cable systems were originally designed to deliver broadcast television signals efficiently. To ensure that consumers obtain cable data service with the same TV sets that receive over-the-air broadcast TV signals, cable operators recreate a portion of the over-the-air radio frequency spectrum within a sealed coaxial cable line.

Standards for cable modem products revolve around the Data Over Cable Service Interface Specification (DOCSIS), which is the standard in North America and other International markets. EuroDOCSIS, which is a variant of the DOCSIS standard, is the dominant standard in Europe.

Existing coaxial systems do not utilise anything above the 860MHz. However, this spectrum can be exploited to boost the bandwidth limitations of existing Hybrid Fibre Coaxial Cable (HFC) systems. Currently, Narad Networks is one company that has successfully utilised previously unused cable spectrum from 860MHz to 2GHz to provide switched Gigabit Ethernet at speeds up to 1Gbps over the existing last mile portion of cable networks. Using this technology, operators can offer high-speed bi-directional services that leverage on the performance and reliability of switched Ethernet connections, without affecting existing cable services that utilise the 5-860MHz spectrum. In the future, we can expect to see more technical innovations in utilising the higher ends of the cable spectrum.

Recently, CableLabs has announced plans to develop DOCSIS 3.0 standards. This plan is still in the preliminary stages, but DOCSIS 3.0 is expected to offer downstream bandwidth of 200Mbps and upstream bandwidth of 100Mbps per channel upstream, surpassing the capacity offered by the VDSL2 standard. The timeframe for this standard will depend on how quickly members want to move ahead with it.

3.7.3 Last-Mile Optical Fibre

There is no doubt that optical fibre access is the way of the future for broadband wireline access. According to data from Cahners In-Stat Group, RHK, and Corning, worldwide FTTH subscribers is expected to surpass the 12 million mark in 2009. Today, we are also seeing pockets of rapid FTTH deployments in different parts of the world. In Japan, you can get a 100 Mbps FTTH service for as low as US\$30 per month. Its FTTH subscriber base has also reached the critical one millionth subscriber mark way back in Feb 2004 and is expected to pass the two millionth mark by end 2004. In Canada, the Canadian Research and Innovation Network (CANARIE), which promoted the use of "dark fibre" as a vehicle to create "customer-empowered" networks⁷, have successfully used his technique to build the Alberta SuperNet⁸, a telecommunications backbone covering the entire province of Alberta, Canada, including 4700 government-related facilities in 422 communities.

Specification	Data Speed	Applications/Services	Remarks
DOCSIS 1.0	30 Mbps downstream, 5 Mbps upstream	• High-speed data • Internet access	• Original Specification
DOCSIS 1.1	30 Mbps downstream, 10 Mbps upstream	• Tiered Service • QoS applications and services • IP Multicast enhancement • Operations • Security	• Double upstream capacity • Lower operation costs
DOCSIS 2.0	30 Mbps downstream, 30 Mbps upstream	• Symmetric services such as business applications and peer-to-peer applications	• S-CDMA and FA-TDMA are mandated as the modulation technique • Up to 20 times the capacity of T1
DOCSIS 3.0	200 Mbps downstream, 100 Mbps upstream	• Wide range of IP-based services including entertainment quality video	• Faster than VDSL2 standard

Table 3. Comparison of Various DOCSIS Specifications

⁷ See <http://www.canarie.ca> for examples.

⁸ See www.albertasupernet.ca/ for details.

Beyond the promise of near infinite bandwidth, there are a number of other reasons for preferring fibre access over copper and cable. First of all, the lifetime costs of the all-glass solution are less than those of any copper-based solution, since the others include costly finite-lifetime electronics with backup power sources distributed throughout the service area. Second, glass is transparent with respect to legacy or future bit rates and formats. As more advanced broadband formats and systems become available, the fibre need not be replaced. Third, fibre's low attenuation translates not only into lower-power transmitters and less sensitive receivers, but also into much more convenient design rules for their installation. With DSL or cable, constraints on segment lengths, cable types, variable attenuator settings, and so on are much tighter and add to complexity and cost. Fourth, the passive nature of fibre, that is electronics are only used at the ends, means that provisioning and re-provisioning are accomplished much more quickly than with systems embodying electronics along the right of way. Lastly, optical equipments are becoming less expensive. Recent developments from NanoOpto Corp. showed that advancements in their miniaturisation and integration process had made it easier to mass produce optical devices. More importantly, the cost of packaging can be reduced and at the same time the unit-to-unit uniformity improved.

Currently, there are two broad categories of optical fibre technologies:

1. Optical Implementation of Ethernet

Gigabit Ethernet is a high-speed optical networking implementation of Ethernet that supports speed of 1Gbps and above. Presently, Ethernet is the most popular networking technology accounting for over 90% of today's Internet end points. Ethernet is deployed as a "last feet" solution in LAN environment. Gigabit Ethernet is a natural evolution to a higher-speed Ethernet networking platform. It is easily interfaced with earlier forms of Ethernet, and due to its higher speed, it is now being used as an access technology for last mile, metropolitan and even wide area networks. More importantly, it offers cost savings on optoelectronics on a per Mbps basis compared to Synchronous Optical Network/Synchronous Digital Hierarchy, the most popular networking platform for Metropolitan Area Network (MAN)/Wide Area Network (WAN).

On the standards front, the IEEE 802.3ae⁹ Task Force has approved the 10 Gigabit Ethernet standard in Jun 2002. This clears the way for vendors to begin shipping non-proprietary and interoperable 10Gbps Ethernet equipments. Compared with the earlier Gigabit Ethernet standard (IEEE 802.3z that was approved in 1998), the new 10 Gigabit Ethernet standard is able to move data 10 times faster over single-mode and multi-mode fibre, over distances of up to 40km. Currently, the IEEE study group looking at running 10 Gigabit Ethernet over FDDI-grade multimode fibre-optic

lines achieved task force status. The task force was designated as IEEE 802.3aq or 10GBase-LRM¹⁰.

Supporting the IEEE 802.3ae group is an industry alliance, 10 Gigabit Ethernet Alliance¹¹ (10GEA) that was formed to facilitate and accelerate the introduction of 10 Gigabit Ethernet into the networking market. Another industry consortium, Metro Ethernet Forum¹² (MEF), is also pushing for the accelerate adoption of optical Ethernet as the technology of choice, but targeting the metropolitan area networks.

2. Passive Optical Networks (PONs)

PONs are splitters connecting a few subscribers onto one shared fibre network by using passive components between the Optical Network Unit (ONU) and Optical Line Terminating (OLT). The former is to be installed in or close to customer premises while the later is needed in the local exchange. PONs eliminate bandwidth bottleneck by bringing the fibre closer to the building/curb/home. Today, most of these network elements are still expensive to deploy. Cost-effective ONU and OLT equipment are much needed. Beside price, electrical powering these network elements and the absence of compelling high-bandwidth applications are prime considerations to the early deployment of PONs in access network.

On the standards front, Broadband Passive Optical Network (BPON) and Gigabit Passive Optical Network (GPON) are the key class of PON-based standards. BPON was previously referred to as ATM-based passive optical network (APON), and its development is spearheaded by the FSAN consortium. It is defined under ITU G.983.x Recommendations and contains the basic set of common requirements for broadband access systems to support a full range of integrated broadband and narrowband services. GPON is the latest effort aimed at standardising PON systems that operates at higher bit-rates than the BPON systems. The new Recommendation G.984.1 issued in Mar 2003 describes a flexible optical fibre access network capable of supporting the bandwidth requirements of business and residential services and covers systems with nominal line rates of 1.2Gbps and 2.4Gbps in the downstream direction and 155Mbps, 622Mbps, 1.2Gbps and 2.4Gbps in the upstream direction. Both symmetrical and asymmetrical (upstream/downstream) GPON systems are described.

Ethernet Passive Optical Network (EPON) is the other key class of PON standard, defined under the point-to-multipoint fibre sub-area in the Ethernet in the First Mile (EFM) working group. The IEEE has approved the 802.3ah standard for "Ethernet in the First Mile, EFM"¹³ in Jun 2004. The EFM working group was formed because Ethernet is a technology well-suited to provide access to customers and address the issue of bandwidth bottleneck in aggregation networks, also called the first mile broadband access.

⁹ <http://grouper.ieee.org/groups/802/3/ae/>

¹⁰ <http://www.ieee802.org/3/ae/>

¹¹ <http://www.10gea.org/>

¹² <http://www.metroethernetforum.org/>

¹³ <http://www.ieee802.org/3/efm/>

Figure 18 shows how the resulting 802.3ah standard complements existing Ethernet standards.

3.7.4 Future Landscape

In most developed countries with an existing fixed line broadband infrastructure, it is likely that broadband wireless Internet will be complementary to the fixed line broadband Internet. Fixed line broadband technologies can transport significantly more data than wireless broadband technologies and this is not going to change for the foreseeable future. High speed Internet access will provide better user experience, for example faster movie downloads or data transfer in high-end grid applications. However, higher speed will not be the only factor in determining user adoption because broadband wireless Internet technologies offer every individual the "always on" broadband connectivity that wireline technologies can never provide.

In developing countries and areas of low population density with no existing broadband infrastructure, wireless broadband technologies are likely to substitute fixed line broadband technologies. This is because technologies like WiMAX is most likely going to be a more cost-effective way to provide broadband connectivity compared to DSL or cable modems.

Towards Tbps Ethernet Systems

100 Gigabit Ethernet is the next logical step from 10 Gigabit Ethernet because traditionally each Ethernet speed increase was by a factor of 10. Today, the fastest commercial bit rate on a fibre transmitter/receiver pair offered by most vendors is 80Gbps, although some vendors have announced prototypes that can deliver speeds of 160Gbps. A potential solution to achieve speeds of 100Gbps and above is to run Ethernet protocols over Dense Wavelength Division Multiplexing (DWDM), which has the potential to deliver up to 10Tbps solutions. From a technology evolution perspective, each new Ethernet standard has historically taken about 4 years

to appear. Therefore, we may be seeing the birth of a 10Tbps Ethernet standard sometime in 2014.

Next Generation PON Solutions

Similar to Optical Ethernet developments, Wavelength Division Multiplexing (WDM) techniques will be used to boost the capacity of single-fibre PON strands to 10Gbps and beyond. Currently, Coarse-WDM PON systems have just been marketed by some companies like OFS. Going forward, we expect DWDM-PON systems to be the only means to compete against next generation Ethernet systems, especially if we are looking at Terabit Ethernet systems in ten years time. Research is towards reducing the cost of DWDM-PON systems, so that commercial deployment of such systems at the local access loop can be viable.

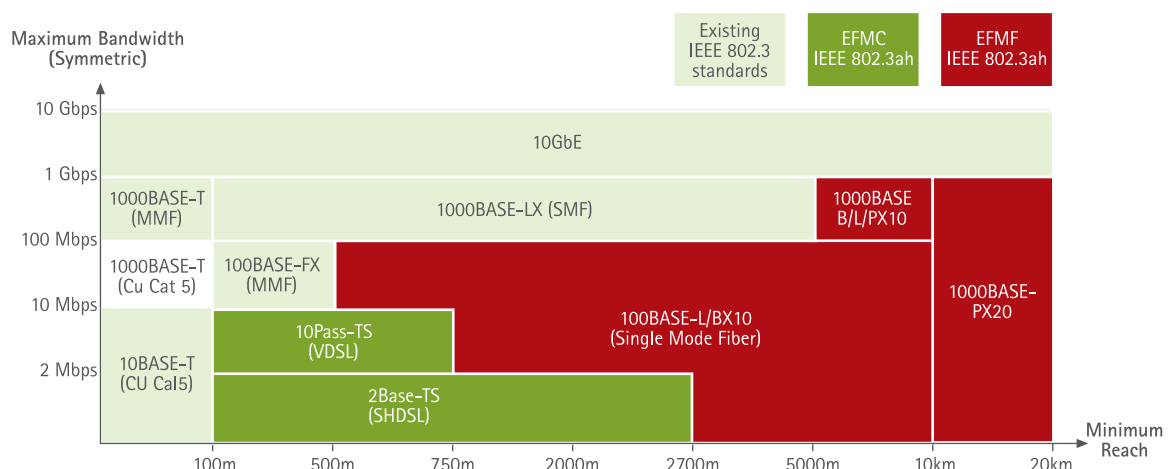
Radio Frequency (RF) over Fibre

Devices that allow the direct transport of analogue microwave/RF signals over fibre for in-building distributed antenna systems in cellular networks and WLAN can be expected a few years down the road. Engineers from Bookham Technology plc and Cambridge University Department of Engineering have demonstrated prototypes of an un-cooled directly modulated Distributed Feedback (DFB) laser that will allow optics to move into the wireless area by resolving the issue of providing low-cost fibre-fed radio access points.

3.8 Backbone Core

At the backbone core communication infrastructure, optical fibre has taken over copper as the transmission medium of choice. Data is transmitted as pulses of electrons for copper wire, while light wave is used for optical fibre transmission. Light is good for transmission, allowing optical fibre to carry far more data than copper wires. However, some properties that make light so superior for carrying data make it difficult to manipulate for switching and routing.

Figure 18. Snapshot of Global Ethernet Standards



Source: IEEE

Electricity, on the other hand, is much easier to manipulate and so is better for switching and routing.

Today, optical networks resolve this issue by converting the optical signal to an electrical one for routing, and then back to an optical signal for onward transmission. At current traffic volume, existing backbone routers can still employ this conversion process, but as the traffic volume continues to increase, this conversion process will become the bottleneck that limits the increase of future router capacity.

The Holy Grail is to have an all-optical network, where the signal can be kept in optical form throughout the switching and routing process. However, there remain several research challenges to overcome for this to happen, elaborated below.

3.8.1 Backbone Traffic Status

According to a 2003 study by TeleGeography, a research division of PriMetrica, Inc, trans-oceanic Internet traffic and capacity growth from 2003 to 2006 will experience growth of approximately 67% annually (see Table 4). If this traffic growth rate is sustained over the next ten years, then we can expect the amount of traffic to be around 100 times that of today.

		2003	2004	2005	2006
Trans-Atlantic	Internet Bandwidth (Gbps)	388	648	1,082	1,806
	Peak Internet Traffic (Gbps)	100	167	279	466
	Average Internet Traffic (Gbps)	70	117	195	326
Trans-Pacific	Internet Bandwidth (Gbps)	92	153	256	427
	Peak Internet Traffic (Gbps)	28	47	78	130
	Average Internet Traffic (Gbps)	20	33	56	93

Table 4. Trans-oceanic Internet Traffic and Capacity Forecast, 2003 – 2006

Source: Global Internet Geography Database and Report, PriMetrica Inc.

In May 2004, Cisco launched its new CRS-1 Carrier Routing System. A single shelf system has a total capacity of 1.2Tbps and this is scalable up to 92Tbps for a multi-shelf system. Based on the above traffic growth projections, it is reasonable to assume that the CRS-1 and its subsequent improvements are sufficient to meet the future traffic demands for at least another eight years.



Figure 19. Cisco CRS-1 Carrier Routing System

Source: Cisco

3.8.2 Transmission Capacity of Optical Fibre

The state of optical transmission technology that determines the fibre transmission capacity can easily meet any existing or future traffic demands. The key breakthrough that led to this scenario is the use of WDM. WDM is a technique that allows many different colours (wavelengths) of light to transmit different streams of data over optical fibres in a telecommunication network at the same time. Currently, prototypes that combined wavelengths in excess of 1000 λ have been demonstrated¹⁴.

Much research in this area is preoccupied with developing photonic components that could work at higher channel rates, wider optical bandwidth and closer channel spacing through a variety of innovations. The aim is primarily to achieve higher capacity and better reliability for the next generation optical transmission system.

Closer Channel Spacing

Higher transmission capacity can be achieved by increasing the density of multiplexing, i.e. narrowing the separation between adjacent optical signals. To pack more channels in the much narrower spacing, researchers will have to overcome a series of technical challenges. Amongst these challenges include narrow bandwidth and low crosstalk optical filter design and laser diode wavelength stabilisation. Currently, thin film filter is one of the most widely used filters for DWDM optical communication systems. Moving forward, the research is towards creating tunable filters based on things like Fibre Bragg Grating and Arrayed Waveguide Grating. Another approach to alleviate the requirement on optical filter design is to use inter-leavers together with optical filters. This allows closer channel spacing and at the same time provides a smooth upgrading path. Today, most commercial optical network systems use channel spacing of 100GHz or 50GHz. Although companies such as Essex Corporation have demonstrated prototype systems with 6.25GHz channels spacing using their hyperfine WDM technology in the Optical Fibre Communication Conference and Exposition since 2002.

¹⁴ Foresight Exploiting the Electromagnetic Spectrum: Switching to light: all-optical data handling, UK Foresight report.

Wider Optical Bandwidth

A wider transmission bandwidth allows a greater number of wavelengths of multiplex optical signals to be multiplexed, thus increasing the transmission capacity. There are two broad technology areas driving an increase in the operational bandwidth for optical communications: new fibre materials with better transmission characteristics and optical amplifiers that boost signals in previously unused bandwidth.

In recent years, research has gone into discovering new fibre materials with better transmission characteristics than that of silica glass. One very promising material is the fluoride glass. Compared with silica fibre, fluoride fibre (FF) has many unique characteristics in wide operating wavelength and emission efficiency when rare-earth elements are doped into. However, it has poorer glass stability and higher reactivity in humid atmospheres. Furthermore, FF is more difficult to manufacture than silica fibre. Figure 20 shows the theoretical transmission wavelength range among three different kinds of glass materials. Compared to silica and telluride, fluoride covers wider range in transmission wavelength range, and is only material applied to over 2000nm wavelength band. However, development of optical amplifiers in this broader range needs to be addressed first before it becomes feasible to be used for long-distance transmission.

Another means of improving the optical bandwidth of the fibre material is through the use of photonic crystal fibre (PCF). Figure 21 shows the cross-section of a PCF: Conventional silica material are penetrated by a number of hollow tubes located in rings around the guiding core of the fibre, this allows the manipulation of the wave-function of propagating optical signals such that entirely

new fibre properties (and applications) become possible. Research has successfully demonstrated optical bandwidth in excess of 400nm for optically pumped PCF¹⁵.

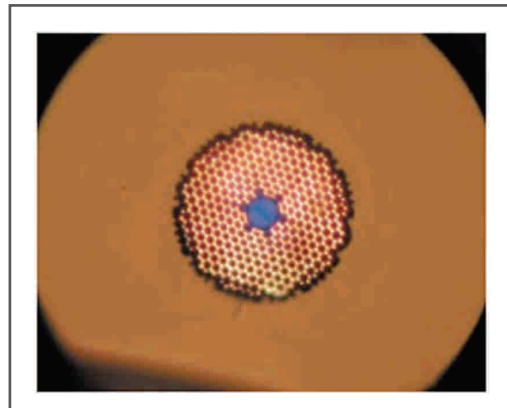
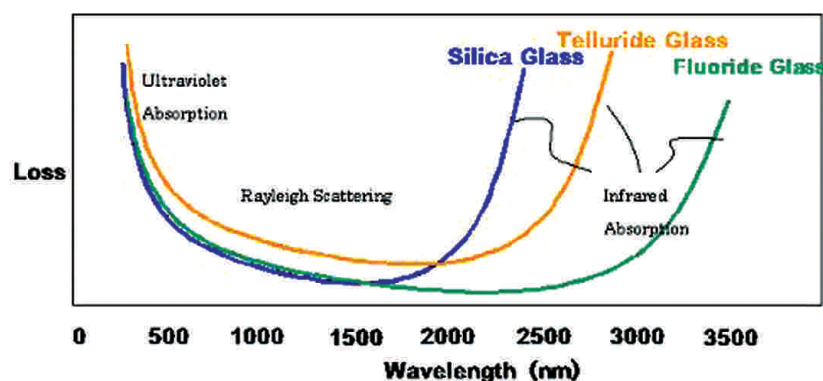


Figure 21. Photonic Crystal Fibre

Source: BlazePhotonics

Optical fibre amplifiers are essential to combat signal losses for long-distance transmission. C-band (1530–1565nm) and L-band (1565–1625nm) are widely used in optical communication. The third waveband, S-band (1460nm–1530nm), is also used in some systems. Currently, Erbium-doped amplifiers and Thulium-doped amplifiers are used to amplify attenuated optical signals in these bands. There are also prototype demonstrations of next generation amplifiers, like Raman amplifiers, which can provide amplification in all wavebands. Beyond these three bands, the long term trend in this area is towards creating better optical amplifiers that can boost signals in previously unused bandwidth, such as O-band (1260–1360nm), E-band (1360–1460nm), and U-band (1625–1675nm).

Figure 20. Theoretical Transmission Wavelength Range



Source: FiberLabs Inc.

¹⁵ R. Baets, "Nano-Photonics," Proc. 29th European Conference on Optical Communication (ECOC 2003), vol. 5, Rimini, Italy, 200–235 (2003)

Higher Channel Rate

Besides multiplexing multiple wavelengths (channels) onto a single fibre, another means of increasing transmission capacity is through multiplexing on a single channel. Existing systems make use of Time Division Multiplexing (TDM), but Optical Time Division Multiplexing (OTDM) is expected to be the way to achieve speeds of 160Gbps per channel and beyond. OTDM combines different stream of optical signals of the same wavelength via optical means into a high data-rate bit stream. Besides OTDM, there are research exploring Optical Code Division Multiplexing (OCDM), based on the code-division multiplexing (CDM) scheme (also commonly known as spread spectrum techniques). Systems that achieve 160Gbps channel rate using OCDM have been demonstrated. Challenges in this area include difficulty with synchronisation and complexity in the multiplexing and de-multiplexing system.

Another way to increase the transmission capacity is through better modulation and coding techniques. Most of the existing system makes use of binary modulation that has a theoretical spectral efficiency limit of 1b/s/Hz (see Figure 22). However, with better photonics components, coherent modulation techniques, such as Quadrature Phase Shift Keying, can be used. This will allow spectral efficiency of several b/s/Hz to be achieved. Employing these techniques require more complex signal processing at the receiver and greater input power density.

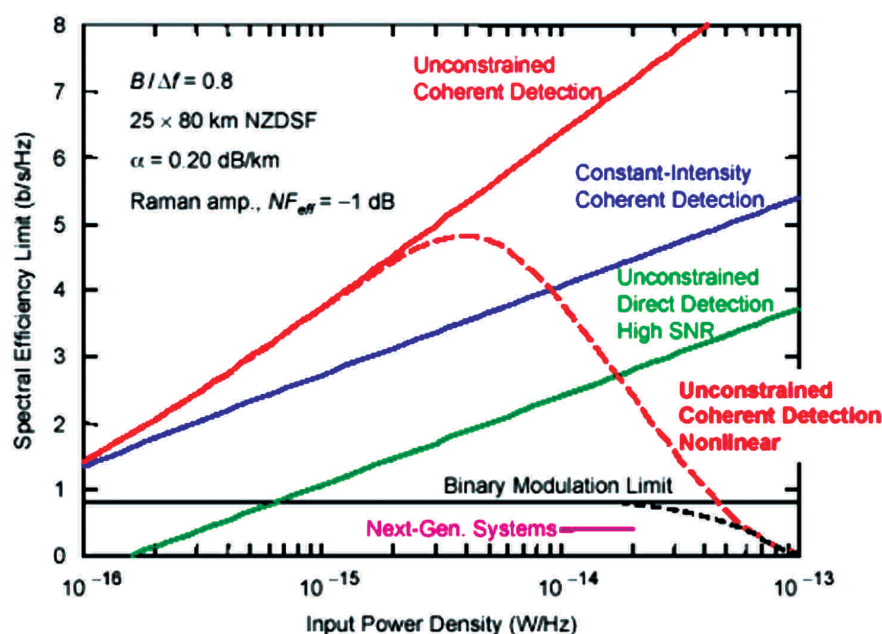
3.8.3 Optical Switching, Routing and Processing

Optical Switching and Routing

Optical switching or routing refers to the re-directing of an optical signal from one network node to another node. To reach a destination, the signal carrying information hence travels or switches through a series of nodes that then make up the optical path taken by the signal from point A to point B. Two main approaches can be used to implement an optical switch to direct an optical signal from a given input port to a given output port:

- **Optical-Electrical-Optical (OEO switching).** An optical signal coming to the input port of an optical switch has to be converted to an electrical signal for conventional electronic switching equipment to understand this signal, and then reconverted to optical signal for re-transmission to the outgoing port. It is also known as an opaque switch because an optical signal cannot pass through an OEO switch without being converted into an electrical signal. This approach offers the advantages of being able to use existing electronic switching technology and the ability of providing signal re-amplification, re-shaping, and re-timing whenever optical signal passes through the switch. However, it does not provide bit rate, service and protocol transparency;

Figure 22. Spectrum Efficiency Limits Versus Input Power Density in Amplified WDM Systems



Source: StrataLight Communications

- **All Optical Switching or (OOO switching).** An "all optical switch" uses all optical means to direct the optical signal from the input port to the output port without changing it to electrical signal. It is also known as a transparent switch. It provides bit rate as well as service and protocol transparency. However, it does not offer complete signal regeneration and based on current technologies switching speed is still low and size is small.

An optical switch can be used for circuit switching (lambda switching), burst switching and packet switching. In lambda switching optical signal is directed from the input port to the output port based on its wavelength. The connection is typically long and the switching time required is in the order of sub-millisecond. Optical circuit switching network is the form taken by almost all the optical networks now. Optical switches are used in such networks in areas of Protection Switching, Optical Cross Connect (OXC), and Optical Add Drop Multiplexer (OADM).

Optical burst and packet switching are forms of statistical optical TDM. In the former, the goal is to set up the wavelength connection for the duration of a data burst. Burst data need to be buffered at the input of the switch while the wavelength connection is being set up. Very fast switching is required. This is still not easily done all optically (OOO), although one possibility is to use Semiconductor Optical Amplifier (SOA) arrays. Optical packet switch is essentially the optical equivalent of a electronic packet switch. It needs to read optical header and switch optical packet at very high speed. Both input optical buffer and output optical buffers are required. Although researchers have demonstrated optical burst switching, they are still not practical today because it is still extremely difficult to recognise or read optical packet headers via entirely optical means. At the same time, there is no good way to buffer optical signal and do optical packet routing today. True all optical packet switching is generally agreed to be at least 10 years away from commercialisation.

Generally, the path towards all optical switching still necessitates further research work in the areas of:

- Optical buffering (memory) so that burst switching and optical packet switching can be implemented;
- Large optical switching fabrics with sub-nanosecond switching speed for optical packet switching;
- Technology for implementing optical switching fabric with large port count, low insertion loss and reliability; and
- Non-intrusive optical signal monitoring & grooming for correction of transmission impairments.

Optical Processing

There is no good way to do optical processing. Today, photonic bandgap structures offer the best prospects for creating optical circuits with tiny components and waveguides that can do optical processing. A photonic bandgap structure

consists of a material (such as glass) into which a periodic pattern of holes has been etched. The pattern of the holes determines the path of the light, which can be designed to deflect light round sharp bends. Tiny waveguides can therefore be created, unconstrained by the bending-limit disadvantage of optical fibre. Photonic bandgap devices can also be made from fibre. This innovation opens up the possibility of designing optical switches within the fibre itself. Today, photonic crystal fibre (see Figure 21) is the most commercialised photonic bandgap technology. More futuristic prototypes that are being researched include three-dimensional photonic crystals (see Figure 23).

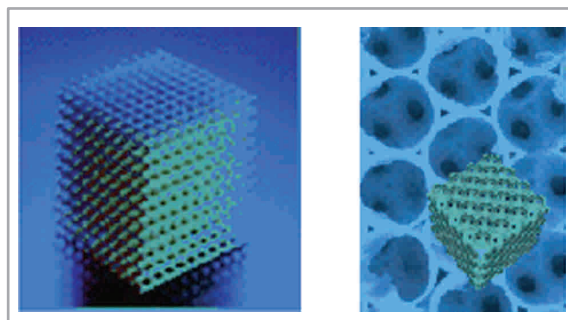


Figure 23. Three-Dimensional Photonic Bandgap Crystals

Source: University of Toronto

Optical Regeneration

In an optical transmission system, an optical signal is attenuated and distorted due to attenuation, dispersion, crosstalk and non-linearity associated with optical fibres and other components in the system. Since the effects are accumulative, optical signal regeneration is needed. Three types of regeneration are possible: 1R (re-amplification), 2R (re-amplification and re-shaping) and 3R (re-amplification, re-shaping and re-timing). Currently 1R is done optically while 2R and 3R are carried out using Optical-to-Electrical, Electrical-to-Optical converters and electronic regenerators. With the increase in transmission speed, an all-optical method of regenerating hundreds of wavelengths simultaneously is one of the most important requirements to resolve the OEO bottleneck.

1R regeneration. The simplest form of regeneration involving signal amplification only. It restores the signal level and can be easily accomplished using various types of optical amplifier. However, crosstalk is also amplified and noise is added.

2R regeneration. Another level of regeneration involving signal amplification and reshaping. It suppresses crosstalk and noise such as amplified spontaneous emission noise introduced by optical amplifiers. Currently, it is typically done electronically through the use of Optical-to-Electrical and Electrical-to-Optical conversion and electronic regenerator.

It is also possible to do it optically through the use of SOA and Raman Amplifier. However, challenges still remain to do 2R regeneration simultaneously for multiple wavelength channels and at higher channel speeds.

3R regeneration. The ultimate form of regeneration involving signal amplification, reshaping and retiming. Today, this is achieved electronically in commercial systems. 3R regenerative devices based on SOA and Raman Amplifier have been demonstrated experimentally. These devices require the implementation of optical clock recovery and decision circuits. Mode locked laser, self-pulsating DFB laser and Fabry Perot optical filter can all be used for the clock recovery function. While mode locked laser, self-pulsating DFB laser, active optical interferometer and nonlinear optical loop mirror can be used for the decision circuits. These techniques have all been demonstrated experimentally, however, commercial viable is still a few years away.

Soliton Transmission. Another approach to resolving the issue of signal degradation is through the use of soliton transmission. Solitons are light pulses that maintain their shape even when transmitted over very long distances. They actually leverage on the non-linear effects that occur in the fibre, self-phase modulation, and on the linear effects, chromatic dispersion, to offset each other resulting in enhanced performance.

Solitons have many other real world advantages over more traditional modulation methods (see Figure 24). For example, experimental soliton systems have achieved all-optical transmission distances of more than 5,000km without the need for electrical regeneration at every 320km. This is due to its ability to propagate over long distances without any distortion of its waveform and its resistance to chromatic

dispersion and polarisation mode dispersion.

Several challenges must be addressed before solitons can be applied effectively. A major challenge is that the effective functioning of solitons requires the use of signal that is significantly more intense than existing systems. This is a major hurdle to practical implementation of soliton because high power gain translates to higher costs. Other issues before practical application is possible in telecommunication system include the need for refined control techniques capable of separating solitons and the ability to master and regulate slight differences in soliton amplitudes.

3.9 Future Internet Architecture

The present Internet architecture was developed in the 1970s and has not undergone any major changes since. However, the "eco-system" of the Internet has evolved quite significantly; from a single group of academic researchers in the past to the present landscape of individual users, commercial Internet Service Providers (ISPs), private sector network providers, service providers and resellers, governments, intellectual property rights holders, and so on.

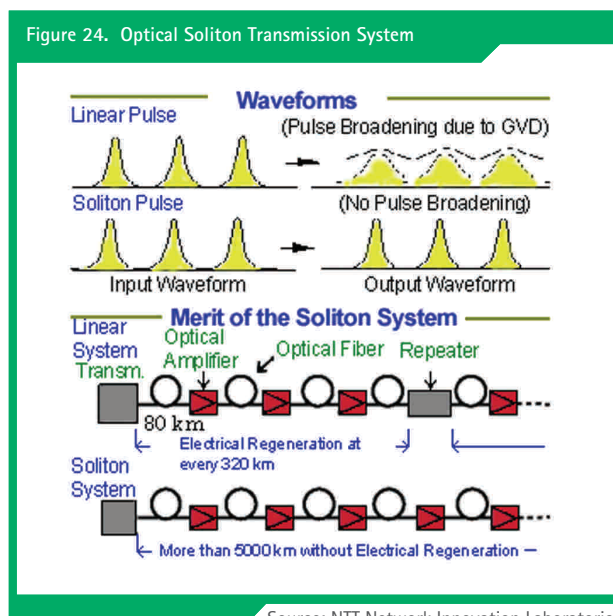
Presently, there are a several efforts looking at how the future Internet Architecture should evolve. We will highlight a few below:

Internet Engineering Task Force (IETF). The IETF is an international organisation dedicated to the evolution of the Internet architecture and the smooth operation of the Internet. It is the principal body responsible for the development of Internet related information and specifications, better known as RFCs (Request For Comments). Most of the specifications are adopted as Internet standards.

ITU Telecommunication Standardization Sector (ITU-T) Next Generation Networks (NGN) Project. The NGN project was started to study the new telecommunication landscape characterised by factors, such as open competition between operators due to market deregulation, explosion of digital traffic, increased user demands for new multimedia services, increased user demands for greater mobility. The project coordinates all the ITU-T activities related to the establishment of implementation guidelines and standards for the realisation of a Next Generation Network. It aims to produce its first Recommendations by the end of the 2001-2004 study period.

EuroNGI project. A European Union effort on designing the Next Generation Internet architecture. This project, which is still in the early stages, aims to master technology diversity for the design of efficient and flexible NGI architectures, provide innovative traffic engineering architectures adapted to the new application requirements, and develop the corresponding appropriate quantitative methods.

Figure 24. Optical Soliton Transmission System



NewArch project. This is a project sponsored by Defense Advanced Research Projects Agency (DARPA) to define a future architecture that the Internet can evolve towards and to demonstrate selected components through prototyping. Some high level design principles have been identified by this project and different technical architectures have been proposed to address these design issues. One proposal is the Role-based Architecture (RBA). RBA modularises different network functionalities, instead of the existing layering architecture, allowing for more flexible modularity and composition. Another proposal is the Forwarding Directives, Associations, Rendezvous, and Directory Service (FARADS) Architecture. FARADS is an architectural framework that allows different network entities to establish shared context. It separates the concept of a network entity from the physical concept of a host or a process, allowing for different choices of visibility and accessibility to be made between consenting senders and receivers, and supports a wide range of naming options, rather than assuming the use of a global namespace.

3.9.1 Evolutions on the Network Layer

The success of Internet has often been attributed to its simple best-effort, end-to-end datagram delivery model. After IP won the "war" against ATM in the 1990s, IP has become the de-facto network layer of choice for Internet traffic. It provides a simple, single, global address to reach every host, enables unfettered access between all hosts, and adapts the topology to restore reach-ability when links and routers fail. More importantly, IP hides heterogeneity as it provides a single, simple service abstraction that is largely independent of the physical links over which it runs. Therefore, IP can provide service to a huge variety of applications and operates over extremely diverse link technologies.

Internet Protocol version 4 (IPv4)

The most commonly used version of IP is version 4, which was formally standardised in 1981 and is used in most IP-based networks including the Internet today. However, the success of IPv4 has actually emphasized its limitations. Version 4 is proving inadequate for supporting the increasing use of the Internet for multimedia communications including real-time voice and video, as well as the increasing number of networked devices. The most obvious limitation of IPv4 is its address field. IP relies on network layer addresses to identify end-points on networks, and each networked device has a unique IP address. IPv4 uses a 32-bit addressing scheme, which gives it 4 billion possible addresses. With the proliferation of networked devices including PCs, cell phones, wireless devices, etc., unique IP addresses are becoming scarce, and the world could theoretically run out of IP addresses.

Migration to IPv6

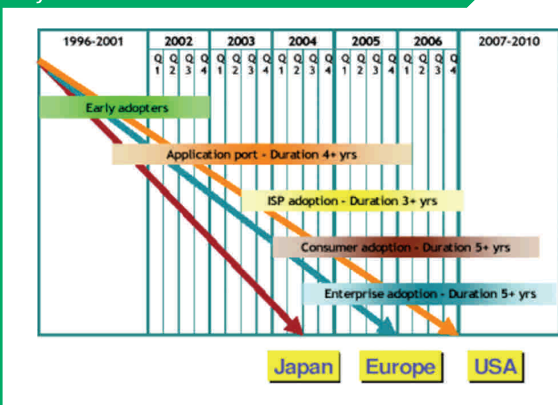
With the limitations of IPv4, a new version of the protocol, IPv6, was developed and finalised in 1998. IPv6 promises to solve the address shortage completely with its 128-bit address. The new version also addresses other limitations of IPv4. IPv6 packets have been simplified compared to IPv4 packets to speed up router processing. In addition, IPv6 packets are labelled to provide QoS for priority applications such as real-time video and voice. IPv6 also natively offers improved security features with support for authentication and privacy. IPv6 is designed as an evolution of IPv4, not a radical step away from it. Many features of IPv4 remain in the new protocol, and the two can coexist during the transition to a complete IPv6 internetworking environment.

Due to the huge size and coverage of the Internet, the transition of IPv4 to IPv6 has been slow as it is impossible to expect a centrally coordinated cross-over. For many organisations, such a transition will also be costly, therefore, the resistance is strong. Technologies such as CIDR (Classless Inter-domain Routing Protocol) and NAT (Network Address Translation) that provide work around solutions to the address limitation of IPv4 further delayed this transition.

Existing Landscape

Countries around the world have begun IPv6 migration efforts. Figure 25 gives an overview on the current and expected deployment timeline of the major economies around the world. In Jul 2004, Internet Corporation for Assigned Names and Numbers (ICANN) announced that it will start assigning IP addresses and domain names using IPv6. Initially, IPv6 support will be seen on Japan's (.jp) and Korea's (.kr) country codes. France (.fr) will be next.

Figure 25. Expected IPv6 Deployment Timeline in Major Economies Worldwide



Source: IPv6 Task Force Steering Committee

In the Asia Pacific region, countries that have announced IPv6 rollout include Japan, China, Taiwan, and South Korea. Japan is one of the earliest countries in the world to announce nationwide IPv6 migration plans. The Japanese government has allocated a research and development budget of two billion yen (around US\$18 million) for IPv6, in an effort to upgrade all existing systems in every business and public sector by 2005. Major carriers in China have also started building multiple high-level networking platforms connected by IPv6, known as the China Next Generation Internet, with completion scheduled for 2005. In Taiwan, the government will invest NT\$26 billion (around US\$78 million) into the development and testing of IPv6, with rollout slated for 2007. South Korea has made an initial investment of 83.6 billion won (around US\$72 million) at the end of 2003 to begin the initial planning process and plans to implement full support for IPv6 technology before 2011.

The European Commission sees IP address saturation in 2005-2010 and initiated an IPv6 Task Force in Apr 2001 to design an IPv6 Roadmap, sending a strong signal on the importance of IPv6. As of Q2 2003, majority of the western European countries have set up an IPv6 task force. They include Spain, France, UK, Portugal, Switzerland, Germany, Finland, Denmark, and Sweden.

In America, deployment of production IPv6 networks is expected to be slower than in Asia and Europe because of its significantly larger IPv4 router base. Today, NTT/Verio is the only ISP offering commercial IPv6 services. The US Department of Defence, however, has initiated a huge "push" with the announcement that all IT purchases must be IPv6 capable as of Oct. 2003, and have set a goal of 2008 for the agency to migrate all of its communications to IPv6.

Future Landscape

IP Network will replace Public Switched Telephone Network (PSTN). Today, VoIP allows users to talk to each other for close to nothing. There is therefore, little doubt that VoIP will eventually replace the traditional PSTN telephony. The only question is when. According to Forrester, the complete western European migration to VoIP will only take place in 2020, citing inhibitors like the need for telecommunication operators to invest heavily in order to replace the huge amount of existing telephone switches and the lack of an integrated migration strategy. However, the actual timeline may be much earlier given the recent announcement by BT, in Jun 2004, of plans to begin mass migration from PSTN to IP in 2007. BT expects to transform its UK telecommunication infrastructure into a pure IP-based network by 2009.

IP is conquering the wireless world. IP is also conquering new grounds, moving from the wireline world into the wireless world. Today, Internet access is already available to users of 2.5G and 3G networks. An all IP-based service delivery platform is also expected for future 3G and 4G networks. For example, IPv6 is expected to be built into the next release of 3GPP specifications.

On the broadcast front, there are also early signs that IP will eventually take over. For example, the German capital, Berlin, is the world's first jurisdiction to do away with analogue TV and go all digital in Aug 2003. The benefits were immediate because 27 digital channels were delivered using just 7 out of the original 12 analogue channels. For device manufactures, companies like Texas Instruments have developed digital TV chips, which support the European Digital Video Broadcasting-Handheld (DVB-H) standard and the Japanese Integrated Services Digital Broadcasting-Terrestrial (ISDB-T) standard, for mobile handsets. Early field trials are expected in specific cities of Europe and Japan in 2005. Mass deployment of mobile digital TV infrastructure can be expected in 2007.

IP will remain for many years to come. Based on the earlier discussion, we are already seeing trends of the Internet becoming the sole communication infrastructure, displacing those of telephony and broadcast TV. We can safely predict that IP will remain the network layer of choice for the next 20 years. It may evolve to a new generation of IP specification further down the road, but it is unlikely to be replaced in the near future.

3.9.2 Extensions on the Transport Layer

In the Open Systems Interconnection (OSI) 7 layer Reference Model, the transport layer is the lowest layer that operates on an end-to-end basis between two or more communicating hosts. This layer lies at the boundary between these hosts and an internet-work of routers, bridges, and communication links that moves information between hosts. A good transport layer service allows applications to use a standard set of primitives and run on a variety of networks without worrying about different network interfaces and reliabilities.

Essentially, the transport layer isolates applications from the technology, design, and idiosyncrasies of the network. Dozens of transport protocols have been developed or proposed over the last two decades. The three key transport layer protocols on the Internet transport layer are Transmission Control Protocol (TCP), User Datagram Protocol (UDP), and Stream Control Transmission Protocol (SCTP).

Transmission Control Protocol (TCP)

TCP is a protocol used along with the IP to ensure reliable delivery of data between two entities over the Internet. TCP is connection oriented. It can guarantee the delivery of data and ensure that the data packets are delivered in the same order as they are sent.

The origin of TCP goes back all the way to 1974 with a publication by Cerf and Kahn. The first specification of the TCP first appeared in RFC 761 and was finalised in RFC793 in 1981. Along the way, the TCP underwent several revisions and extensions. There was the addition of congestion control mechanisms to TCP in 1987, known as the Tahoe TCP. Further modifications to the Tahoe congestion control mechanisms

resulted in other versions like Reno, Vegas, and New Reno. TCP's congestion control mechanisms were finally standardised in RFC2001 and updated in RFC2581 and RFC 2582.

User Datagram Protocol (UDP)

UDP is an alternative protocol to TCP that is standardised in RFC 768. It is a stateless protocol that makes no provision for acknowledgment of packets received. In other words, unlike TCP, it does not guarantee packet delivery, nor does it provide sequencing of packets.

Stream Control Transmission Protocol (SCTP)

SCTP (standardised in RFC 2960) is designed to transport PSTN signalling messages over IP networks, but is capable of broader applications. Like TCP, SCTP provides a reliable transport service, ensuring that data is transported across the network without error and in sequence. SCTP is also a session-oriented mechanism, meaning that a relationship is created between the endpoints of an SCTP association prior to data being transmitted, and this relationship is maintained until all data transmission has been successfully completed. Unlike TCP, SCTP provides a number of functions that are critical for telephony signalling transport and at the same time can potentially benefit other applications needing transport with additional performance and reliability. In particular, it supports multi-streaming and multi-homing.

The name Stream Control Transmission Protocol is derived from the multi-streaming function provided by SCTP. This feature allows data to be partitioned into multiple streams that have the property of independently sequenced delivery, so that message loss in any one stream will only initially affect delivery within that stream, and not delivery in other streams. Multi-homing is the ability for a single SCTP endpoint to support multiple IP addresses. The benefit of multi-homing is potentially greater survivability of the session in the presence of network failures.

Next Steps

We believe the following three trends will influence the design of future transport layer protocols:

1. Higher capacity and longer distance links. Advances in optics and photonics have resulted in underlying links that have higher transmission capacity and are longer in distance. These changes to the underlying communication infrastructure have resulted in networks with larger end-to-end bandwidth-delay products. These so-called "Long Fat Networks" require extensions to the transport protocols so that fast and efficient transfer of increased amounts of data is possible.

2. Changing landscape of applications and services. As the Internet slowly evolves to be the global communications backbone, new applications, such as transaction processing (e-commerce), audio/video transmission (broadcast), and maybe even virtual reality, will result in new and widely varying network service demands.

3. Emerging sensor worlds. A world filled with clouds of tiny sensors doing things like monitoring weather or environment or tracking of goods and service in supply chains. Depending on the application, the monitoring of a wild-life eco-system may consist of billions of tiny sensors communicating with each other wireless. Such a network may require new transport protocols that can allow information capture to be more efficiently communicated to the central monitoring office.

3.9.3 Achieving End-to-end Quality of Service

Research on providing QoS on the existing Internet architecture has been around for over ten years, but we still do not have end-to-end QoS in the Internet. Most of the open issues related to them are economic ones. It is acknowledged that more applied research that takes explicit consideration of the economic issues of deploying and operating a QoS-enabled IP network is required before the vision of end-to-end QoS can be achieved.

The two key QoS paradigms defined by IETF are Integrated Services (IntServ) and Differentiated Services (DiffServ):

- **Integrated Service (IntServ).** IntServ is a per-flow based QoS framework that supports applications with delay and bandwidth requirements. To achieve QoS guarantees, a signaling protocol for applications to reserve network resources dynamically, called Resource ReServation Protocol (RSVP), was used. RSVP is a receiver-initiated reservation process that can be used for a multi-cast environment. This framework unfortunately, suffers from complexity and scalability issues because of the need to introduce flow-specific state in routers.
- **Differentiated Service (DiffServ).** To alleviate the complexity issues of Intserv, the DiffServ framework was proposed. The DiffServ architecture differentiates between edge and core routers. Edge routers maintain per-flow state information and perform per-flow operations like buffer management, scheduling and admission control. The assumption is that at the network boundary, there are fewer traffic flows, therefore, edge routers can perform operations at a finer granularity. At the network core, traffic flows are aggregated. Core routers only need to maintain state information for a few classes of aggregated traffic flows. As the number of classes defined is small, packet processing can be efficiently implemented. Hence, this differentiation between edge and core routers makes the DiffServ architecture highly scalable.

Key Challenges

One of the key factors that hindered QoS deployment has been the transition of the Internet infrastructure from the state of congestion in the early 1990s to the state of excess capacity in backbone links. To the service providers, over-provisioning the links is the more cost-effective solution, especially with decreasing cost of fibre deployment.

Another development is that of more resilient voice/video coding techniques that are better suited for the best-effort Internet compared to the older coding techniques that were originally designed for circuit-switched networks.

Finally, business models are not consistent with inter-domain QoS, i.e. providing QoS services between two different Internet service providers. Today, routers provide best-effort forwarding of IP packets without regard for whether the source or destination of the packet is a direct customer of the operator of the router. This property is a significant contributor to the scalability of the Internet. However, it also makes QoS deployment difficult because it is unclear how a network operator could bill or otherwise recover costs associated with providing a preferred service. Furthermore, it is impractical to authenticate the identity of the sender of would-be preferred traffic while still forwarding traffic at line rate.

3.9.4 Extensions to Routing

The existing routing system works well but there remain several areas that can be improved upon.

Inter-domain routing

Currently, the Internet inter-domain routing system has routing prefixes about 150,000 to 200,000. This number is expected to increase significantly over the next few years because of new approaches like multi-homing and an increased number of devices connected to the internet. As the number of routing prefixes increases beyond 200,000, an important research area will be to develop new routing algorithms that are more scalable and have shorter end-to-end convergence time.

Routing Integrity

Today, there remains no mechanism for authenticating actual routing data in the Internet inter-domain routing system. There are proposals for resolving this issue in inter-domain routing that leverages on a single trust hierarchy. However, there are concerns about the centralized administration of this trust system, making actual deployment unlikely to materialise.

It appears that an alternative approach to routing data authentication needs to be developed. In particular, this new approach should use non-hierarchical trust models so that concerns related to centralised administration are non-existent. Furthermore, it should have the ability to perform partial authentication of routing data so that incremental deployment of routing authentication mechanisms is possible.

Policy-based Routing

The existing Internet routing system locates the best path by finding the shortest path. Naturally, the assumption that the best path is the shortest path may not be true. However, this has been a good approximation so far.

Today, there are studies exploring policy-based routing or routing with alternative metrics. Examples of alternative metrics include QoS parameters like packet loss probability, delay, delay jitter, and economic cost parameters like the monetary cost of the path. In many cases, routing policy is directly tied to the economic issues for the network operators, so routing should ideally take into account economic considerations as well as technical considerations.

Transitioning from the current inter-domain routing system to any new inter-domain routing system is unlikely to be a trivial exercise. Therefore, great importance must be placed on applied research that studies economic and commercial issues, so that effective deployment strategies and transition mechanisms can be developed.

Mobile and Ad-Hoc Routing

Mobile and ad-hoc routing will be an increasingly important research area given the huge growth potential of IP-based mobile devices over the next ten years. Important issues related to this topic include the security challenges associated with the highly distributed and dynamic nature of mobile end-node devices. In particular, issues related to Authorization, Authentication, and Accounting (AAA), and security key management. Routing scalability is another important issue for wireless networks. Hierarchy-based routing will be the most obvious approach but this can be limiting. Alternative approaches that are currently being explored include leveraging wireless link characteristics such as link quality, sub-layer congestion conditions, or transient channel behaviour to derive better network layer routing.

3.9.5 Internet Security

With Internet being increasingly used as an e-commerce platform, issues of security and trust have taken centre stage. Network security can be broadly grouped into three categories:

1. Threat Defence. Threats, which can be both internal and external, refer to attacks to network systems. Examples include worms, Denial of Service (DoS) attacks, man-in-the-middle attacks, and Trojan horses. Today technologies that guard against these threats include: firewalls, network-based intrusion protection sensors, detection instrumentation, and traffic isolation techniques. Advanced networking intelligence is also increasingly being used to provide a stronger defence against these attacks.

2. Secure Connectivity. Security at the connectivity level refers to the need to provide data integrity and privacy when two parties communicate with each other. Technologies in this category are based on encryption and authentication that include: IP Security (IPSec), Secure Sockets Layer (SSL), Secure Shell (SSH), and Multi-protocol Label Switching (MPLS)-based Virtual Private Network technologies.

3. Trust and Identity Management. It enables reliable e-business and underpins the creation of any secure network or system. It entails allowing or denying access to business applications and networked resources based on a user's specific privileges and rights. Technologies in this category focus on network-based admission control that include: secure access control server, authentication protocols like 802.1X, and AAA frameworks that can provide a high level of detail in access rights and to create quarantine zones for non-compliant endpoints, and the ability to block unauthorized access entirely.

Efficient Deployment of Security Mechanisms

This goes beyond basic fundamental research that looks into cryptography, crypto-analysis, security algorithms, security protocols, and systems. One of the greatest challenges is that security mechanisms need to be incrementally deployable and easy to use. If it is not easy to use, then it may not be configured correctly. And if it is mis-configured, security will be lost although the system remains functional. Security patch management, especially in the area of software patches against viruses and worms, has therefore, become a very important area.

Today, the speeds at which virus and worms can replicate themselves are getting faster and faster. In 2003, fast viruses like Slammer, MSBlaster and SoBig, infected tens of thousands of machines within hours of being launched. Newer viruses like Flash Worm and Warhol Worm are even more deadly. Flash Worm can infect an entire PC network within 15 seconds, while Warhol Worm can spread worldwide within 15 minutes. Normally, time is required to detect a new virus attack, formulate a new security patch, and distribute the "patch" to infected computers. Therefore, present day defences are too slow to prevent damages by such attacks. Significantly more work is required to cope with the war against viruses.

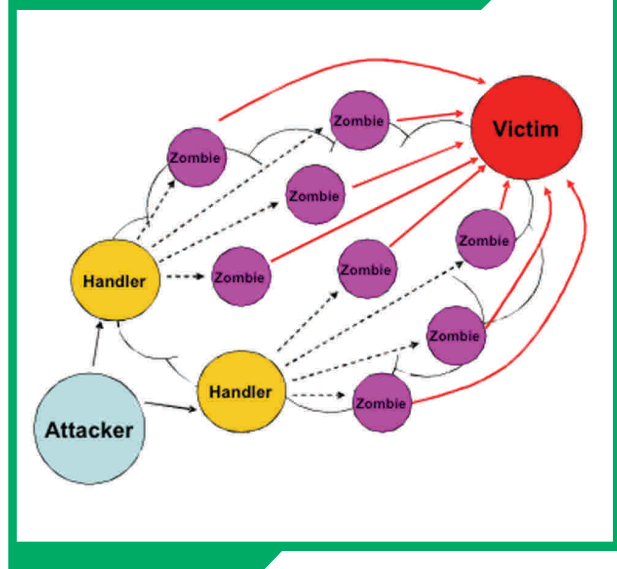
Denial of Service (DoS) Protection

According to the Internet's leading security watchdog, Distributed DoS (DDoS) attacks is posing a major threat to e-commerce and e-business. According to mi2g, DDoS attacks alone have caused between US\$3.4 to 4.1 billion of economic damage in Q1 2004, which exceeds the total damages from DDoS in 2003, estimated to be between US\$1.3 to 1.6 billion. This indicates that the threat of DDoS attacks continues to escalate.

DoS attacks occur when a computer network is overwhelmed by streams of seemingly normal service requests so that legitimate users cannot gain access to network resources, hence the name denial of service. DDoS attacks involve the use of multiple unwitting "zombie" computers sending requests to the victim site (see Figure 26). This approach is more deadly because of its ability to create a significantly greater mass of requests to deny service and the difficulty

involved in identifying and stopping the origin of the attack, especially when the attacker's source addresses is "spoofed" (i.e. modified).

Figure 26. Architecture of a DDoS Attack



Some work has been done on DDoS protection but more is needed. Today, technologies that guard against these attacks include network-based intrusion protection sensors, detection instrumentation, and traffic isolation techniques. Advanced networking intelligence is also increasingly being used to provide a stronger defence against these attacks.

On the research front, new architectures that differ from existing "detect and prevent" solutions have been proposed that can better maintain the reliability of network systems. Researchers from Columbia University have proposed a Secure overlay Services (SOS) architecture that proactively prevents DoS attacks, geared towards supporting Emergency Services or other similar types of communications.

3.9.6 PlanetLab: A Middleware for Network-centric Applications and Services

PlanetLab is a project that aims to provide an open, globally distributed testbed for developing, deploying and accessing planetary-scale network services, overlaying on top of the existing commercial Internet. It enables users to test and validate new planetary-scale services in an environment that is intended to replicate the environment of the Internet but does not disrupt the Internet's performance. Started in 2002, this research project has grown to become a huge consortium with participation from over 150 universities and industrial research labs, including IT industry leaders like Intel and Hewlett Packard, and top academic institutions like MIT, Stanford, UC Berkeley, and Princeton.

The concept behind PlanetLab is to add an additional layer of middleware with computational functionalities over the existing Internet infrastructure. This is similar to the early development of the current Internet, which started as an overlay to the telephone system that added data communication functionality. For PlanetLab, this additional layer of computational resources embedded throughout the network has the potential to make the Internet more intelligent and adaptive, allowing the Internet to do things such as detect and warn of worm attacks on its own, dynamically re-route network traffic to avoid delays and improve video webcasting.

PlanetLab and Globus

Some people are seeing PlanetLab as the next big thing after Globus (the de-facto grid middleware platform). Both PlanetLab and Globus are platforms that connect distributed resources, but have different focuses. The PlanetLab project focuses on deploying and managing a worldwide infrastructure testbed for experimenting with a new class of network services. The Globus Alliance focuses on developing a general, standards-based, software toolkit for running distributed applications over aggregated shared resources. Therefore, the applications and services targeted by the two communities have different resource requirements:

- Grid applications are often compute-intensive, although some also consume significant amounts of disk and/or network bandwidth as a result of tasks like the integration of large scale data repositories.
- PlanetLab services are generally network-intensive and rarely have significant CPU demands. Experimental services include network measurement, application-level multi-cast, and content distribution networks.

Commercial Services

PlanetLabs is already being used as a platform to roll-out planetary-scale commercial services. For example, the Public Broadcasting Service has collaborated with Intel and HP to create an integrated digital system for automating and monitoring the broadcast operations. Another example is

the joint research project between Intel and BP, which involves the use of a wireless sensor network to do continuous monitoring of engines at BP's Loch Rannoch crude oil tanker.

Related Research Projects

Currently, there are many research efforts on PlanetLab and other similar overlay network concepts.

Public Health for the Internet (PHI). The PHI project aims to improve the overall security and efficiency of the Internet by having users monitor the network condition from a large number of different locations and sharing this information among themselves. PHI can be used to analyse and understand how viruses spread across the Internet or locate congested or faulty parts of the network.

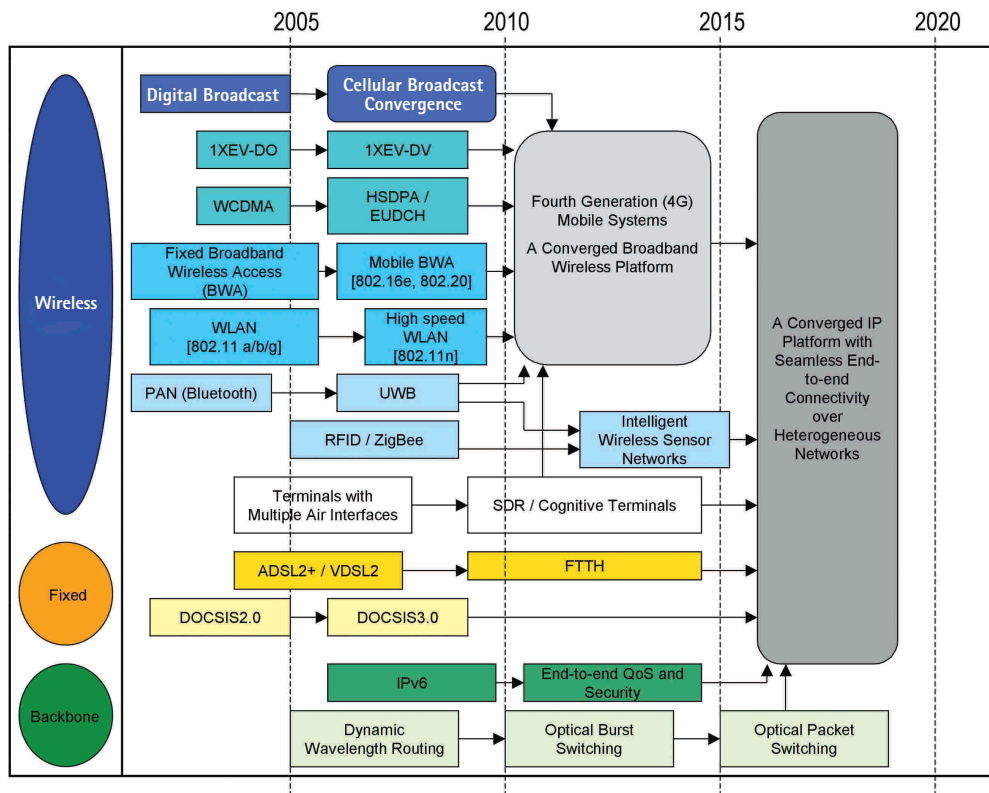
Delay Tolerant Networking (DTN). The DTN project aims to create a reliable networking infrastructure for hard-to-reach places with the objective of bring information and communication technology to the four billion people in the developing world. This effort is a collaboration between UC Berkeley and Intel, and is funded by National Science Foundation.

Tor. Tor is another innovative project that allows users anonymous Internet communication. It is based on onion routing and works like this: Messages, or packets of information, are sent through a distributed network of randomly selected servers, or nodes, each of which knows only its predecessor and successor. Messages flowing through this network are unwrapped by a symmetric encryption key at each server that peels off one layer and reveals instructions for the next downstream node. It does not guarantee perfect anonymity, but its level of security is proportional to the number of nodes in the system. With tens of thousands of nodes, a service based on onion routing is almost impossible to compromise. This system, which was originally developed in the US Naval Research Lab, is able to provide Internet users the necessary privacy when they are using TCP-based applications like web browsing, secure shell, and instant messaging.

3.10 Summary: Technology Roadmap

Summarising our above discussion, we present the technology roadmap below in Figure 27.

Figure 27. Summary of Technology Roadmap



Singapore Landscape

4.1 Introduction

Singapore has a well-developed communications infrastructure. Coupled with rapidly developing research capabilities, this helps provide the fertile ground for Singapore's infocommunications industry.

Fixed-Line Market

The fixed-line telephony subscriber number has been steadily decreasing since Aug 2001, when a peak of 1.95 million subscriptions was reached. As of end Sep 2004, the total number of fixed-line subscriptions stands at 1.87 million, which translates to a fixed line population penetration of 44.7%.

Broadband in Singapore remains a wire-line phenomenon. As of end Sep 2004, the total number of broadband subscriptions has reached 483,500. Residential broadband subscriptions accounts for 90% of this figure, which translates to a household penetration of 40%. DSL is the leading access technology accounting for 57.3% of the total market. Cable is a close second accounting for 41.6% of the total market. According to IDC, the number of broadband subscriptions is expected to surpass the 1 million mark in 2008.

The three dominant broadband access service providers (BASPs) in Singapore are SingNet, Pacific Internet, and Starhub Online.

Mobile Wireless Market

As of end Sep 2004, the total number of mobile phone subscriptions (including pre-paid SIM card subscriber) has reached 3.74 million. This translates to a mobile phone penetration of 89.4%. Currently, the mobile market in Singapore is dominated by the three service providers: SingTel Mobile, MobileOne and Starhub Mobile.

3rd Generation Mobile Systems. On 11 Apr 2001, IDA issued three provisional 3G licences to M1, SingTel Mobile and Starhub Mobile at S\$100 million each. M1 and Starhub have selected Nokia to supply their 3G network equipment, while SingTel Mobile has chosen Ericsson. All three operators have started 3G trials and commercial deployments are expected by Apr 2005. According to Gartner, the number of 3G subscribers in Singapore will exceed 0.5 million in 2008.

Broadband Wireless. According to IDC, there are 25,000 subscribers to public WLAN hotspot services in Singapore at end 2003. This number is projected to grow to 45,000 by the end of 2004. To date, local operators such as SingTel and StarHub maintain more than 600 public WLAN hotspots in Singapore. Supported by IDA, local operators are making WLAN roaming easier and more convenient for users by extending their WLAN coverage with the addition of more hotspots and through roaming agreements with other operators. For example, McDonald's 125 outlets in Singapore are Wi-Fi enabled by SkyNetGlobal. Subscribers of PacNet and StarHub can log on to these Wi-Fi hotspots because these ISPs are roaming partners with the service provider. Another example is the Wi-Fi hotspots found in public libraries under the National Library Board.

Backbone Connectivity

Singapore is well connected with the rest of the world. Submarine cables with a total capacity of 26Tbps are landed into Singapore providing international and regional telecoms connectivity. On top of it, Singapore has more than 14Gbps of extensive and direct Internet connectivity to over 20 countries. This comprises 5Gbps Internet connectivity to the USA and over 180Mbps to each key Asian economies, like Hong Kong, Japan, India, Korea, Taiwan and China. Furthermore, our direct internet connectivity to key ASEAN countries is at least 100Mbps per country.

4.2 Key Players in Singapore

Government Bodies

Infocomm Development Authority of Singapore (IDA).

IDA is committed to growing Singapore into a dynamic global infocomm hub. IDA uses an integrated approach to developing infocommunications in Singapore. This involves nurturing a competitive telecoms market as well as a conducive business environment with programmes and schemes for both local and international companies. Some of the initiatives that IDA has embarked on are:

1. Building capabilities in new growth areas such as grid and utility computing (through the Adaptive Enterprise@Singapore initiative with HP, and the Grid Innovation Zone@NUS set up by IDA, IBM, Intel and NUS) and Web Services with the S\$40 million WEAVE programme to spur Web Services developments. Other new growth areas identified include infocomm security and RFID.
2. Helping local companies expand their business overseas through the Overseas Development Programme and the Singapore Solutions Centre established in Shanghai, China.
3. Positioning Singapore as a Digital Exchange with the development of the Digital Cinema Exchange and the Digital Games Bazaar.
4. Architecting cluster-based plans to harness infocomm in the manufacturing (Collaborative High-Tech Manufacturing Plan) and fast moving consumer goods (e-Supply Chain Management Ecosystem) sector.
5. Taking e-Government to the Next Level with the implementation of the e-Government Action Plan II, a S\$1.3 billion programme, to integrate more e-Government services for public access.
6. Creating an infocomm-savvy population through public education programmes like the e-Celebrations Campaign, the National IT Literacy Programme, Great Singapore Surf, and the Connecting the Homes Call for Collaboration.

Agency for Science, Technology and Research (A*STAR).

A*STAR is the government agency that promotes and encourages science, engineering and biomedical research, and nurtures talent to help advance Singapore's transition to a Knowledge-Based Economy (KBE). The agency comprises the Biomedical Research Council (BMRC), the Science and Engineering Research Council (SERC), the Corporate Planning and Administration Division (CPAD) and the wholly-owned subsidiary, Exploit Technologies Pte Ltd (ETPL). Both BMRC and SERC promote, support and oversee the public sector's R&D research activities in Singapore. ETPL manages the Intellectual Property created by the research institutes and facilitates the efficient transfer of technology from the research institutes to industries. CPAD supports the two Research Councils and ETPL in performing the functions of Finance, Human Resource, Corporate Policy and Planning, Legal, Corporate Communications, Information Technology and Audit. I2R, IME, IMRE, and SIMTech are examples of research institutions that are under A*STAR's purview.

Singapore Economic Development Board (EDB). Established in 1961, EDB is the lead government agency responsible for the formulation and implementation of economic development strategies that will develop Singapore into a compelling global hub for business and investment across manufacturing and internationally traded services. For the Infocomms and Media industry, EDB's mission is to develop Singapore into a global hub in Asia for the digital economy where companies can create, develop and deliver content and innovative services for the global market. The EDB has been attracting leading global companies here while developing Singapore's capabilities in the key areas of electronic commerce, Internet services, media and digital entertainment, telecommunications and specialist information publishing. For example, EDB managed to attract Lucasfilm, one of the world's leading film and entertainment companies, to establish Lucasfilm Animation Singapore (03 Aug 2004). Other more recent initiatives include (1) the launch of the Wireless Community, a collaborative group of 11 founding partners with EDB and Nanyang Polytechnic to create a holistic and supportive environment to nurture Singapore-based start-ups and enterprises in the wireless industry, and (2) the EXCITE@one-north programme, a collaboration between the public and private sectors to further enhance Singapore as a hotspot for innovators to test-bed and commercialise their creative inventions in the 200-hectare one-north research hub.

International Enterprise Singapore (IE Singapore).

IE Singapore is the primary agency to develop Singapore's external economic wing. It aims to help Singapore-based companies with the potential to grow and expand into regional and international markets successfully. For example, IDA and IE Singapore jointly led a business mission to Dalian and Beijing from 28 July to 3 Aug 2004. This mission trip provided a platform for Singapore infocomm companies to explore opportunities in the infocomm arena with Chinese companies. The companies who participated in the mission included CrimsonLogic, IPACS e-Solutions, iSprint, NCS, NETS, ST Electronics and System Access.

Standards, Productivity and Innovation Board (SPRING).

The mission of SPRING Singapore is to raise productivity so as to enhance Singapore's competitiveness and economic growth for a better quality of life for our people. SPRING Singapore focuses on three areas: productivity and innovation, standards and metrology, and small and medium-sized enterprises and domestic sector. For example, SPRING, IDA, and Singapore Article Number Council embarked on a two-year project to build an e-Supply Chain Management Eco-System for the Retail/Fast Moving Consumer Goods industry. The project promises to enhance Singapore's position as an e-Business hub for the wholesale and retail industry.

Research Institutes

Institute for Infocomm Research (I²R). Established in 2002, its mission is to advance infocomm technologies for the benefit of humanity and prosperity of Singapore. I²R integrates R&D in communications and information technology to develop holistic solutions across the ICT value chain.

I²R's research capabilities are in wireless and optical communications, and information technology and science. It has three research groups in:

1. Services and Applications (Infocomm Security, Knowledge Discovery);
2. Communications and Devices (Multimode Devices, Radio Systems, Networking, Digital Wireless, Lightwave); and
3. Media (Media Processing, Media Semantics, Human Computer Interaction).

Research activities undertaken by I²R include:

- Data mining, informatics, database systems
- Internet technologies
- Cellular mobile technologies
- Wireless technologies in microwave/radio frequency
- Wireless & satellite communications
- Network technologies
- Distributed computing
- Mobile computing
- Computer security, cryptography
- Human-machine interface

Institute of Microelectronics (IME). Formed in 1991, IME's mission is to increase value-add to the electronics industry in Singapore by engaging in relevant R&D in strategic fields of microelectronics; supporting and partnering the electronics industry; and developing skilled R&D personnel. IME helps to drive the continual growth of Singapore's electronics industries through high calibre research and development for semiconductor applications. The Institute has three research focus areas: (1) Integrated Circuits & Systems (RFIC & ASIC Design & Modelling); (2) Semiconductor Process Technologies (Advanced Interconnect, Process Modules and Silicon Micro-photonics and Devices; and (3) Microsystems, Modules & Components (MEMS, Micro-Modules, Interconnects & Integration, and Microsystems Reliability). Recent R&D efforts include: SiGe devices, 10 Gbps optical communication IC and microphotonics for optoelectronics integrated circuits.

Research activities undertaken by IME include:

- Advanced packaging
- VLSI design
- Nanoelectronic devices
- MEMS/NEMS
- Semiconductor physics processing methods

Institute of Materials Research & Engineering (IMRE).

Established in 1996, IMRE undertakes research in selected fields of materials science and engineering such as optoelectronics, nano-materials, chemicals and polymers. It seeks to partner with international organisations and industry in a synergistic, multidisciplinary and collaborative approach to materials research and development. To this end, IMRE develops core competence and interdisciplinary teams in critical technology areas, enabling it to make fundamental new discoveries, develop advanced materials that can lead to new commercial products, and transform various technologies.

Research activities undertaken by IMRE include:

- Polymer science and chemistry
- Nanomaterials
- Advanced materials characterization
- Performance materials
- Nanoparticles
- Macromolecular chemistry
- Surface science

Singapore Institute of Manufacturing Technology (SIMTech).

Officially formed in 1993, SIMTech is committed to enhancing the competitiveness of Singapore's industries through the generation and application of advanced manufacturing technology. Its areas of research focus include Production and Logistics, Advanced Forming and Joining Technology, Machining Technology, Mechatronics, Precision Measurement, Advanced Automation and Product Design and Development.

Research activities undertaken by SIMTech include:

- Advanced automation systems
- Control systems
- Precision metrology
- Robotics control systems
- Mechatronics, systems engineering
- Micro-manipulation technologies
- Laser processing and design
- Photonics
- Optics
- Product development life cycle management
- Artificial intelligence applications
- Materials processing casting technologies
- Supply chain methods
- Operations research

Nanyang Technological University (NTU) Network

Technology Research Centre (NTRC). Established in Nov 1991, NTRC provides a focal point within NTU for coordinating and deploying NTU's academic and research staff with interest and expertise in communications and computer networking.

Key research activities are focused on three main areas in:

1. Optical Communications. Areas of expertise include Fibre Bragg gratings (FBGs) based devices and systems, Dense wavelength division multiplexing (DWDM), Non-linear fibre optics, generalised multi-protocol label switching (GMPLS), Photonic crystal fibres (PCFs), Radio-over-fibre (RoF) systems, Micro-Electro-Mechanical Systems (MEMS), and Laser splicing of optical fibres.

2. Powerline Communications (PLC). Areas of expertise include Power Line Channel Modeling, MAC Protocols for PLC Systems, PLC Systems with Low Electromagnetic Interference Radiation, and Building Monitoring and Control System.

3. Network Control and Engineering. Areas of expertise include High-speed access systems (xDSL, cable modems), Scalable QoS in the Internet, Network traffic control (congestion/admission control and buffer management), Reliable multicast protocols, Digital watermarking, Bluetooth embedded systems, Interactive network applications.

Fixed-Line Broadband Market

SingNet. The incumbent telecommunication operator, SingTel, used to operate two BASPs in Singapore – SingNet and SingTel Magix, but they have been merged into SingNet. SingNet has the largest broadband subscriber base. Currently, 1.5Mbps is the highest access speed offered. SingTel has started trials of the higher speed ADSL2 technology and commercial deployment can be expected in 2005.

StarHub Online. StarHub has an FBO license to operate fixed and mobile telecommunications services in Singapore. In Oct 2002, it acquired Singapore Cable Vision (SCV), the only cable network operator in Singapore. SCV MaxOnline, the broadband cable modem Internet service, was renamed MaxOnline. As of end Sep 2004, MaxOnline offers the highest download access speed at 3Mbps. Its cable network infrastructure is based on DOCSIS 1.1 and cable telephony services have been offered since 2003.

Pacific Internet (PacNet). The other significant ISP in Singapore, PacNet is the largest telco-independent Internet Communications Service Provider in the Asia Pacific region with direct presence in seven markets. In Singapore, PacNet has the second largest ADSL subscribers behind SingNet. It is also offering broadband cable service through a wholesale agreement with StarHub Cable Vision. For the last few years, PacNet has built up a significant broadband subscriber base by targeting the online gaming community through its "PAN Asia Gaming Network" (paGn).

Mobile Wireless Market

SingTel Mobile. The incumbent and dominant provider of telecommunications services in Singapore has over 1.5 million mobile subscribers in Singapore as at end Sep 2004, representing over 40% of the market share. Over the last few years, its focus has been on regional expansion. Together with its regional partners, SingTel is Asia's largest multi-market mobile operator, serving more than 56 million customers in six markets, including Australia, India, Indonesia, the Philippines, Singapore and Thailand.

MobileOne – M1. M1 was formed in August 1994 as a joint venture between Keppel Telecoms, SPH Multimedia, and Great Eastern Telecommunications. In May 1995, it won the license to operate Singapore's second cellular telephone service as well as a radio paging service. Both services were launched on 1 April 1997. On Dec 2002, M1 became a public listed company. As of end Sep 2004, M1's total mobile customer base reached 1.143 million, representing over 30.6% of the total mobile market.

Starhub Mobile. StarHub, launched in April 2000, is the third major mobile operator in Singapore. It started as a joint venture between Singapore Technologies Telemedia, NTT Communications, British Telecom, Singapore Press Holdings and Media Corporation of Singapore. On Oct 2004, it was listed on the Singapore Exchange (SGX). As of end Sep 2004, StarHub has 1,084,000 mobile customers representing 29% of the total mobile market. This is an increase of 34.5% as compared with 806,000 customers as at end Sep 2003. It captured 79% of the market net additions for the nine-month period in 2004.

Conclusion

In this report, we have examined global trends and future development of the communication landscape through the analysis of standards development, deployment status, and research developments. Some related market and policy trends were also discussed.

Singapore recognises the importance of a good infrastructure for the competitiveness of the nation. It is one of the first few countries in the world to have a broadband infrastructure through the construction of the Singapore ONE. This effort has been successful in making Singapore one of the leading broadband nations in the world.

Today, we have a high mobile penetration rate of around 90% and a respectable broadband household penetration of around 40%. In 2005, all three mobile operators will launch their 3G services to begin an era of broadband wireless Internet services. However, we do not expect 4G to come before 2010. For the fixed line broadband market, we expect ADSL and cable to replace dial-up as the dominant means for accessing Internet within the next three years. Migration to faster technologies like ADSL2+ and DOCSIS 2.0 can also be expected within the same timeframe. By 2010, we can expect to see the introduction of VDSL and FTTx services. By 2015, FTTH services should become the norm.

On the user side, more people are reaping the productivity gains from having a high-speed broadband connection. Currently, popular Internet usage includes peer-to-peer file-sharing (e.g. movies and music), online gaming, multi-media e-learning, and tele-working. On the mobile services front, multimedia broadcast and multicasting, location-based services, mobile tele-working, and other rich multi-party multimedia communications are expected to become common over the next few years. On the horizon, new business models based on business process outsourcing, such as application service provision, grid or utility computing, and on-demand computing, will also push the need for greater bandwidth and QoS. Further down the road, we may see the proliferation of new applications due to the advent of intelligent wireless sensor networks.

From the above discussion, we have identified two major focus areas for Singapore's communication sector.

Firstly, Singapore should focus its efforts on the cluster of broadband wireless technologies. This is because we believe broadband wireless technologies have the potential to disrupt the existing cellular technologies to create an alternative low-cost wireless Internet infrastructure. Today, the flag-bearer for broadband wireless technologies is the IEEE 802.11b (Wi-Fi). Wi-Fi has been very popular with the consumers because of its low cost. Furthermore, there are efforts on enhancing security, QoS, and roaming. Higher speed standard, 802.11n, is also being developed with products expected within the next three years. Together with the IEEE 802.16e, the IEEE 802.20 (MBWA) and the IEEE 802.22 (WRAN), we expect this cluster to have a significant impact on the future communication landscape within the next 5 years.

Beyond its potential disruptive impact, this cluster of technologies is device-centric, allowing Singapore to leverage off its already strong electronics manufacturing sector. The manufacturing sector accounts for around 25% of the country's GDP and the electronics industry leads this sector, accounting for 31% of Singapore's total industrial output. Furthermore, research institutes like I²R have strong research capabilities in this area. This provides opportunities for collaboration between the industry and researchers.

Secondly, Singapore should focus its efforts on the cluster of short-range wireless technologies. The long-term market opportunity for this cluster of technologies is in the creation of wireless sensor networks for remote monitoring and control. Today, the early promises of wireless sensor networking are delivered through technologies like UWB, RFID, and ZigBee. Similar to broadband wireless, this is another device-centric area whereby Singapore can leverage off its manufacturing sector.

Beyond manufacturing, this cluster of technologies has many usage opportunities that can lead to greater productivity for the country. For example, RFID has many ready applications in the logistic and healthcare sector, which complements with Singapore's push to be logistic and healthcare hub in this region.

Computing Revolutions with Nano & Bio

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Nano-Bio Computing Landscape 2015

1.1 Introduction

Nanotechnology is an emerging platform technology that cuts across the traditionally defined technologies and industries. It has already spawned many new research areas in recent years, from short-term material properties improvement to long-term molecular nanotechnology vision. It is about working at the atomic, molecular and supramolecular levels, in the scale of 1 nanometre (nm) to 100 nm, in order to understand, create and use materials, devices and systems with new properties and functions because of their small structures.

The US national nanotech initiative (NNI) defines nanotechnology if it involves all of the following attributes:

- Research and development at the atomic, molecular or macromolecular levels, in the length scale of about 1 - 100 nm range – in other words, technologies that are simply very small, smaller than the micro technologies we familiar today;
- Creating and using structures, devices and systems that have novel properties and functions because of their small and/or intermediate size – in other words, technologies that are useful because of properties or capabilities that only a nanoscale device could exhibit;
- Ability to measure, control or manipulate matter at the atomic scale in order to change those properties and functions.

Computing with Nano. We cover here the impact of nanotechnology on the future of info-communication technologies, touching all dimensions of life around the year 2015. Nanotechnology will play a key role to advance storage technologies, processors' design, display, power and telecommunication system. These developments will further

be enabled by the confluence of material science, biotech, smart sentient technologies and info-communication – a result we called "**nano-convergence**." The interplay of nanotech and infocomm can be summarised in the following diagram:

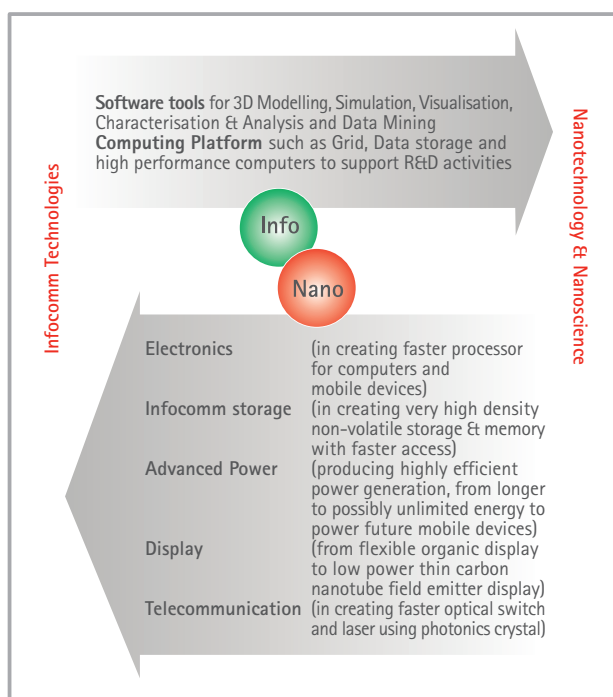


Figure 1. Interplay of Nano and Info Technologies

Infocomm technologies will remain a crucial tool to nanotechnology and nanoscience. Software technologies in 3D modelling, simulation, visualisation, characterisation & analysis and data mining will be needed to support research on nanoscience. This will allow researchers study new material properties exhibited at nanoscale and analyse complex molecular interaction at this scale. A common research platform based on grid will allow collaboration between research communities and industry. High performance computers and data storage are also part of the critical elements of this infrastructure. This will enable the

development of better processor, memory and storage, photonics (optical communication), advanced displays and power. By 2015, we believe this nano-info convergence will drive the development of many ambient intelligence applications, making inroads for innovative products that are vastly more powerful and conscious of the environment to be introduced into the market. Besides improving our work productivity, it will also enhance our quality of life.

Computing with Bio. On the other hand, an exciting new realm of growth is also happening with bio-info convergence. Some handphone models from Korea today incorporate biosensors on battery packs. Lab-on-a-chip designs allow bio-sensing capabilities to be embedded into any IT device or interface. IT or conventional bioinformatics today has brought technologies like grid, database management, collaborative workspace software suites, high performance computing for simulation and modelling.

In the future vision, new bio-inspired computing will mature into new ways of low cost manufacturing with organic engineering, molecular self-assembly via the confluence of nanotechnology and biotechnology, smarter and simpler programming paradigms for complex computing systems with amorphous computing or swarm computing or botanical computing, as well as more robust self-learning systems with neural networking and neuro-silicon chips.

However, many of these bio-inspired computing technologies are only going to mature in the longer term beyond 2015 before it can reach a productive level of usage. From now to 2015, we still need to conduct much research and development to understand how biological systems, plant organisms, swarm behaviour in nature and neuro-systems work. From there, we can then learn how to manufacture, compute and programme bio-inspired intelligence into IT systems.

1.2 Vision for Computing with Nano and Bio

Infocomm Technology has remarkably transformed the way we live, work, learn, communicate and conduct business over the years. We have witnessed new innovative applications arising from the use of infocomm technologies, riding on the critical physical net such as the Internet, Intranet and the broadband wireless networks. This era of physical connectivity is beginning to be augmented by an increasing focus on logical connectivity, in particular through better business integration & automation, service-oriented architectures, grids computing middlewares and semantic web interfaces.

By 2015, many of these applications and technologies will be integrated into our life, enabling us to recognise, mine and synthesise massive amount of information. These capabilities are plausible as miniaturisation, network and

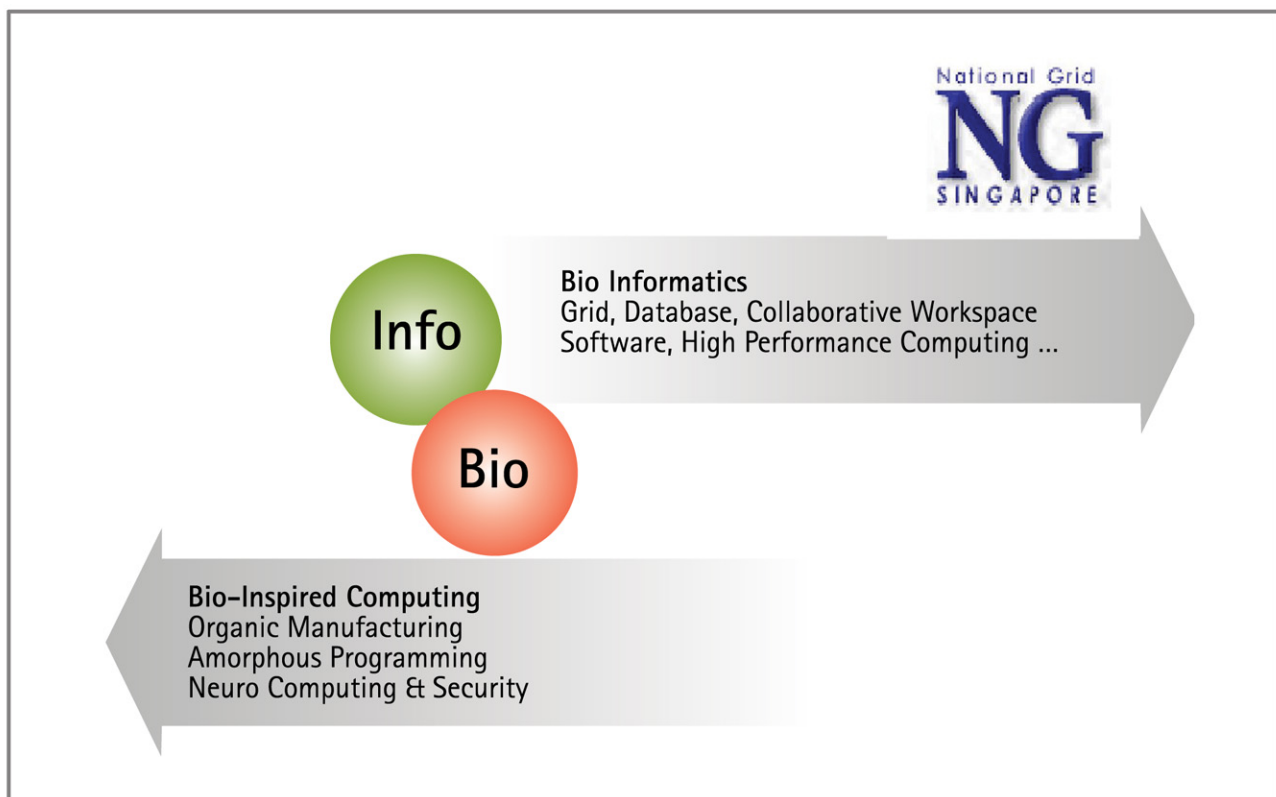


Figure 2. Interplay of Bio and Info Technologies

storage improve, and the convergence of smart material, infocomm and nanotechnology creating smarter devices. Computing power will become more abundant, connectivity will be made easier and cost per function will become cheaper, with virtually every product embedded with some form of processing power, storage, communication and networking capabilities. Nanotechnology will become a critical technology to enable this era of "**nano-convergence**." More importantly, in infocomm, it enables the creation of 'sexier' products with new capabilities, new markets and new opportunities.

Nanotech will usher in a few waves of innovative development in product design, from short-term improvement of existing products, to the creation of new products in mid to longer-term. When the research in nanoelectronics and nanomaterials, such as organic polymer, nanowires, carbon nanotubes and quantum dots comes to fruition, we will see the emergence of molecular computers and ultra-fast chipsets that could process information at tremendous speed not possible today, and storage devices capable of storing terabytes of information in a really tiny structure.

1.3 Global Outlook

Many countries have vested interested in nanotechnology. Some have already embarked on big programmes to advance their R&D capabilities. Below provides a few of these iconic programmes.

1.3.1 US National Nanotech Initiative

The National Nanotech Initiative has directed various agencies into specific areas of research. The "grand challenges" that

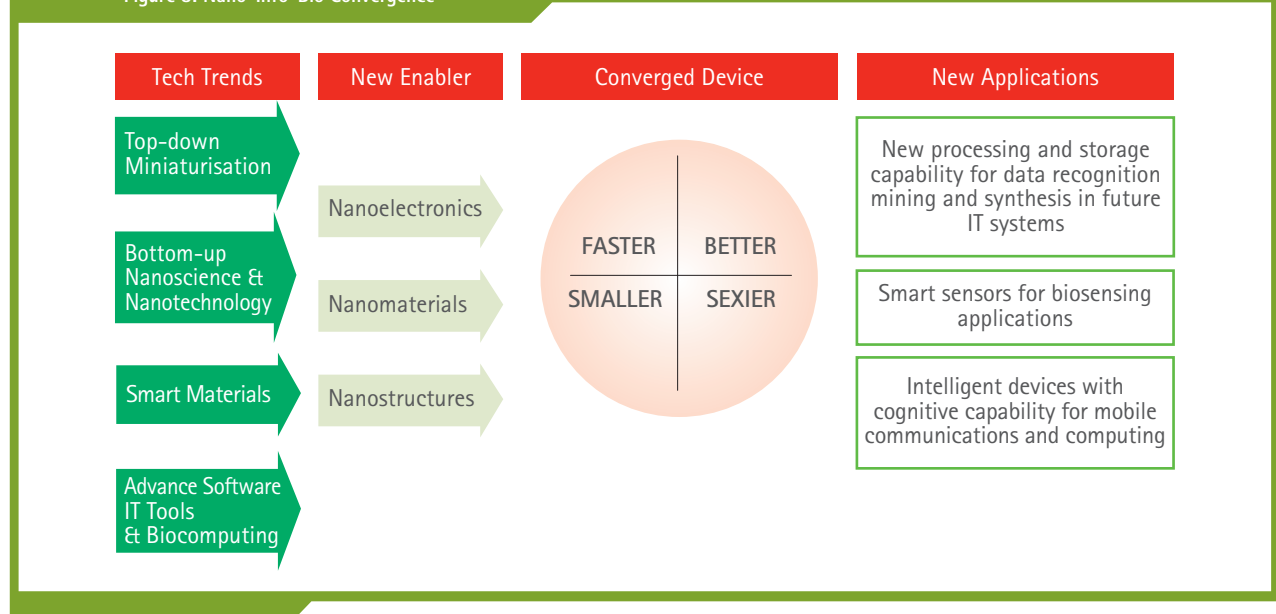
have been identified focus on nine specific R&D areas that are more directly related to applications of nanotechnology that have the potential to realise significant economic, governmental, and societal impact. These include:

- Nanostructured materials by design;
- Manufacturing at the nanoscale;
- Chemical-Biological-Radiological-Explosive detection, and protection;
- Nanoscale instrumentation, and metrology;
- Nanoelectronics, Photonics and Magnetics;
- Healthcare, Therapeutics, and Diagnostics;
- Efficient energy conversion and storage;
- Microcraft and robotics;
- Nanoscale processes for environmental improvement.

1.3.2 DARPA

The Defense Advanced Research Projects Agency (DARPA) initiated the Moletronics (Molecular Electronics) program in 2000. The purpose of moletronics is to demonstrate the integration of molecules or nanoparticles into scaleable, functional electronic devices that are connected to each other and to the outside world in a realistic and practical manner. The interconnected devices pass information by either a conventional current or an electronic charge potential (by reshaping the electron density about the molecule). Innovative interconnect and input/output concepts are also being examined. The long-term goal is to provide moderate computational power and high-density memory in an extremely small, low-power format, which will not require multibillion-dollar fabrication facilities.

Figure 3. Nano-Info-Bio Convergence



The applications targeted by moletronics fall into two principal areas, emphasises mainly in design of circuit architecture:

Logic devices – Ability to replicate the functionality of a silicon chip by design, synthesis, and testing of two interconnected molecular logic gates connected to the outside world, to produce circuits with a correct truth table. The devices need to operate at room temperature, with ability to scale up to densities greater than 10^{12} gates per cm^2 . Projects include quantum dot automata, molecular AND-OR gate pair and molecular cascade array;

Memory devices – Ability to produce molecular memories that will allow terabit level memories within desktop computers. Specifically it called for the design, synthesis, and testing of low-power, high-speed circuit architectures for high-density, terabit-level memories. The devices are expected to have a functional 16-bit molecular memory connected to the outside world at a density of 10^{15} bits per cm^3 . Some of the projects include the multi-porphyrin molecular memories, 3D memories and the 64-bit molecular memory chips.

The program also called for device and interconnects schemes to be implemented with techniques such as directed self-assembly. The desire for molecular electronics is to use molecules or nanoparticles to achieve further miniaturisation, greater functionality, and faster clock rates for advanced electronic systems that operate under a wide range of temperatures and preferably take advantage of 3D architectures.

1.3.3 European Framework Programme (FP) 6

The nanotechnologies and nanosciences, knowledge-based multifunctional materials, new production process and devices (NMP) initiative is one of the EU program under the FP6 Third Thematic Priority 2002–2006 that is related to Information Society Technologies. About €43 billion has been allocated in the following areas of R&D:

a) Nanotechnologies and nanosciences;

- long-term interdisciplinary research into understanding phenomena, mastering processes and developing research tools;
- nanobiotechnologies;
- nanometre scale engineering techniques;
- handling and control devices;
- applications.

b) Knowledge-based multi-functional materials;

- development of fundamental knowledge;
- technologies for production, transformation and processing;
- engineering support for materials development.

c) New production processes and devices;

- new processes and flexible and intelligent/manufacturing systems;
- systems research and hazard control;
- optimising life-cycles.

More details of the projects under NMP can be obtained from this website: <http://www.cordis.lu/fp6/projects.htm>

Infocomm Society Technologies (IST) Future Emerging Technology (FET). This initiative complements mainstream integrated circuit developments with advanced research in hybrid and molecular electronics, and prepares silicon technology beyond the limits of CMOS scaling. This initiative covers a time horizon beyond 2009, corresponding to that covered in the "Emerging Research Devices" (ERD) section of the ITRS roadmap. The scope is limited to a number of non-CMOS options listed in the ERD document.

Many effects characteristic of molecular and other nanometre-scale structures have recently been discovered or demonstrated, paving the way for technological developments complementing those on the mainstream semiconductor platforms. The emerging nanoelectronics initiative aims at consolidating and further advancing this research and to prepare the bases for industrial research and development programmes on non-CMOS nanometres technologies in information society applications. Three long-term directions are:

- Research on *hybrid molecular electronics* to develop new functions or to improve the implementation of known functions, by incorporating new molecular-scale developments on appropriate submicron scale semiconductor platforms;
- Research on *one-dimensional structures such as nanotubes or nanowires* for the development of devices, functions, interconnections, etc;
- Research on *single molecules* for the development of reproducible functions and to compose circuits. This research is likely to require progress on the understanding of electrical characteristics of single molecules and contacts. Special interest is given to organic molecules, their potential for self-assembly and the multidisciplinary research they would motivate.

1.3.4 Japan Nanotech Program

The Ministry of Economy, Trade and Industry (METI) has vested interests in nanotechnology development. Priority R&D programs include the following:

- Nanomaterial and processing technology;
- Nanoprocessing and measurement technology;

- MEMS technology;
- Fusion of Nanotech with IT, Biotech and Environment.

The Japanese government has also approved 94 billion Yen budget for Nanotech and Nanomaterial R&D in 2004.

1.3.5 Korea National R&D Program

This Korea Nanotech Development program includes developing infrastructures such as the National Nanofabrication Centre, Application-specific Nanofab Centres, and Nano Clusters to accommodate private R&D centres and their manufacturing facilities in the long run. The National Nanofab Centre is now under construction within the campus of the Korea Advanced Institute of Science and Technology (KAIST).

The national program for tera-level nanodevice was established in Jul 2000 as one of the "21st Century Frontier R&D Project" funded by Korea Ministry of Science and Technology (MOST). The aim of the program is to develop tera-level integrated circuit test element group (IC TEG) through overcoming the technological limits imposed upon upcoming semiconductor technologies. This is a 10-year program consisting of 3 phases. The first phase will be operated as a versatile basic cell development for tera-level nanodevices. In the 2nd phase, great efforts will be made for the development of integration process of the nanodevices and the 3rd phase will be concentrated on the development of tera-level IC TEG. The focal areas are listed below:

- Nano Electronics
(Terabit SEM, Nano-CMOS, THz devices, SET Logic)
- Spintronics (Terabit MRAM)
- Molecular Electronics (Terabit Nanotube, Molecular Electronics)
- Core Technologies (Nanopatterning, Nanodeposition, Nanoanalysis)

1.3.6 Taiwan National Nano Science and Technology

The Taiwan government has approved a US\$650 million National Nano Science and Technology Program in 2003 to be invested over a 6-year period. One-fifth of the R&D program resources go into technologies for the near-term (within one to two years) that can be immediately commercialised. These include many traditional commercial applications, such as nano-powders, pigments, coatings and inks, nanotechnology-reconstituted plastics and polymers, fibres for textiles, paper products, inorganics and ceramics, as well as metals and alloys.

Majority of the resources (about three-fifth) have been allocated to major infocomm-related and other disciplines for medium-term. These include technologies such as ICs, displays, data storage, packaging, mobile communications, optical communications, biotechnology and energy applications that are likely to bring radical advances due to nanotech. The remaining one-fifth of the program will fund exploratory research projects that are truly revolutionary nanotech and will take 10 to 20 years to reach commercial maturity.

1.3.7 Industries Initiatives

At the industry level, nanotech is also been actively promoted. An association known as the NanoBusiness Alliance (<http://www.nanobusiness.org>) was formed to advance the emerging business of nanotechnology by creating a collective voice for the emerging small tech industry and develop a range of initiatives to support and strengthen the nanotechnology business community in US.

The European has similar industry initiative. The European Nanobusiness Association (ENA) (<http://www.nanoeurope.org>) is an industrial and trade organisation founded to promote the professional development of the emerging business of nanotechnology at the European level. Reports and surveys on nanotech are available for download.

Nanoelectronics market forecast. According to FTM, it is projected nanotech will grow at 45.3% over the next 10 years. Key findings from the report (Nanotechnology: Impact of Nanoelectronics on the US Electronics Industry) indicated that the hard disk drive segment is expected to be the largest over the 10 year period at US\$36.3 billion, and the market for nanotubes used in ICs is projected to be US\$11.3 billion in 10 years. The study segments the nanoelectronics market into two major developments: (1) the first-generation

products consisting of nanotubes, nanowires, etc. and (2) the second-generation products, consisting of molecular electronics, quantum computing and the combination of biotechnology with nanoelectronics to self-assemble nanoelectronics devices. The first-generation products are expected to emerge during the next ten years through 2014. The second-generation products, currently under basic research are expected to emerge after that.

IC Nanoelectronics Forecast by Technology \$(M)					CAGR (%)
	2004	2009	2012	2014	2009-14
Nanotubes	0.0	563.0	3,234.5	11,276.3	82.1%
Nanowires	0.0	293.8	781.7	1,675.8	41.7%
Nanoparticles	0.0	0.0	404.3	653.3	
Nanocells	0.0	0.0	215.8	312.4	
Molecular Chips	0.0	0.0	0.0	710.1	
Organic Transistors	0.0	0.0	0.0	113.6	
Total	0.0	856.8	4,636.3	14,741.5	76.7%

Table 1. Impact of Nanoelectronics on US Electronics Industry

Source: FTM Consultant Inc.

Impact of Nano/Bio Computing Revolutions

2.1 Introduction

Nanotechnology is expected to create a big impact on many vertical industries. The electronics sector is believed to represent one of the greatest beneficiaries of nanotechnology, as its demand for infocomm technologies remains a critical engine of growth for businesses and economies. There is however health and environment concern arising from contact with toxic nano-engineered materials. This section identifies some key impacts and implication of nanotechnology has on government policies, businesses, environment, society and individuals.

2.2 Impact on Businesses

Nanotech will continue to garner strong investment from many stakeholders. According to Cientifica most recent data, public spending on nanotech in 2005 is expected to reach US\$6.4 billion, while industry is estimated to spend about US\$6.5 billion, surpassing government investment for the first time. Tech leaders such as IBM, HP, Motorola, Intel and NEC are also investing on nanotech R&D. Singapore has also invested a total of S\$65 million on nanotech research in 2003. It has also setup nanotechnology applications development centre to help companies in pilot trials and testing of novel products. These huge investments create opportunities for new business development.

Nanotech can improve companies' competitiveness with new innovative products offering. Nanotech can create new inventions and invigorate markets with enhanced or new products, fuelling research and businesses through the development of nanoelectronics components, smart organic and inorganic nanomaterials, as well as carbon nanotubes and nanowires. Nanotech will also require new manufacturing processes using self-assembly and nano-imprinting techniques that could potentially offer lower manufacturing cost than

existing method. By exploiting nanotech in new methods of fabrication, it is believed that it will facilitate the production of ever-smaller computers that store vastly greater amounts of information and process data much more quickly than before at a lower cost. These computing elements are expected to become so inexpensive that they can even be woven in fabrics as sensors for healthcare-related applications, such as monitoring diseases i.e. sudden infant death, in the future.

2.3 Impact on Government

Nanotech has high strategic values to governments as it promises major growth investment opportunities. It is slated to disrupt to a host of science & technology breakthrough, creating new opportunities both for public and private sectors. Governments from countries like USA, Japan and Europe have strongly backed R&D in this area. In the US, the National Nanotech Initiative has budgeted about US\$961 million for 2004 in nine areas of grand challenges in nanotechnology. The budget is expected to increase by an additional 2% to US\$982 million for 2005. Another US\$3.7 billion is expected for 2005 to 2008, under the 21st century Nanotech Research and Development Act.

Likewise, the European Union (EU) has set aside €19 billion (up from €17.5 billion as of May 2004 as a result of EU enlargement) for R&D investment under its 6th Framework Programme (FP6) from 2002-2006. A sizable proportion of this fund i.e. €1.1 billion/year (US\$1.5 billion at current exchange rates) in total (EU plus member state programs) has been earmarked for nanotechnology and nanoscience, knowledge-based functional materials and new production processes and devices. Japan, too has invested heavily, about US\$880 million on nanotech.

By funding nanoscience and nanotech research & development, Singapore can leverage on this area of science and engineering and move into upstream research. The government can provide coordinated support for long-term basic research and shorter-term technological developments to create the technological base and prove the potential of the new technology. It also plays a key role in assisting and promoting the development of initiatives in this new field.

Training people in multidisciplinary science and technology is keyed for long-term success. A main challenge is to educate and train a new generation of skilled workers with multidisciplinary perspectives necessary for rapid progress in nanotechnology. The concepts at the nanoscale (atomic, molecular and supramolecular levels) should penetrate the education system in the next decade in a similar manner how microtechnology approach made inroads in the last few decades.

Nanotech and Biotech are critical technologies for total defence. It is envisaged that better technologies will be needed in readiness against imminent threats from terrorism for national security. Nanotech and biotech will be critical to the realisation of smart sensing devices to provide early warning and surveillance system used in civil, police and military applications.

Nanometrology Standard is critical. Currently, there is no standard in the measurement of scale on nano-enabled products. A nano-enabled product that measured 1 nm at one location could mean 5 nm when measured at another location. This is definitely not acceptable and trade dispute could arise out of this non-consistency. Standardisation in this area is necessary. There is also a need to standardise characterisation of nanomaterials – as an example, look at the wide range of definitions of nanofibres!

Regulatory and Privacy matter. As nanoengineered materials are potentially toxic, government policies and guidelines in controlling the use of carbon nanotubes, buckyballs and other nano-related materials would be needed prior to mass commercialisation. In UK, as a result of the public feedback on concerns with nano-sized particles and the possible dangers it may cause, the Royal Society in its report on nanotechnology recommended the following actions:

- R4: Until more is known about environmental impacts of nanoparticles and nanotubes, we recommend that the release of manufactured nanoparticles and nanotubes into the environment be avoided as far as possible (section 5.7);
- R6: We recommend that, as an integral part of the innovation and design process of products and materials containing nanoparticles or nanotubes, industry should

assess the risk of release of these components throughout the lifecycle of the product and make this information available to the relevant regulatory authorities (section 5.4);

- R14: We recommend that manufacturers of products that incorporate nanoparticles and nanotubes and which fall under extended producer responsibility regimes such as end-of-life regulations be required to publish procedures outlining how these materials will be managed to minimise human and environmental exposure (section 8.3.4).

Also, as nanotech is expected to enable tiny powerful devices that are barely visible to our naked eyes, such as nano-electro-mechanical-system (NEMS) and tiny embedded sensors, there could be concerns on privacy. However, this issue will need to be addressed differently for different countries with different contexts.

Quality of Intellectual Property. As with other emerging area of technology, protection of knowledge is achieved primarily through patents, copyright and trade secrets. However, patents are the primary tool for such protection. Unfortunately, there is usually a lag period between the time an area in nanotechnology is discovered and the time the patent and trademark office is able to put in place examiners skilled to quality control on the patents being issued. Coupled with the lack of good knowledge in nanoscience, poor quality patents could be issued by the granting office. This may prevent innovative patents from being granted and stall technology exploitation and further innovation of nanotechnology.

2.4 Impact on Society and Individuals

Improving quality of life by enabling new medical applications. Our aging affluent population is driving demand for better medical applications. Nanotech and biotech can enable a new generation of biomarkers and detection system (e.g. MRI contrast) to assist surgeons in better understanding and visualising patients' pre-surgical diseases and medical conditions. In healthcare, personalised medicine and targeted drugs delivery could be developed to improve our quality of life.

Solves global water and energy issues. Nanotechnology can help solve water and energy issues in a number of ways. It can make existing expensive technologies to become economically feasible and offer new solutions to existing problems. It offers radical new technologies for desalination, purification or waste water recovery. An initiative that aims to address this issue is NanoWater from Cientifica.

In the short term, nanotech will improve existing consumer products. By harnessing nanomaterials' properties, better sport equipments such as low resistance skiing boards, bouncy tennis balls, high tensile strength rackets and golf clubs and highly effective personal care cosmetics and stain-proof textiles will be developed for lifestyles and entertainment purposes.

Early incorporation of nanoscience as a core subject in the education system. As nanotechnology is expected to create huge social and economic impact, it is thus important to groom our next generation with knowledge in nanoscience and nanotechnology. Schools should start to include these subjects into their courses syllabus early. Areas that could expedite teaching this new field include the use of interactive and interesting multimedia courses to spur students' interest in multi-disciplinary nano-related subjects. Practical experiments should be complemented with visualisation software to aid understanding.

Technology and Standards Development

3.1 Introduction

Today, miniaturisation of transistors for electronics devices has already entered into the nano realm, below 90 nm. Smaller, faster and cheaper silicon-based computers are realised, greatly boosting our performance and work productivity. In this **evolutionary, top-down shrinkage** of the transistor feature size, challenges are anticipated in high power dissipation, memory latency and current leakages problems. As it is, performance and reliability issues are starting to challenge new development as technology enters the 90 nm node. Besides the technical challenges, the escalating cost of fabrication facilities is a commercial concern.

According to IC Knowledge, the capital cost of building and equipping a semiconductor fabrication facility has increased exponentially over time, from about US\$6 million in 1970, to more than US\$2 billion for 300-mm fabrication plants these days. If the current cost of these facilities continues to rise, then by 2007, it will exceed US\$10 billion, and reach US\$18 billion by 2010. The magnitude of these costs has led several observers to question whether the semiconductor industry can afford to produce and maintain the equivalent or lower cost per function for chipset into the next decade.

As feature size approach 10 nm in about 15 years from now, the fundamental law of physics will prevent scaling of feature size any further. The chip industry has already felt these challenges and has started to focus on innovation in device structure and design improvement. Technologies that are currently being used to boost transistor performance are strained silicon, high-k dielectric and multi-gate transistors,

as well as exploring new materials for building future powerful transistors. As this "top-down" miniaturisation reach sub-10 nm scale, alternative approaches will be needed to continue the trend of Moore's Law. Improving computing performance would also require re-architecting existing system design concept.

Nanotechnology promises an inexpensive "bottom-up" alternative in which electronics or other devices could be assembled from simpler components such as molecules and other nanostructures. This approach is similar to the one that nature uses to construct complex biological system. Interests in molecular electronics and nano-manufacturing are currently being pursued actively by many prestigious laboratories, universities and research institutions. Today, many researchers are experimenting new nanomaterials properties and novel methods of harnessing silicon, as well as new fabrication technique based on self and directed assembly. This chapter summarises these fundamental nano-engineering building blocks such as carbon nanotubes, semiconductor nanowires, molecular electronics, plastic electronics and software & tools that are critical to the future of infocomm development.

When R&D on the above nano-technologies and techniques come to fruition, we will see its impact on some key segments of technologies relevant to infocomm. This chapter thus covers the application of nanotechnology in creating future novel computing architectures, higher density non-volatile memories/storage, larger & flexible display, faster telecommunication & photonics devices and long-lasting power.

Nano Building Blocks. Nanomaterial technology is an important area of research for storage, photonics, optical systems, information display and for human computer interaction to make better haptic interfaces for tactile

sensation. Embedding intelligent sensing nanomaterials in homes and environment would also help to create a smarter info-space. Smart nanomaterials and nanostructures will be progressively built into systems and will be employed in many infocomm products that have impact on our personal lives and business environment. Take an example, nanotechnology can be used to create tiny nanostructures barcodes i.e. nano-barcodes in products that are required for security reasons. Understanding and controlling the different properties of these fundamental building blocks such as carbon fullerene, carbon nanotubes and semiconductor nanowires at atomic scale will result in the realisation of vastly superior electronics, data storage, optical system, display and power system.

3.1.1 Carbon Nanotube

Carbon nanotubes (CNTs) are made of carbon atoms arranged in a cage-like sheet of hexagons. It exists in a variety of structures corresponding to the many ways a sheet of graphite can be wrapped into a single tube. The way it is rolled determine whether it is metallic, semiconductor or insulator. There are basically 2 basic types of nanotubes; single-walled CNT (SWNT), and multi-walled CNT (MWNT). SWNT has much superior properties compared to MWNTs. SWNT has diameters between 0.4 to 3 nm, while MWNT is between 1.4 to 100 nm. As a comparison, semiconductor physical gate size is about 50 nm.

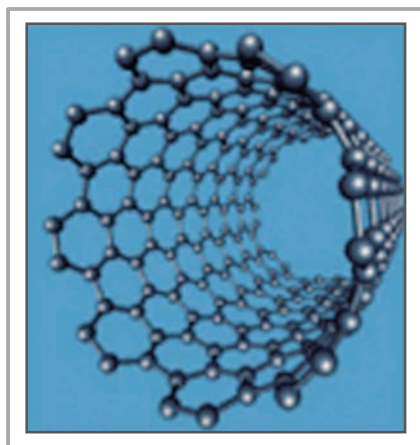


Figure 4. Carbon Nanotube

Source: Infineon Technologies AG

CNTs have exceedingly good electrical, mechanical, thermal properties. The electrical properties have been found to be dependant on the chirality of the tube. Many companies are starting to make batches of nanotubes, but precise control of the nanotubes' chirality is still difficult. Unable to control chirality will result in some nanotubes to be metallic, some semi-conducting and some insulator. In terms of mechanical

properties, SWNTs are about 100 times stronger and weigh six times lesser than steel. A bigger issue is the ability to integrate CNTs with current manufacturing process, techniques and equipments, and ability to mass produce them cost effectively, or at a lower than silicon-based technology. Table below compares some unique properties of CNTs with some well known materials.

Property	Carbon Nanotubes	Others
Size	0.4–100 nm in diameter	Silicon wires is at least 50 nm thick
Strength	45 billion Pascals	Steel alloys have 2 billion Pascals
Resilience	Bent and straightened without damage	Metals fractured when bent and re-straightened
Conductivity	Estimated at 10^9 A/cm ²	Copper wires burn at 10^6 A/cm ²
Cost	Ranges from US\$100/gram for multi-wall nanotubes to 750/gram for single wall purified nanotubes (BuckyUSA)	Gold is about US\$15/gram

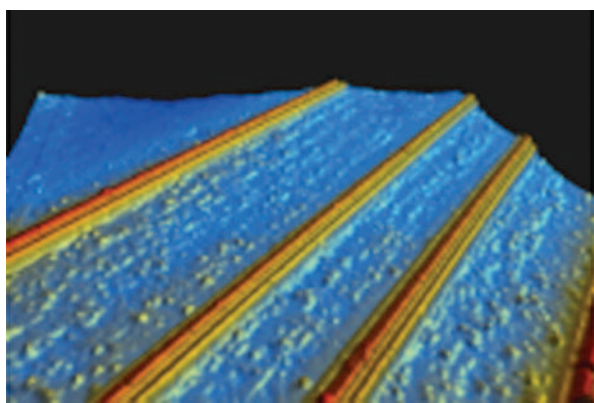
Table 2. Properties of Carbon Nanotubes

These properties make them very attractive for many applications, including high-strength composites materials, tiny sensors, CNTs field emission displays and nanoelectronics devices. As an example, a recent breakthrough (Nov 2004) in carbon nanotube for nanoelectronics was reported by Infineon Technologies AG. Infineon reported the construction of a nanotube transistor, with a channel length of only 18 nm. To build the nano-transistor, the researchers grew CNTs, each measuring about 0.7 to 1.1 nm in diameter, in a controlled process. The CNTs carry electrical current virtually without friction on their surface due to "ballistic" electron transport and can therefore handle 1000 times more current than copper wire. The nanotube transistor can deliver currents in excess of 15 μ A at a supply voltage of only 0.4 volt, instead of the nominal 0.7 volt. A current density some 10 times above that of silicon was observed.

Market development. Carbon nanotubes are currently very expensive with prices ranging US\$100 per gram for multi-wall nanotubes to about US\$750 per gram for single wall purified nanotubes (BuckyUSA). The carbon nanotubes world market was about US\$1.4 million in 2000 and estimated to be in excess of US\$430 million in 2004. Carbon Nanotechnologies Inc. has installed 50kg/day plant for SWNTs recently. According to some estimates, the world market is expected to reach several billion dollars by 2009. Some electronics devices based on carbon nanotubes are close to manufacturing stage.

3.1.2 Semiconductor Nanowires

Over the past few years, alternative nanoscale structures have attracted attention. One in particular is nanowire, a 1D device that holds promises for building future electronics devices. These nanometre size solid wires can be grown from a variety of different materials and have one major advantage over carbon nanotubes in that their chemistry is relatively easier to control. By growing nanowires from different semiconductors, materials whose conductivity lies somewhere between a conductor and an insulator can be produced. Nanowires offer potential for future nanoelectronics devices i.e. nanotransistors, nano-LED, nano-laser and nanosensors. Some researchers have already used them to build transistors and diodes. Others have used it to construct lasers and biological sensors. In fact, a researcher at NUS in Singapore has already developed a working SiGe nanowires transistor.



A view of parallel dysprosium disilicide wire grown on silicon surface and imaged using a Scanning Tunneling Microscope. The nanowires are six atoms wide and are separated on average by nine nanometres.

Figure 5. Nanowires

Source: Hewlett Packard Lab: Doug Ohlberg and Yong Chen

The development of techniques to fabricate complex electronic devices and circuits using semiconductor nanowires is expected to play a pivotal role in manufacturing high-density transistor chipsets. Nanowires can be grown from semiconductors such as silicon and gallium, and a variety of polymers. Nanowires can be produced using lithography or nano-imprinting onto a surface, or by chemical growth process in either a gaseous or liquid environment, or using self-assembly directly on a surface.

Researchers from the Oregon Health and Science University and Sharp Laboratories of America have found a way to grow nanowires between pairs of metal electrodes deposited on silicon wafers. The process is a step toward a new way to make smaller, faster electronics components. An electric field was used to direct the growth of silicon nanowires

between specific electrodes. The researchers found that they could grow smaller nanowires at lower temperatures, and could vary the density of the nanowires by changing the pressure. Uniform nanowires with diameters of 17 nm were produced. The researchers are now testing the electrical properties of the nanowires. Several challenges are anticipated in making the process practical, including making practical contacts, finding the best composition for the nanowires, and handling the effects of surface impurities.

In Jan 2004, scientists at HP Labs have successfully devised a method of growing and connecting semiconductor nanowires in place, which could eventually lead the way to more effective sensors for detecting toxic gases and other chemical or biological substances. The nanowires were grown from one wall and extend across the space between walls, then attached firmly to the other wall to form strong mechanical connections. The scientists said that by using large numbers of these "nanobridges" in parallel, they were able to obtain the high surface-to-volume ratio needed for sensors. Other potential applications include interconnecting "leads" in nanometer-scale electronic circuits and devices within nanowires. This technology also provides a platform for molecular electronic devices.

More recently, Lars Samuelson and colleagues from Lund University, Sweden demonstrated a technique for growing a class of tree-like nanowire structures, known as *semiconductor nanotrees*, which could not only aid the development of nanowire electronics, but also lead to new possibilities for photonics and solar-energy conversion. Their technique is based on the use of gold nanoparticles to catalyse and control the growth of individual nanowires. The process begins by growing the 'trunks' of the trees from gold seeds deposited on a substrate's surface. Then, after a second layer of gold seeds is deposited onto these trunks, the 'branches' of the nanotrees are grown. The process involves the self-assembled growth of semiconductor nanowires via the vapour-liquid-solid growth mode. This bottom-up method uses initial seeding by catalytic nanoparticles to form the trunk, followed by the sequential seeding of branching structures. Each level of branching is controlled in terms of branch length, diameter and number, as well as chemical composition.

3.1.3 Carbon Fullerene (or C₆₀ Buckyball)

Fullerene, notably known as C₆₀ buckyball (buckminster fullerene) is a spherically caged molecule with carbon atoms arranged in interlocking pentagons and hexagons. It has attracted attentions for its unique features, such as high pressure resistively, strength and stability. However, high production cost and limited availability has been the main obstacle in the development of the fullerene market.

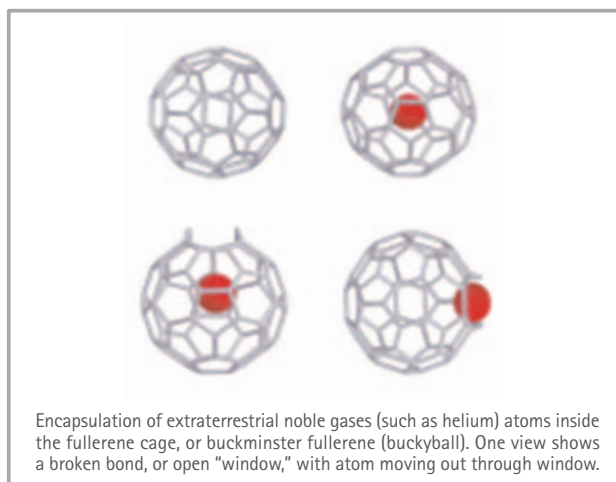


Figure 6. Buckyballs

Source: NASA Ames Research Center

Fullerene-based products started to emerge in 2003 mainly in the sports industry such as high performance tennis racket and balls, bowling balls and golf clubs. Fullerenes are particularly useful for medical & biological applications as nanocapsules in medication and for encapsulating radioactive nanoparticles for targeted drugs delivery. It can also be used in fuel cells and photovoltaic cells for efficient energy conversion, as well as in photo-detector applications.

3.1.4 Nano Electronic Devices

Nanoelectronics will have a significant impact on the electronics semiconductor industry. Almost all electronics-related products like memory devices, storage devices, display devices, and communication devices are all experiencing shorter life-cycles as technologies progresses. From transistors to the computers they fit in, every single device will undergo transformation with nanoelectronics. Nanoscale devices will enable the creation of new innovative products, such as smart adaptive sensors, biological sensors, molecular memories, spin-based electronic products, and highly efficient flexible photovoltaic cells.

Molecular electronics is also expected to catalyse the growth of nanoelectronics. Breakthroughs in molecular electronics from Hewlett Packard (HP) and many other research laboratories are pushing new frontiers in nanoelectronics. HP's research Lab has successfully created the highest density electronically addressable molecular memory reported. The other main driving factor has been the emergence of spintronics within nanoelectronics. It is believed that spin-based electronics will be used as memory first by 2015 and computational logic elements after that.

The importance of nanoelectronics is also top on SEMI and Semiconductor Industry Association (SIA) agenda. In Jan

2005, both organisations reported to start a joint study on nanotechnology applications in the electronics industry. This study will provide definition of the rapidly-emerging global nanoelectronics markets and offer a global perspective of requirements and opportunities for equipment and materials suppliers. According to SIA President George Scalise: "The nanoelectronics era will revolutionise the semiconductor industry as we utilise new materials, new device structures and new assembly methods to extend Moore's Law." The study is scheduled for completion in Q3 2005.

3.1.5 Single Electron Transistor

Single Electron Transistors (SETs) are starting to become candidates for future low-power, high-density IC elements because of their ultra-low power operation involving only a few electrons. As a comparison, CMOS transistors have about 100 electrons at any given time underneath the gate. Research is ongoing to take that to the extreme to have only one electron beneath the gate.

SET is a new type of switching device that uses controlled electron tunneling to amplify current. The basic structure of an SET is a quantum dot, measuring about 1 to 10 nm, with three leads. One is a source lead, another is a drain lead. This enables electrons to tunnel from the source lead to the quantum dot, and then from the quantum dot to the drain. The third lead is a gate electrode that is capacitive-coupled to influence the potential of the quantum dot.

There are two major technical issues that SET must overcome before it can be used for practical applications. Currently SET operates at about 4.2 to 20 Kelvin and is very sensitive to background charges. The future challenge is to make SET able to operate at room temperature. Also, capacitance and thermal fluctuation limitations require that the island size of the SET be no larger than 10 nm, a feature size out of the range of present conventional fabrication processes. Another challenge for industry is the method to reliably manufacture bulk SETs in a CMOS-compatible process. Initial applications of SETs are likely to be used in memory and special applications in metrology, such as primary thermometers and super-sensitive electrometers.

3.1.6 Resonant Tunnelling Diodes

Resonant Tunnelling Diodes (RTDs) are devices whose inherent multi-stability allow for very compact circuit design and ability for operating in the gigahertz regime. The basic concept of the RTD is negative differential resistance produced in a double barrier structure with a resonance peak at some voltage, which corresponds to resonant tunneling of electrons through a sub-band energy in quantum well between barriers.

RTD is normally a vertical tunneling transistor. The dimensions in the tunneling direction are typically a few atomic layers thick while the lateral dimensions are restricted by lithographic and process capability.

RTD is extremely sensitive to the thickness of the tunneling well as the tunneling current depends exponentially on the thickness of the tunneling barrier. RTD is one of the devices which have demonstrated switching at speeds greater than 350 GHz. Problems of tunneling barrier thickness need to be resolved else RTD will remain a niche product for high-speed switching, analogue-to-digital conversion, digital-to-analogue conversion and low power applications.

Presently, RTD can only be realised using III-V semiconductors, although demonstration of inter-band tunneling in Si/SiGe devices has been reported recently. The preferred RTD system would be Si/SiO₂ RTDs with CMOS circuit but there are problems with growing single crystal silicon between SiO₂ barriers. For THz oscillator applications, a high output power RTD device is necessary which is still not possible.

3.1.7 Molecular Electronics

Molecular electronics, also known as moletronics, is a radical approach to build new computing logic and memory elements. It is a discipline that uses both organic and inorganic molecules to create electronic devices. Significant advances in recent years have been achieved in the utilisation of nanoscale molecular components for electronic applications. A variety of materials, including carbon nanotubes, custom-synthesised organic molecules, metallic nanoparticles, and biological molecules, have been used to build devices and simple circuits that demonstrate switching, logic and memory functions. These research works represent a critical step in the development of molecular electronics elements for building future electronics circuit.

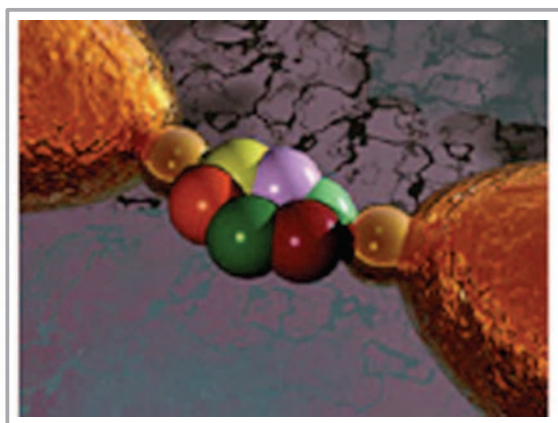


Figure 7. Benzenes Bind to Gold Electrodes
Source: National Science Foundation

Currently, molecular electronics is still in early phase of research, with little opportunity for commercialisation in the near term. Challenges faced in realising commercial applications include the difficulty to integrate molecules into ordered structures, the reliability and degradation issues of the organic molecules caused by environmental stress. Another challenge is to understand the electronic interaction between the molecules and the surfaces with which they are interfaced so as to interconnect these molecules for system-level applications.

Most researchers projected that utilising molecular electronics for processing will take more than 10 years to achieve commercial possibilities. However, by 2010, we should see commercial molecular electronic devices in the form of sensors or detectors, fabricated with a molecular sensing unit to record change in resistance from nanowires or nanotubes as the molecules bind to the sensing surface. By 2015, memory devices made from molecules will be developed. These are likely to be hybrid devices that combine molecular electronics with existing technologies, such as silicon. In the long term, the ability to manipulate and tailor molecules to self-assemble into nanoelectronics components will allow the industry to create a very low-cost high performance molecular processor.

As early as in 2000, DARPA has identified molecular electronics as a very fast moving area of research, key to complement or replace silicon limitation in scaling over the next decade. Computing devices based on moletronics benefits in terms of smaller size and lower power dissipation. Potentially, molecular logic and memory could produce ultra-high density storage system in the order of a terabit per cm² and switching speeds in the range of a few picoseconds, while still operating at very low power. Modern chemistry techniques have rendered atomic control over a wide variety of molecular structures feasible, allowing molecular electronics systems to be proven viable.

The UCLA, Caltech and University of California, Santa Barbara Rapid has also reported rapid progress in the development of molecular electronics in Dec 2004. Over the past decade, scientists around the world have taken a few model molecular systems, including bistable catenanes and rotaxanes, and have addressed many of the fundamental scientific principles related to harnessing their potential in electronic circuits. The current research summarised in its paper described experiments in which the team has achieved. The researcher described:

*"When we apply a positive voltage, they turn on, and when we apply a negative voltage pulse, they switch off instantly."
"We have verified that the same mechanism works in a*

device, in solution and in two other environments. In addition, we have measured how fast the bistable molecules switch in different environments. We can slow down the switching on the order of 10,000 times on going from solution to device. What takes 10 minutes in a device takes one-tenth of a second in solution. This type of control allows us to store bits of memory using these molecules."

The UCLA/Caltech team verified that bistable catenanes and rotaxanes can work as molecular switches that can be turned on and off when they are attached to surfaces and when they are buried in polymer blends.

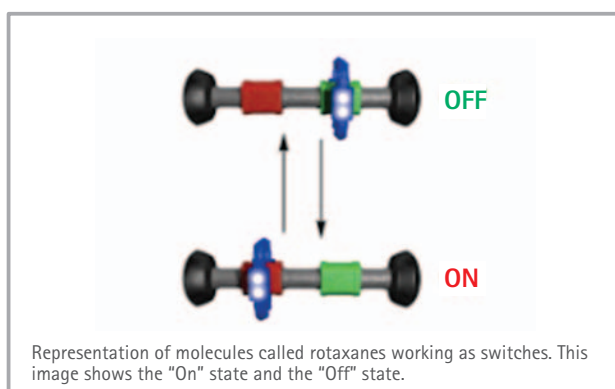


Figure 8. Molecular Electronics Rotaxanes

Source: Stoddart Supramolecular Chemistry Group, UCLA

Scientists in Japan have also made a new type of molecular photodiode, whose current switches direction depending on the wavelength of the light used to excite it. Designed at Kyoto University, the device consists of two helical peptide molecules, whose dipole moments point in opposite directions. This technique could be used to make a wide variety of molecular electronics devices.

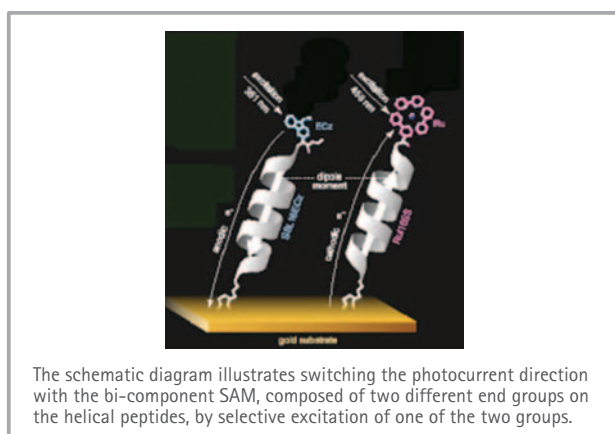


Figure 9. Molecular Photodiodes

Source: Science 304 1944

Few technology leaders such as IBM and HP are also pioneering this area of research. As early as Sep 2002, the Quantum Science Research group (QSR) in HP's lab has successfully created a circuit to demonstrate a 64-bit memory using molecular switches as active devices. QSR hopes to achieve 128x128 cells (a 16 kilobit array) about 10 times smaller in the next phase. Zettacore is another company focusing on developing molecular memory. The technology is based on the properties of a specially designed molecule, called multi-porphyrin nanostructures, which can be oxidized and reduced (electrons removed or replaced) in a way that is stable, reproducible, and reversible for memory applications.

3.1.8 Plastic / Polymer Electronics

The field of plastic or polymer electronics has emerged in recent years as an increasingly important technology poised to disrupt electronic circuits and display technologies. Fabricated on plastic substrates, the active device, usually the thin-film transistors can be bent, folded, worn or conformally mapped on to any shape and surfaces. When integrated with organic semiconductor, it offers a new perspective in the development of cheap flexible electronics for use in the rapidly growing market of smart identification, product tagging and flexible display, potentially displacing the use of barcodes and paper-based signages.

An interesting research work on flexible display was reported by the Philips Research Laboratories in Netherlands in 2004. The researchers demonstrated a flexible active-matrix monochrome electrophoretic display based on solution-processed organic transistors on 25µm-thick polyimide substrates. The displays can be bent to a radius of 1 cm without significant loss in performance. With 1888 transistors, these are the largest organic integrated circuits reported to date. More importantly, the operating frequency of 5 kHz is sufficiently high to allow integration with the display operating at video speed. This work therefore represents a major step towards 'system-on-plastic'. Polymer Vision is also an initiative from Philips Research Lab to develop rollable polymer display, using ultra-thin flexible active-matrix based on organic electronics with the flexible electronic ink display technology.

Polymer/plastic is an attractive technology due to low-cost production and therefore can be pervasively deployed in many infocomm products. They can be printed directly onto large substrates without the need for very expensive vacuum deposition equipment used for fabricating silicon semiconductors. Polymers can also be used to product light. Recently, some companies have developed polymer light emitting diode displays which have the potential to be much lower cost and more energy efficient than liquid crystal displays. However, the stability and long-term reliability of this technology is still not mature for commercialisation.



Figure 10. Plastic Electronics
Source: Infineon Technologies AG

Applications of plastic or polymer electronics. The possibility of integrating the electronics driving the screen and display has enormous benefits, both in terms of manufacturing cost and product form-factors. Organic light emitting diodes (OLEDs) are the most prominent type of an organic optoelectronics device suitable for future display. Organic transistors are also suitable for simple integrated circuits used in smart cards and electronic tags. Infineon Technologies has also developed prototype of smart electronic devices such as MP3 audio player system integrated seamlessly into textiles.

The European Commission has also spearheaded projects related to plastic electronics under its Sixth Framework Programme (FP6):

NAIMO (NAnoscale Integrated processing of self-organising Multifunctional Organic Materials) aims to develop nanofabrication techniques to manufacture nanoscale smart plastics materials and to learn about 'the interplay of structure and electrical and chemical properties at the molecular level, as well as to develop modelling capabilities. Started in mid 2004, it is a four-year project with the end result of developing new nanoelectronics products, such as organic electronic chips and displays, sensors, flexible solar cells and magnetic structures.

PolyApply. This is an EU consortium project that intends to develop generic technologies with a meaningful impact in the mid- and long term. The group developed polymer electronics technologies related to ambient intelligence applications which include simple RF tags at ultra-low cost to RF communication devices with complex functionality such as integrated re-writable memory, sensory inputs, display, etc.

3.1.9 Learning From Nature (Self & Directed Assembly)

An interesting trend in technology research recently is to seek nature for source of inspiration. Self-Assembly is the process by which a system of non-living chemical components became organised into a well-defined, stable structure. In other words, the system will change from a disorganised state to a more "ordered" or "organised" condition, exhibiting some form of structure. It is a very important concept in biological systems and has increasingly become a focus of non-biological research. This technology will change the way we produce devices in the future while expanding their capabilities.

The Motivation. As features decrease in size from microscale to nanoscale, conventional fabrication technologies such as photolithography or electron beam lithography will become more expensive to use. Self-assembly and directed assembly methods are touted as the next bottom-up manufacturing evolution to produce low-cost electronics parts – simply allowing products to "make themselves." Though unlikely to happen on a wide scale by 2015, these methods could ultimately provide a challenge to top-down semiconductor lithography.

According to the ITRS roadmap 2004, critical research is needed to establish the fundamental size limitation of different self-assembly techniques to fabricate useful nanostructures. Exploratory research should also be conducted on atomic and molecular crystals, bio and DNA-based assembly structures to understand their size limitations and registration abilities. As well as to determine the potential ability of directed assembly with electromagnetic fields, fluid

flow, strain, optical fields, and other methods to align nanostructures and self assembled material in a high density form. Many researches in self-assembly have started to address these areas. The following listed a few research activities on self-assembly.

A team from the National Microelectronics Research Centre (NMRC) in Cork demonstrated a method of self-assembly known as field configured assembly (FCA). FCA is an integration technology inspired by self-assembly processes in nature by exploiting the fact that most devices are charged and therefore respond to an appropriately configured electric field. This field can be used to direct and accurately position a device on a chip substrate, eliminating the use of tweezers altogether.

Another group of researchers from Duke University, Rambus Inc. and the University of North Carolina at Chapel Hill have recently devised a pair of computer architectures that would be built from self-assembling DNA. Computers assembled by DNA will be extremely small, fast and inexpensive, and would consume very little power. Researchers have tapped the self-assembly ability of DNA by producing strands of artificial DNA that have segments of base pairs that connect together in certain patterns. Previous research has shown that it is possible to coax DNA to self-assemble into 3D structures. DNA can also be engineered to attach to other materials in order to include those materials in the self-assembly process.

The researchers' architectures call for single-stranded artificial DNA molecules that have silicon nanorods attached to their ends to assemble into circuit patterns. The DNA junctions between rods are then plated with metal to form the circuitry. Because the self-assembly process is error prone, the system design accommodates expected errors by building redundancy into circuitry. The key is to design a system with a large number of simple components so that any one circuit failure will have a minimal effect on the whole system. The architectures involve as many as one trillion small processors working in parallel.

The researchers' approach is distinct from DNA computing research, which taps the ability of DNA to self-assemble to form strand arrangements that represent computations. In contrast, the researchers' DNA architectures harness DNA self-assembly to form nanoelectronics circuits. According to the researcher, it will be 5 to 10 years before a proof-of-concept self-assembled DNA computer can be built, and more than 10 years before such a computer could be ready for practical use.

3.1.10 Software & Tools

Infocomm system in computational nanotechnology has also become even more critical in assisting researchers perform

basic and applied nanoscience research. If we looked back into the last two decades, the success of microelectronics industry was driven in part by the development of simulation software and tools that result in lowering the overall cost of producing electronic devices. Now, new powerful tools will be needed to conduct research at nanoscale, especially in developing molecular electronics devices. Researchers will need to rely on nano-computational software and visualisation tools to discover, understand and control complex molecular and atomic properties and their interaction at nanoscale.

Nanoscale device design involves predicting the physical, electrical and chemical properties of the materials; modelling and characterising the fabrication and assembly processes; analysing the simulated device under operational conditions; and controlling and optimising simulated device operation. Computational nanotechnology consists of 3D software tools that help in observing new properties exhibited at nanoscale and ability to image, characterise and manipulate them. These tools will help to shorten research works as well as product development cycles. The following highlighted some initiatives in this area.

The nanohub is a web-based initiative spearheaded by the Network for Computational Nanotechnology at the University of Purdue. It provides an online simulation services in the areas of nanoelectronics, NEMS, and their application to nano-biosystems.

The Phantoms computational hub, managed by Cientifica is launched in Apr 2002. Under the initiative of the European Commission IST programme, the hub holds a repository of simulation codes useful for modelling and design of nanoscale electron devices, promoting the application of computational science to nanotechnology. The mission of the Phantoms hub is to become the virtual venue where many of these codes can be run by registered users, sharing insights and comparing results.

There are also freeware simulation tools available; the Nano-Hive Nanospace Simulator, an open source software for simulation and make mpeg output, and NanoCAD, an open source nanotech design system Java applet base software to simulate the behaviour of molecules.

Intel has also been exploring nanotechnology for some time. In Mar 2002, it launched a Computational Nanovision project to create high-precision analysis tools in new vision and image processing techniques for analysing nanoscale particles. This technology combines probability theory with semiconductor testing procedures in the aim to reduce cost of testing.

Nanotitan is another company in this field that offer application software in design and analysis of nanodevices. Its nanoXplorer is a software application designed to explore nanodevices properties, including its molecular structure, operational characteristics, and integration with other nanodevices. Its nVisualizer can also explore and understand data in 2D and 3D space.

Atomistix is a software company engaged in the development of modelling tools for nanotechnologies. Its TranSIESTA-C software package is used for electronic structure and quantum transport calculations. The software combines non equilibrium greens functions techniques with density functional theory for electronic structure calculations.

Accelrys is a provider of software for computation, simulation, and the management and mining of scientific data used by biologists, chemists and materials scientists, including nanotechnology researchers for product design as well as drug discovery and development. The company has also launched a Nanotechnology Consortium in Nov 2004 to provide a project framework and a detailed scientific proposal that addresses the challenges of rational nanomaterials and nano-device design. Its goal is to extend existing and create new software tools that enable the rational design of nanomaterials and nanodevices. Accelrys informatics tools cover a wide variety of applications and data types across genetics, biology, chemistry, and materials science. These tools apply and combine specialist technologies tailored to specific research problems such as gene sequencing or 2D molecular sketches. For example, Accelrys' DS ViewerPro can create and visualise 3D molecular structures, analyse chemical features, and create interactive reports and presentations. The Materials Visualizer provides extensive model building and visualisation capabilities for materials types including polymers and crystals.

FEI is another nanotools company providing state-of-the-art software tools and systems capable of sampling images down to sub-Ångstrom resolution. Its Xplore3D is an intelligent electron tomography package suitable for a wide range of 3D applications for life sciences, material sciences, semiconductor and nanotechnology labs.

Zyvex is also another early pioneer on nano-manipulation and testing tools used for nanoscale research, development, and production applications. As an example, the nano-manipulator has four positioners that helps researchers manipulate nanotubes to test and measure a variety of properties including durability.

3.2 Nanocomputing Architectures

Applications today require more processing power than before. For instance, research projects such as human genome and brain science studies, real-time DNA analysis, particle

physics, and weather and earth simulation computation are consuming more processing power and storage capacity. Also, future applications such as natural languages understanding, 3D multimedia visualisation, peer-to-peers networking, sensor data mining, human computer interaction, and cognitive radio are envisaged to require more computing power. The next decade promises to be an exciting one for computer architects. They will need to construct high performance processor chip to meet these demand. Nanotechnologies will continue to drive Moore's Law, providing a doubling of the transistor density every two years. With billions of transistor available on the silicon and issues of heat and memory latency set in, will there be a radical shift in processor design? This section covers some potential computing architectures that are currently in the research and development phase.

3.2.1 Reconfigurable Hardware

Most general computer architectures to date have been based on a "stored program" paradigm that differentiates between memory and processing and relies on communication over buses and other long distance mechanisms. Nanoelectronics may change this concept. As processing elements cost per function decreases with technology, new computing architecture can merge the memory and processors onto a single chip to narrow the processor-memory performance gap. This will tend to move computer architecture in the direction of locally connected, reconfigurable hardware meshes.

Reconfigurable hardware combines the advantage of a computer architecture adapted to a specific task with the flexibility of a programmed solution. The classic computers typically consist of software and hardware. The hardware is fixed when the computer is manufactured and the software is loaded and removed when the computer is in field usage. Reconfigurable computing structures change this classical model of computer systems. Computers built from reconfigurable structures do not rely on a fixed hardware, but adapt their architecture to the application under execution. Making hardware soft leads to a paradigm shift in computing and is expected to radically change the way we construct and use computing systems for future context aware technologies.

Reconfigurable systems have shown to outperform state-of-the-art computers for solving problems in database search, genomic sequence scanning, and cryptography. In embedded systems, reconfigurable technology accelerates system functions, reduces system cost and power consumption, and enables hardware-on-demand functionality. Research on Intelligent RAM (IRAM) and Reconfigurable Architecture Workstation (RAW) represent the initial works on these new architectures.

The UC Berkeley Intelligent RAM (IRAM) project is one of the reconfigurable architecture designed for general-purpose computer systems. It integrates a processor and DRAM onto a single chip. IRAM is touted to offer several advantages over today's solutions, including considerably reduced latency and dramatically increased bandwidth to main memory, reduced power and energy consumption, and reduced space and weight for embedded, portable, desktop, and parallel computer systems. Testing is currently proceeding on the latest prototype, called VIRAM1 (Vector IRAM). This prototype was implemented in 0.18 μ m CMOS and has over 125 million transistors.

The Reconfigurable Architecture Workstation (RAW) is another research project in developing radically new processor architecture. Led by MIT and IBM, the RAW strives to exploit these chip level resources by implementing thousands of tiles, each comprising of a processing element and a small amount of memory, coupled by a static 2D interconnect. The RAW architecture overcomes the "wire delay" limitations of traditional processors by exposing all circuit interconnections to the compiler for better performance. Higher chip densities, faster switching speeds and growing compiler sophistication will allow RAW processor performance-to-cost ratio to surpass that of traditional architectures for future, general purpose workloads. RAW architectures are field programmable, therefore they are a cost effective alternative to custom hardware in many situations.

IBM is also collaborating with University of Texas to develop an adaptive, high-performance microprocessor, called TRIPS (Tera-op Reliable Intelligently adaptive Processing System). TRIPS is designed to provide supercomputer performance on a chip, ultimately scaling to deliver more than one trillion operations per second by 2010. It is a concept designed to perform block-oriented execution. Instead of operating on only a few computations at a time, the TRIPS processor operates on large blocks of computations mapped to an array of execution units on the chip. This approach allows many more instructions to execute in parallel, thus offering higher performance. These computation arrays include support for "polymorphism," which adapts them to match the type of software application currently running on the hardware.

3.2.2 System-on-a-Chip

System-On-a-Chip (SOC) is an architecture for integrating many different functional modules onto one single chipset. This technology is especially important for wireless communications system design, as the ability to integrate RF front-end, baseband protocol handling and power management subsystems into a functional chipset would result in reduced power consumption as well as reduced form factor and lower material cost. In optical communication, SOC will improve the overall optical system performance,

using highly integrated advanced optoelectronics components. However, with today's technologies, it may be too expensive to put these modules together, with problems such as RF crosstalk, interference and varying reliability of different technologies affecting MTBF of the overall chipset. Nanotechnology is expected to enable easier integration of the various technologies into a single chipset (see figure below).

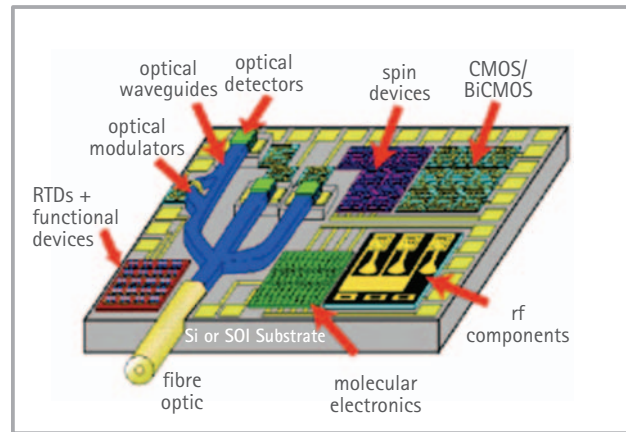


Figure 11. The SOC of the Future

Source: IST Tech Roadmap for Nanoelectronics, Future and Emerging Technologies

3.2.3 Multi-core Processor

Multi-core processing architecture in desktops and mobile platforms has become a growing industry trend in 2004 as single core processor is rapidly challenging chip designer in term of complexity, speed and power budget. It is a concept based on high-performance computing for servers as a way to increase processing power and speed. At sub-100 nm, nanotech will fuel the development of multi-core chipset design, alleviating the problems of heat dissipation faced in single-core architecture.

Single-core Chip Architecture. Existing single-core chipset usually employed two methods to boost system performance of desktops PC and mobile platforms; by increasing clock speed; and by adding more cache memory. Both methods add additional power constraint to chip designers.

Two basic approaches in multicore processor design are usually adopted i.e. Symmetric multiprocessing (SMP) and asymmetric multiprocessing (AMP). SMP essentially build two equal processors into a single piece of silicon, so that the chip provides the same computing power as a dual processor server. This approach saves computing real estate and increases overall performance of processor because the chip cores share a common cache memory and buses. In AMP, the two internal chip cores differ from each other and perform specific functions, off-loading work from the central processor.

Several chip makers are now moving to multicore designs to gain system performance. ARM and NEC Electronics are teaming up to develop a multiprocessor core for multimedia devices and mobile handsets to increase the performance of multimedia applications such as streaming video. It is licensing MPCore, an embedded processor design that can be configured with one to four ARM11 cores expected to be ready in 2006.

Multicore approach was also adopted in the design of Cell Processor, a collaborative effort between Sony Group, IBM and Toshiba that was announced in 2001. The joint effort planned to R&D a supercomputer-on-a-chip for a new wave of devices in the emerging broadband era. Cell could become an important advanced chip architecture design that overcomes the imminent transistor scaling, power and performance limitations in conventional technologies. IBM likened the Cell Processor as the cells in a body that unite to form complete physical systems. A "Cell" architecture thus allows all kinds of electronic devices (from consumer products to supercomputers) to work together, signalling a new era in Internet entertainment, communications and collaboration.

Cell is a vector processing architecture for high performance distributed computing. Specifically, Cell is design based on multicore and comprises of a 64-bit Power processor core and multiple synergistic processor cores capable of massive floating point processing. An in-depth description on cell architecture can be obtained from <http://www.blachford.info/computer/Cells/CellIO.html>.

Cell is optimised for compute-intensive workloads and multimedia applications, including computer entertainment, movies and other forms of digital content. Primarily designed for PlayStation 3, Cell will substantially enhance the performance of future broadband-empowered consumer applications such as Blue-ray, HDTV, HD Camcorders, digital television, home media server and advanced mobile communication handsets. It will raise the user-friendliness of services realised through these applications and facilitate the use of information-rich media and communications. According to IBM, Cell will first be implemented using 90 nm silicon-on-insulator (SOI) technology on computing workstation in 2005 and home servers, high-definition TV (HDTV) systems and game console market in 2006.

Filed under the US Patent, the inventors, Suzuoki, et al. described:

Resource dedication system and method for a computer architecture for broadband networks

A computer architecture and programming model for high speed processing over broadband networks are provided. The architecture employs a consistent modular structure, a common computing module and uniform software cells. The common computing module includes a control processor, a plurality of processing units, a plurality of local memories from which the processing units process programs, a direct memory access controller and a shared main memory. A synchronised system and method for the coordinated reading and writing of data to and from the shared main memory by the processing units also are provided. A hardware sandbox structure is provided for security against the corruption of data among the programs being processed by the processing units. The uniform software cells contain both data and applications and are structured for processing by any of the processors of the network. Each software cell is uniquely identified on the network. A system and method for creating a dedicated pipeline for processing streaming data also are provided.

3.3 Information Storage

Data storage technologies are critical enablers of IT and can be divided into two different types; solid-state memory such as DRAM that a processor chip would use or flash memory for storing images in digital cameras; and disk-based memory, commonly known as secondary storage such as the magnetic hard drives found in all computers. Solid-state memory essentially uses the same processes used to develop computer chips, by packing more transistor cells into a given area to increase memory capacity. It has grown from 1 Mbit in 1985 to 16 Mbit in 1995 to about 512 Mbit to 2 Gbit these days. The development of hard disk however has taken a different route in its evolution as it is based on reading and writing information magnetically or optically on a spinning disk.

Over the years, magnetic storage density has grown from a mere 20 MB in 1985, to about 500 MB in 1995, with typical hard disk size ranging from 40 GB to 80 GB these days. This is about 100 times better than those in 1995!

As solid-state memory increases in storage density, it becomes more attractive for use in products that traditionally used disk-based storage. This trend can be seen, for instance USB thumb drive gaining popularity over diskettes; and digital camera using flash memory. On the other hand, disk-based storage is also starting to compete with solid-based technologies, as can be seen from the development of ultra-thin 1" microdrive with up to 5 GB of storage used in personal music player such as iPod and Zen MP3 players. Hard disk-based storage is still attractive in the consumer electronics space such as in personal video recorders, set-top boxes and gaming consoles. The next 10 years will still see hard disk, whether magnetic or optical, as a dominant technology for large volume mass data storage.

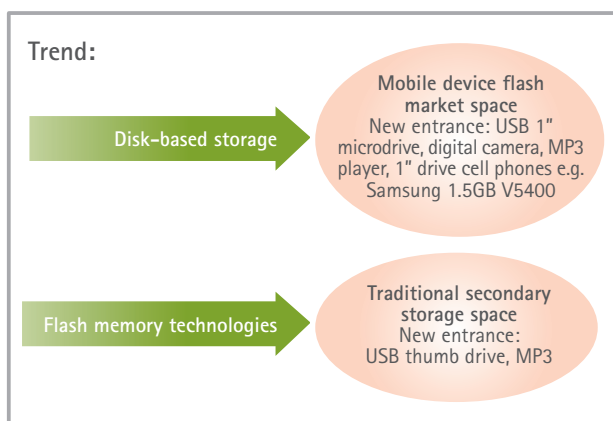


Figure 12. Data Storage Trends

Without doubt, miniaturisation has been the main driving force to meet continual demand for more storage resources. It will continue to influence computing hardware's limit to achieve even smaller form-factor storages, such as high performance micro hard disks and better memories and

new design architectures for high-speed data access. Nanotechnology will be key to this development. It will enable the development of holographic memory with extremely high storage density as well as high performance non-volatile memories (data retention even without power making re-booting process of computers unnecessary) such as MRAM and PRAM. These memory technologies are critical for enabling a new generation of converged portable multimedia devices, supporting applications such as mobile internet and personal multimedia and gaming application.

Nanotech could also enable a new form of high-density nanopores-based storage system. IBM has developed a prototype known as Millipede based on this technology. With potential up to 1 Terabit per inch², it is more than hundred times better than current DVD technology. Also in development are data memories based on biological molecules or quantum dots in the long term.

Table 3 summarises the memories and storage technologies landscape for this chapter.

3.3.1 Solid-State Memory Development

Current development. While the density of solid-state memories has increased exponentially over the last few decades, there is no promise that this trend will continue forever. Factors that could impede the development are the imaging resolution of the lithographic optical systems and the reliability issues of tunnel oxide due to the thinning that affect data retention. At present, the state-of-the-art memories developed for commercial applications are based on 90 nm process.

Technology	Research (Blue sky)	Development (Commercial prototype)	Emerging (New kid in the block)	Established in the market	On the decline
Solid State Device (Volatile)				SRAM DRAM/SDRAM eDRAM/eSRAM	
Solid State Device (Non-volatile)			FeRAM MRAM	NAND Flash (2Gb) NOR Flash (512Mb) EEPROM	
New Material	Organic polymer Nanotube memory Molecular memory Nanocrystals Nanorings	PRAM/OUM Hologram memory (Info-MICA 1GB)			
High Density Storage System	Probe-based storage (NEMS)	Holographic/ Volumetric Disc	Blue Laser e.g. Blue-ray	Magnetic disk Optical disk DVD	Magnetic Tapes Floppy discs

Table 3. Technology Scan (Information Storage)

Future development. Development of existing memory technologies will continue toward higher density based on small cell sizes using 2D and 3D cell approaches. It will trend toward lower power design by scaling down the operating voltage for device reliability and longer battery lifetimes. It will also push for higher speed with high bandwidth and I/O interface as well as adopting a system-based memory solution. The trend is expected to continue in the next ten years as miniaturisation scales toward 22 nm node. By then, memory density would reach 64 Gbits. Beyond this point, new alternatives are needed.

Current Memory Technologies

DRAM and SRAM are mainly used in computer system as temporary scratchpads for processing data. These memories are volatile, meaning that stored information is lost when the power is turned off. By comparison, magnetic disks are non-volatile. However, magnetic disks are large and mechanically fragile, consume a great deal of power and are slowed reading and writing data. SRAM is typically used in super fast computing system, such as for cache memories, workstations and digital signal processors. It is also used chiefly in low power system such as handheld devices and cellular phones. DRAM on the hand is used for large volume temporal storage in PC, printers and embedded mobile processors.

Flash memory is a non-volatile memory that has evolved from EPROM and EEPROM. It is commonly used for mobile phones and computing platform such as PDAs. It is electrically erasable and programmable and can have two architectural flavours, NAND and NOR. The basic NOR cell tends to be faster, but it uses more space, while NAND tends to be slower but much smaller. One disadvantage of Flash is that it requires a high 9 to 20 internal voltage for erasure and programming. Currently NOR flash dominates the market. It is used in mobile phones, PDAs, flash cards, MP3 players, digital cameras, set-top boxes, cable modems, and other telecommunication network components. But the NAND flash is rising exponentially, mainly driven by the proliferation of digital cameras, compact/flash-memory cards, and MP3 players storing digital media. NAND flash typically targets these storage applications, which generally do not need read speed, but require density.

Commercial NAND flash chips of 1- to 2 Gbit are currently available and 8 Gbit devices are expected in the future using multi-level charge technologies. NOR flash however just started to commercialise 512 Mbit. It may have a niche in the lower memory product market. Both Samsung and Toshiba are leaders in this technology. DRAM on the other hand, is targeted for PCs market. Commercial DRAM available are 512 Mbit and the rising cost is expected to put more burdens to PC makers in 2004.

Alternative non-volatile memories for future digital media converged devices.

The next five years will also see parallel development and emergence of a new kind of memory that combined best attributes of existing technologies. Some referred it as 'Universal Memory,' having the attribute of DRAM's density, SRAM's speed and Flash's non-volatility. Few promising candidates have emerged, which include FeRAM, MRAM, PRAM and those based on carbon nanotubes, NRAM. While these advanced memories still cannot compete with existing technologies in term of reliability and storage densities at the moment, demand from future real-time applications will make these technologies a potential alternative in the next few years.

3.3.1.1 Ferroelectric Random Access Memory (FeRAM)

FeRAM is a non-volatile memory that uses a ferroelectric film as the dielectric of a capacitor to store data. Being non-volatile, it can therefore remember its past states when voltage is removed, making it attractive for instant power-up computing in mobile devices, portable electronic platforms and smart cards products. Other advantages of FeRAM include high access speed, very high read/write endurance and low power consumption. The writing speed is also faster by more than 1000 times as it is controlled by the electrical polarisation of the ferroelectrics capacitor upon an electric field, compared to writing by injecting hot electrons or tunnel effect used in EEPROM and Flash memory.

FeRAM come from a family of ceramic materials known as perovskites. When voltage is applied, the crystal polarises like ferromagnets into two stable states, corresponding to binary '1' and '0'. Early perovskites development did not enjoy much success as the material suffered from fatigue after repeated erasure and writing. Recent advances in the ability to deposit ultra-thin film of ferroelectric material and the use of tougher perovskites material have remade FeRAM. The ferroelectric film on the memory cell capacitor can be lead-zirconium-titanate, PZT, or strontium, bismuth and tantalum oxide, SBT.

3.3.1.2 Magneto-resistive RAM (MRAM)

Spintronic is an important technology for future data storage system. Magneto-resistive RAM (MRAM) is one technology that utilise Spintronic principle to represent bits. Spintronic components utilise not only the charge but also the magnetic moment of the electron for data processing or storing. Components that utilise the spin of electrons to represent bits are many times faster than those based on electrical charge. This is so because the switching process would need less energy than a comparable charge transfer.

MRAM uses magnetic field instead of electrical charges to store data. It does not required external power to hold the information. Computing devices and platforms applications could therefore boot-up instantly, without waiting for software to be loaded from external medium. According to IBM, MRAM can reach theoretical write times down to 2.3 ns. That is more than 1000 times faster than the fastest non-volatile flash and is 20 times faster than FeRAM. MRAM access times are as fast as 3 ns or 20 times faster than DRAM. And since such reads require only 2 mA, MRAM consumes less than 1/100 the energy of DRAM.

Manufacturability, in terms of yield and reliability in a high-volume fab, remains a question. Even extremely slight variations in the oxide, on the order of 0.1 angstrom, can change the magnetic tunnelling junction resistance of MRAM by several percentage points, making the device unpredictable. But consistently keeping within the required oxide thickness in a real-world fab environment is tough, even across an 8-inch wafer, let alone the larger one.

Several companies are already producing MRAM samples. Both Infineon and IBM have also demonstrated a 16 Mbit MRAM based on 1-transistor and 1-magnetic tunnel junction (1T1MTJ) cell. Samsung recently entered the race to commercialise MRAM, a good sign since the company is known for executing well on high-volume, relatively high-margin products. Others have made progress, too. Motorola (Freescale Semiconductor) which has researched MRAM for several years is expected to release samples of 4 Mbit device for embedded systems sometime in 2004.

3.3.1.3 Phase-change RAM (PRAM)/Chalcogenide RAM (CRAM)

Phase change memory (PRAM) is a new non-volatile memory that is potentially denser, faster, and easier to make than DRAM. It offers near ideal memory qualities with attributes such as long data retention of more than 10 years, high endurance, high switching speed and low standby current. PRAM relies on phase transitions induced by nanosecond-scale heating and cooling of small volumes of chalcogenide films within the memory cell. The phase conversion is accomplished by heating and cooling the material. When

melted it loses all crystalline structure, and rapid cooling below glass transition temperature causes the material to be locked into its amorphous phase.

The technology, also known as Ovonic Unified Memory (OUM) was originally developed by Energy Conversion Devices (ECD). OUM offers the advantage of cost and performance over conventional DRAM and Flash memories, and it is compatible with current CMOS process. OUM cells have extremely good write/erase cycle with proven track record of about 1 trillion times without failure compared to 1 million times for flash. OUM is suitable for broad usage in embedded devices, system-on-a-chip as well as in other sensors and hardware applications spaces. In future, it could enable a new class of fast computer architectures through the elimination of multiple levels of different memory technologies, such as Flash, SRAM and DRAM, which are used in today's desktops and laptops into a single device.

OUM is currently being commercialised by Ovonyx, and Intel has also entered into a joint development effort. Currently OUM is still too expensive to mass produce compare to DRAM and Flash. Ovonyx is also pursuing development activities with BAE Systems and STMicroelectronics in parallel. Samsung Electronics has developed sample products of 64 Mbit PRAM chips in Aug 2004. Intel has also developed a 4 Mbit prototype based on OUM.

3.3.1.4 Nanocrystal Memory

Silicon nanocrystal memories are part of an advanced class of memory called thin film storage. Charge is stored in nanocrystals instead of floating gates. It reduces floating gate coupling and simplify the manufacturing process. Using traditional deposition equipment, researchers at Motorola's DigitalDNA Laboratories, deposited silicon nanocrystals resembling 50 angstrom diameter spheres between two layers of oxide. The silicon spheres are engineered to hold and prevent lateral movement of charge to other isolated nanocrystals. This is expected to increase reliability and scalability because a single oxide defect does not lead to complete charge loss as in a conventional floating gate non-volatile memory. A 4 Mbit chip has been demonstrated. Research is now focusing on reducing the die size and tightening the technology specifications.

3.3.1.5 Nanotube Memory

Carbon nanotubes can also be developed as elements to represent bits for high density non-volatile memories. This can be done by using electrostatic forces to bend or straighten billions of these carbon nanotubes to represent a '1' or a '0'. When the power is turned off, the nanotubes will remain in their last states, due to the Van der Waals force. This is a key feature for non-volatile memory.

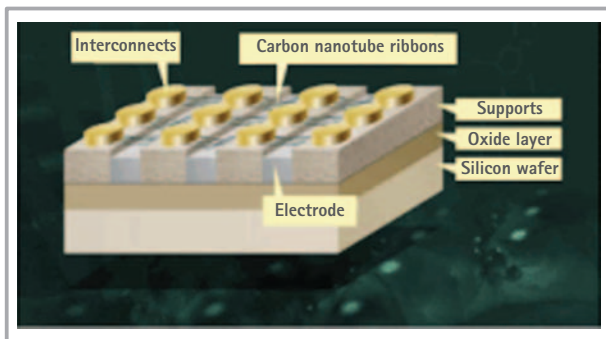


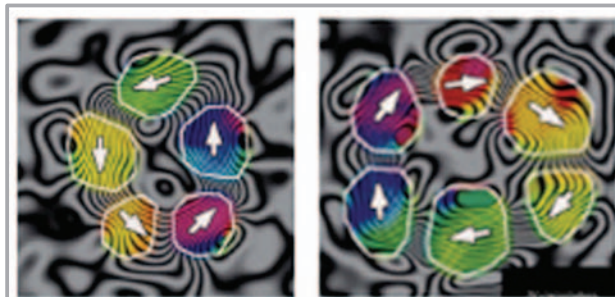
Figure 13. NRAM

Source: Nantero Inc.

Nanotubes Non-volatile RAM (NRAM). Nantero is a nanotechnology company that uses this approach with the aim to commercialise NRAM chipsets. The company was listed as one of the top 10 companies to watch in the next 10 years by IEEE Spectrum Nov 2004 publication. In Jun 2004, it teamed up with LSI Logic to start fabrication on NRAM. Nantero used a manufacturing method that involved depositing a very thin layer of carbon nanotubes over the entire surface of a wafer, and then using lithography and etching to remove the nanotubes that are not in the correct position to serve as elements in the memory array. The present size of the array is 10 Gbit, but the process could be used to make even larger arrays. The main difficulty is to control the growth of carbon nanotubes at the require position and high production yields. It remains to be seen if NRAM can be successfully developed for mass applications.

3.3.1.6 Nanorings Memory

Researchers from Purdue University and the University of Cambridge in England found a way to cause magnetic cobalt nanoparticles to self-assemble into bracelet-like rings that are less than 100 nm across. Each ring contains a magnetic field that can flow either clockwise or counter-clockwise. The two directions can thus represent '1' and '0'. The magnetic dipoles within the nanorings collectively contribute toward a chiral magnetic state known as flux closure, which has potential for spintronics or MRAM application. This technology is able to hold huge amount of information due to the nanosize particles and is non-volatile, which means that it does not need power to retain information. According to the researchers from the Wei Research group, this method could be used to produce practical magnetic RAM in 10 to 20 years.



These images show magnetic flow in a nanoscale cobalt ring. The two directions can represent the 1s and 0s of computing.

Figure 14. Nanoring Memory

Source: Purdue University

The technology was also reported at the Johns Hopkins University by C. L. CHIEN on Spin Torque and Nanorings. Since each magnetic nanoring can acquire one of two chiralities of the vortex state, one can exploit nanorings in magnetic storage for vertical magnetic random access memory (VMRAM) application.

3.3.1.7 Molecular Memory

Memory chips may one day rely on organic compound to store information. This method of making memory, molecular nanotechnology, if successful, will create a significant revolutionary advancement in memory technology at nanoscale. Its attractiveness in term of switching speed, very low power and its natural nanosize has driven researchers in the search for stable reagents to achieve lower defect rates. Known as molecular memory, it is one of the future candidates of ultrahigh density storage technology. Molecular memory can be programmed to self-assemble during the manufacturing process, and does not require expensive semiconductor infrastructures, thus allowing products to be manufactured at a low cost.

In the interim stage, researchers aim to combine organic compound with existing semiconductor manufacturing processes to produce a hybrid device. One key challenge of making molecular memory is to find the compound that could withstand the harsh silicon manufacturing processes. Scientists at the University of California, Riverside has recently reported finding one such material, an organic molecule known as *porphyrin*, which works as a charge-storage element and occurs naturally as part of hemoglobin and chlorophyll.

ZettaCore is another pioneer in molecular electronics. Its molecular memory is based on the properties of specially-designed molecules. The multi-porphyrin nanostructures can be oxidised and reduced in a way that is stable, reproducible, and reversible. In this way, molecules can be used as reliable memory locations for electronic devices.

In another molecular electronics effort, USC and NASA-Ames has demonstrated a molecular memory with three different controllable bit states, representing a total of 8 different states. This multilevel molecular memory unit works by charging or discharging nanowires consisting of molecules into different chemically reduced or oxidised (redox) states. The information stored in the unit can be read back by sampling the resistance of the nanowire; the attached redox molecules act, in effect, as chemical gates for controlling the number of electrons in the nanowire. Initial tests have proven that the data written using this method can last up to 600 hours, compared to retention times of a few hours for one-bit-per-cell molecular memories. The researchers are attempting to make more extended memory chips using the new discovery with potential of data density rates as high as 40 Gbits/cm².

Nanomagnetics has also demonstrated a nanoscale memory based on protein Apoferritin, the main molecule in which iron is stored in the body, to create a material consisting of magnetic particles each about 12 nm in diameter. Currently, about 450 Gbits/cm² of data can be stored. Nanomagnetics believe this could eventually be improved to a maximum of 3 Tbits/cm². The most significant challenge is to align the nano particles in a uniform up or down position, so that they can store a magnetic charge. They are currently not automatically oriented.

Researchers from Princeton University and Hewlett-Packard Lab have also demonstrated using a clear conductive plastic polymer known as pedot (used as coating on photographic film and as antistatic coating on computer screens) to create organic memory. The technology consists of an amorphous silicon diode and pedot printed on a plastic substrate at each intersecting point on a grid of electrodes. A high current passes through pedot will turn it into an insulator, similar to blowing a fuse. These two states thus represent digital one and zero data. The pedot layer that stores binary data is applied using electronic imprint lithography process. It could provide several gigabytes of storage suitable for mobile devices.

Market development. According to a report from NanoMarkets, nanotech enabled memories will not be significant in 2004. This market will rise to US\$18 billion by 2008 and is expected to worth US\$65.7 billion by 2011. The breakdowns are as follows:

Memories Technology	2004	2008	2011
MRAM	2	3,843	12,929
FRAM	5	1,283	4,547
Holographic Memory	0	3,287	6,913
Non-Optical Phase Change	0	1,144	4,836
Media/Ovonic Unified Memory			
Molecular Memory	0	1,408	7,177
Nanotube RAM	0	1,921	8,852
MEMS-Based Systems	0	2,120	6,451
Polymer Memory	0	1,359	7,879
Other	0	1,550	6,129
Total	7	17,915	65,712

Table 4. Revenues from Nanostorage Technologies (US\$ Millions)

Source: NanoMarkets

3.3.2 Mass Data Storage Development

More data are been generated, accumulated, accessed and archived each day, driven mainly by the Internet and new files (music, video, images, etc.) sharing applications. According to IDC, the amount of new storage capacity installed each year is growing almost 80% annually. With the volume of data soaring and new regulations requiring that it be kept safe and secure, existing magnetic storage technologies would reach its limit in no times. New breakthroughs are thus needed in the area of read-write sensor head technologies.

The proliferation of sensor networks in the future is expected to churn out even more data into the Internet. As these dataset get larger, it is critical to be able to store, recognise, mine and synthesis the information quickly, reliably and intelligently. High density, fast access speed and network connectivity are significant parameters in future storage system development.

Current development. Over the past decades, mass data storage technologies have focused mainly on improving the surface area of the disks and reducing the bit sizes to achieve higher capacity. In fact, the amount of data that can be stored on a media platter of the hard disk is governed by the area density of the media. Hence, this creates a need to miniaturise the components and shrink the magnetic grains that store the information. As the area density of the media increases beyond 100 Gb/in², the magnetic grains become too small and tend to cause data loss or corruption, a situation known as reaching the superparamagnetic¹ limit.

Both manufacturers and researchers have found that the current method of reading and writing data to the media using Giant Magnetoresistive Heads are not longer adequate as the read/write heads would have to fly a nanometre distance from the surface of the media. As such most HDD

¹ Thermal instability of the magnetisation of the ever smaller magnetic grains in the medium.

manufacturers are currently working on alternative technologies that would maintain the growth rate of the media area density. These technologies include Perpendicular Magnetic Recording (PMR) and Heat Assisted Magnetic Recording (HAMR).

Market trends. The price per megabyte of disk storage has also been decreasing at about 40% per year based on improvements in area density, even faster than the price decline for flash memory chips. Recent trends in hard disk drive price per megabyte show an even steeper reduction, 50% per year, making magnetic disk drives even more attractive as a storage technology. When considering the continuing price decline of DRAM and flash memory chips, it is at least 10 times cheaper to store information with magnetic hard disk drives as compared to solid-state memories. This lower price per megabyte of storage will also make sub-1" microdrive a compelling choice to flash in digital cameras as well as other consumer-based electronics.

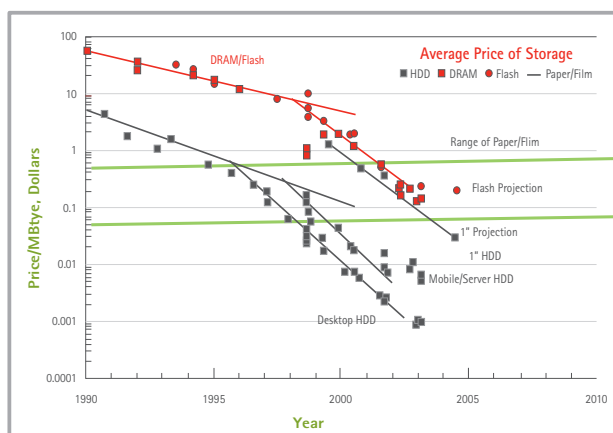


Figure 15. Price of Storage

Source: Hitachi Global Storage Technologies

Future development of magnetic data storage system.

Future magnetic hard disk drives will continue to be enhanced in term of storage density using PMR and HAMR. Perpendicular recording improves the area density of the media by aligning the magnetic grains vertically against the substrate instead of in parallel to the substrate. The read/write head for PMR is higher than the longitudinal read/write head, therefore it avoids some of the issues currently faced by existing hard disks technology. Current PMR enabled media is estimated to be around 100 Gb/in², and expected to improve further to about 500 Gb/in² or higher. The first product using PMR technology is expected to be available in 2005.

On the other hand, HAMR uses a media that contain a film to hold tightly onto the magnetic orientation of the magnetic cells. A laser is then used to heat the cells to write data to the cells. Using this method, it is possible to increase the area density beyond PMR technology. However, HAMR is

only anticipated to be ready for commercialisation in the next 5 to 10 years. Some of the issues that HAMR needs to resolve include accidental heating of the adjoining cells, heat management and power consumption.

Another technology that aims to increase the area density is patterned media constructed using imprint lithography. This self-assembly media is also known as Self Organised Magnetic Arrays (SOMA) media, where the magnetic nanoparticles are organised on the media via self-assembly. It is anticipated that SOMA can potentially reach an area density of 50 Tb/in².

A word on Optical Storage System

The classical CD established optical recording as the main technology for cheap, mass replicated distribution of content. Its storage density is determined by the size of the optical spot which is dependent on the light wavelength (λ) and the numerical aperture of the lens that is used for focusing the laser beam onto the disk. After DVD, the next generation optical recording format is called Blue-ray Disc. The Blue-ray disc utilises Blue-Violet Laser technologies to achieve storage capacities of 23, 25 or 27 GB on a single 12 cm disc. It has a transfer rate of 36 Mbps, enabling it to record 120 min high-definition broadcasting contents as well as making it ideal for professional post-production and consumers use. But Blue-ray is still not a long-term solution as it is based on 2D area storage that has its limitation of up to about 80 to 100 GB.

Another future storage technology is Blue MAMMOS (Magnetically Amplifying MO System), invented by Maxell. The technology magnetically amplifies the recorded signal during readout. Blue MAMMOS employs recording film specially tuned for blue laser wavelength and comes as a 50 GB per side or a 100 GB cartridge. This technology has a 100 Mbps transfer rate with 10⁶ rewritable characteristics, which are suitable for backup media as well as archival usage.

Nanotech will further be enhanced through the application of nanomaterials on sensor head and media to increase storage area density, as well as new mechanical techniques for improved track density operation. These enhancements are expected to extend the life of magnetic hard disk drives well into the future and newer, non-magnetic storage devices must equal or exceed this progress to be competitive.

Figure 16 below depicts a Hitachi storage roadmap up to the year 2015.

On the other hand, advanced storage technologies such as 3D holographic storage will evolve as alternative in the longer term. Other new technology using nano-mechanical probe-based storage is also being successfully experimented. The following sections described these technologies in greater details.

3.3.2.1 Holographic Data Storage

Holographic storage is a promising high-density storage technology that uses the full volume of the medium to store data. The data is stored in pages of 2D arrays that are written and read out in parallel using spatial light modulators and photo-detectors. This parallelism enables very high access of information. Large numbers of such data pages can be stored in the same volume by multiplexing. The notion of holographic memory dates back to 1963, when Pieter van Heerden, a researcher at Polaroid, first proposed using the method to store data in 3D. Existing media store data in only 2D. Adding a third dimension would make storage devices more efficient.

Holography enables storage densities that can far surpass the superparamagnetic and diffraction limits of traditional

magnetic and optical recording. Conventional technologies record data bit by bit; holography allows a million bits of data to be written and read out in single flashes of light, enabling data transfer rates as high as a billion bits per second. The high storage densities in the order of terabytes and the rapid data transfer rates of more than 100 MBps will position holographic storage as a compelling choice for data warehousing and information processing storage needs.

A huge number of holographic files can be stored in an overlapping manner in the same volume of photosensitive material. Initial indication projected this technique can hold a terabyte of data on a CD-sized disk. DVD, by comparison, has a storage capacity of about 20 GB. Moreover, holographic techniques permit the retrieval of data in parallel, at speeds not possible with current storage methods. Transfer rates of a billion bits a second (at least 60 times faster than current DVD) have already been demonstrated in the laboratory. Such fast access times are possible because the laser beams that are central to holographic technology can be moved rapidly, without inertia, unlike the components of a conventional disk drive.

The slow progress of finding a suitable photo-polymer and photo-refractive material in the past have hindered the development of holographic storage.

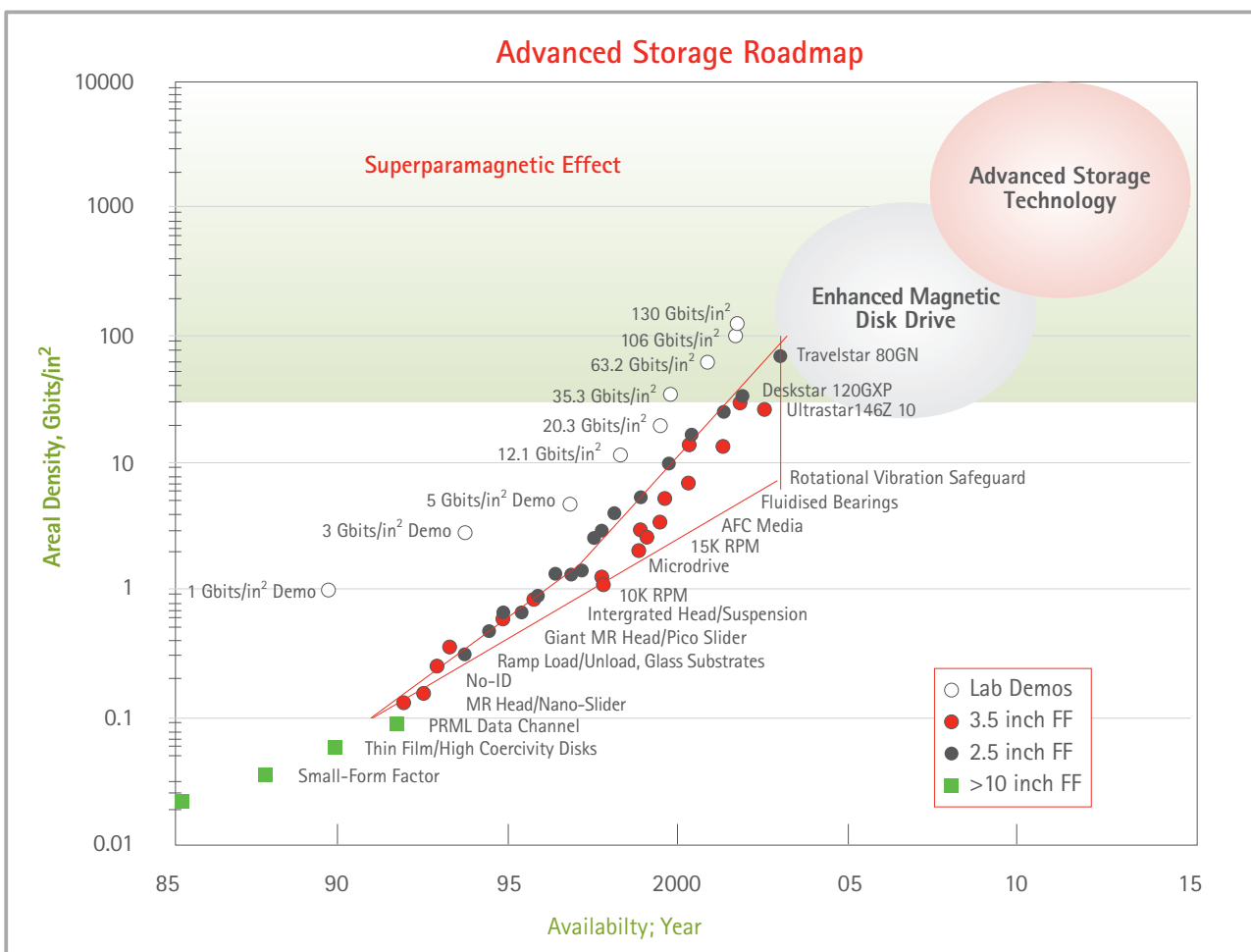


Figure 16. Storage Roadmap

Source: Hitachi Global Storage Technologies

Holographic materials must satisfy stringent criteria; including high dynamic range, high photosensitivity, dimensional stability, optical clarity and flatness, non-destructive readout, millimetre thickness, and environmental and thermal stability in order to achieve good manufacturability and yield. Holographic storage by nature requires high precision optical set-ups with sophisticated opto-mechanical components. The recent years have seen significant progress made in the field of enabling technologies such as materials, sensors, and optical/photonics engineering, bringing holographic storage close to commercialisation.

Holographic storage uses lithium niobate crystals or other novel photo-polymer materials to store data by using the volume of the crystal. Pages of information are recorded as optical interference patterns that form when two coherent laser beams intersect within the photosensitive material. The object beam contains data that has been modulated by a spatial light modulator. Through chemical and physical changes in the medium, a replica of the interference pattern is stored. To read the data, a reference beam will be used to reproduce the optical inference pattern on a photo-detector.

The technology is touted to store huge amount of information in the region of terabytes and still be reliable for at least 50 years. Furthermore, the ability to achieve very high data transfer rate (i.e. 100 MBps) will make holographic technology advantageous for next-generation storage applications. Because holography is a volumetric storage technique, it is well suited to read-only memory and content protection applications. As a result, the first commercial storage devices are expected to be WORM – write-once, read-many 3D storage disk that function as standard interfaces to existing libraries and servers.

Standard on holographic storage has also begun. The Ecma International Standard body has approved the creation of a new Technical Committee (TC44) to undertake standardisation of Holographic Information Storage Systems in Jan 2005. The Scope of TC44 is to maintain an overall view and strategy for standardisation in the field of holographic information storage systems, and to identify and develop standards, technical reports and guidelines in this field. The committee will work on a number of projects, including Holographic Versatile Disc (HVD) cartridges with 200 GB of capacity per cartridge; a 100 GB version of HVD; a credit card-sized Holographic Versatile Card (HVC) with 30 GB capacity per card; and a case for 120 mm HVD read-only disks. These specifications are planned to be finalised by end 2006.

Many companies are starting to develop holographic data storage system. Inphase Technologies just announced its first Tapestry holographic prototype drive with data capacity of 200 GB and transfer rate of 20 MBps on Jan 2005. It planned to achieve 1.6 TB storage with transfer rate of 120 MBps by 2010. Optware, on the other hand, is developing a Holographic Versatile Disc (HVD) cartridge with 200 GB of capacity per cartridge and a credit card-size Holographic Versatile Card (HVC) with 30 GB storage. In Europe, two companies, Optostor of Germany and Optilink of Sweden are also in the race to develop the intellectual property for holographic storage. Also, IBM Almaden Research Center has a research effort in this area as well.

A holographic memory known as Info-MICA (Information-Multilayered Imprinted CARD) is also being developed by NTT. The new memory is capable of storing 1 GB of data within the size of a postage stamp. For data storage, digital data is converted to a 2D image which is then stored using holographic principles, on the special multi-layered media.

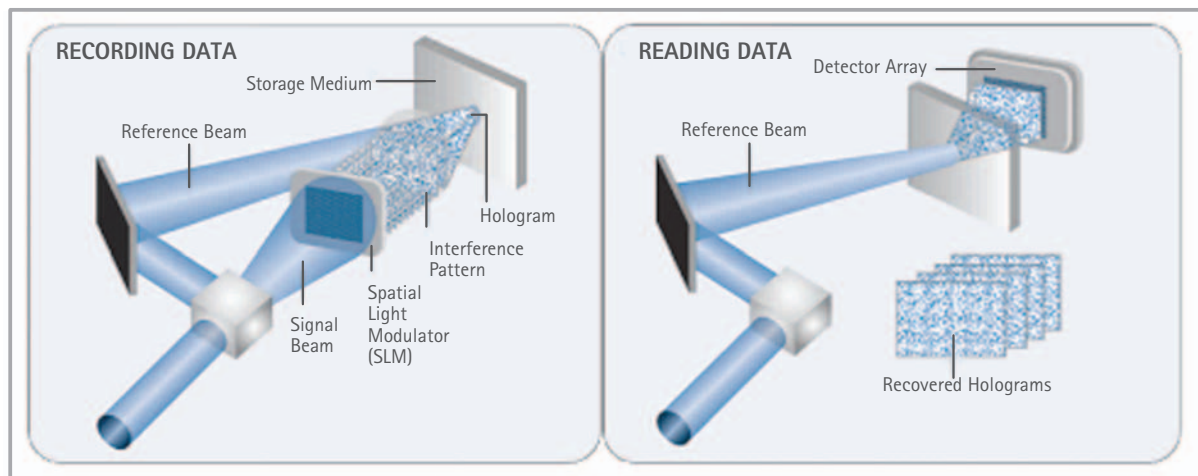


Figure 17. Holographic Storage
Source: Inphase Technologies

For data retrieval, a laser beam will be used to re-convert the interference patterns back to the images and then the original data. A 100-layer prototype has been created along with a prototype drive for reading the data.

3.3.2.2 Atomic Probe-based Data Storage

A potential high-density data storage technology expected to commercialise in 2010 is the "millipede" thermo-mechanical probe storage system. This technology also known as the Atomic Force Microscopy (AFM) thermo-mechanical storage was first conceptualised by IBM in 2002. It works using a modified AFM setup, punching indentations as small as 10 nm in diameter into a thin plastic film coating on a silicon substrate of a few nanometres thick. The indentations represent individual stored data bits that can then be read by the same tip.

Back in 2002, IBM developed this experimental millipede system using a 32 by 32 cantilever array (1024 probes) on a 3 mm by 3 mm silicon based. This technique has demonstrated the ability to achieve data densities of 200 Gb/in². Millipede could pack 10 to 15 GB of data, compared to flash memory which is limited to 1 to 2 GB of capacity into the same tiny format without requiring more power for device operation. The next millipede prototype, which was due to be demonstrated in 2003, is slated to have four times more probes, a 64 by 64 array (4096 probes) in a 7 mm² area.

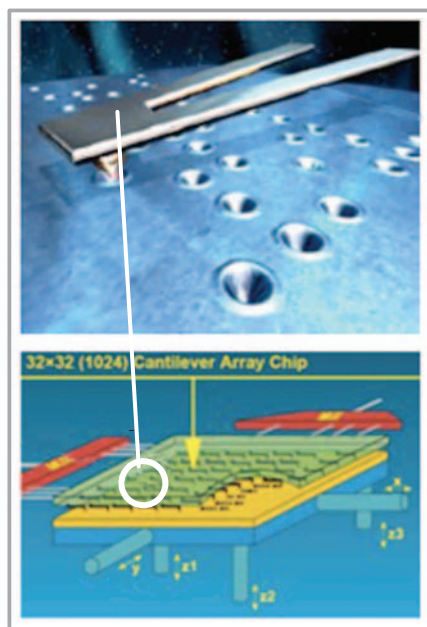


Figure 18. Millipede Nano-Probe Storage System
Source: IBM Zurich Research

The millipede technology is suitable for use as high density storage for portable media players. However, critical issues that need to solve are tip and medium wear, data rates, overall system robustness and suitability for large scale manufacturing.

3.4 Information Display

Display plays an important role in IT, providing visual infotainment for users. Nanotechnology can be exploited for display technologies in enabling low-power, low-cost large format screen with wide viewing angles, as well as flexible display such as e-paper that can be carried about anytime and anywhere in any forms. With nanotech, displays can be made physically slimmer, lighter and more durable than any existing technologies. These features are important to support the future ubiquitous computing environment.

Existing Display Technologies

Current flat panel display technologies are mainly using liquid crystal (LCD) and plasma display (PDP). LCD was the first flat panel display family to challenge the long dominance of CRT in TV monitor and computer screen market. Both monochrome and colour LCD are made of a cell that contains liquid crystal material in neutral state of liquid and solid, sandwiched between two glass plates, thus enabling very thin display. Furthermore, it consumes less power and causes little eye strain and fatigue as well as being less vulnerable to electromagnetic fields compared to CRT monitor. The early product, passive-matrix super twisted nematic (STN) LCD, was not too successful as it could not produce clear colours, but an active-matrix alternative, called thin film transistor (TFT) was developed later and started to offer colours as sharp as CRT, quickly gained market shares. Although LCD has been around for some time in the flat-panel display, it still revealed as many shortcomings like a narrow viewing angle and somewhat slow response speed. LCD also needs backlight and colour filters because liquid crystal cannot create colour images by itself, and production cost is still high.

PDP, which started to make its commercial debut around 1990 and has rapidly gained global foothold especially in the large-sized display market. PDP generates data on the screen using light from plasma, generated during gas discharge and it has advantages fit for making a large-size monitor, typically bigger than 40" across diagonally. Because PDP is self-emitting display, it provides wide viewing angle more than 160 degrees and free from magnetic fields as well as boasting outstanding colour reproduction.

The attractiveness of using large flat panel display for home entertainment is becoming more apparent as multimedia and gaming are fast gaining widespread popularity. This display market is currently dominated by the matured CRT technology, with several others such as Plasma Display Panels (PDP) and Liquid Crystal Display (LCD) also vying for market dominance.

3.4.1 Nano on Future Information Display

Nanotechnology is currently being exploited to develop future flat panel display based on carbon nanotubes. The impetus is really to target large screen display market as carbon nanotubes display can improve picture clarity and allow faster responses rate. Applications could include high definition TV, large wall mount displays and signages.

Nanotechnology can also be applied to enable a revolutionary new type of display that is flexible and portable such that it can be rolled, folded and worn on clothing and carried around easily. This can be realised through exploiting the properties of the nanomaterials and organic polymer (such as plastic) as base material, instead of glass. With the possibility of flexible display, newspapers, magazine, catalogue, etc. could be transformed into smart digital paper, and with wireless technologies integrated, it can allow users to access information, anytime, anywhere. Many different form factors could also be developed to suit various types of cool mobile targets. Most of these displays will be power-efficient, allowing users to use these devices continuously for long period of time, thus enhancing end-users experiences.

Going forward, nanotechnology will also enable small format display for mobile devices using organic LED and carbon nanotube field emitter. Products based on these technologies consume very little power while providing very high clarity images. To enable true virtual presence, researchers are also exploring interactive 3D holographic display in the longer term. Table 5 below summarises the landscape of display technologies.

3.4.2 Flat Panel Display Development

Carbon nanotubes (CNTs) have attracted considerable attention as a field emitter material due to their excellent field emission characteristics, strong chemical stability, and high mechanical strength. Despite a great deal of effort to realise applications of CNTs, it is expected that the first application of CNTs with a large commercial market would be electron emitters for field-emission displays (FEDs). FEDs are characterised by superior display performances such as fast response time, wide viewing angles, wide operation temperatures, cathode ray tube (CRT) like colours, ultra-slim features, low cost, and low-power consumption.

CNT FED emits electrons under the influence of an electric field, just like CRT. It is different from CRT in that it uses numerous tiny carbon nanotubes as electron guns to emit electrons which then collide with the red-green-blue phosphors, illuminating the million of pixels to form an image. CNT FED has the attributes of achieving very thin and light display, faster response times than LCD, wider viewing angle and low power consumption. Colour FED has been demonstrated and proven workable and companies are beginning to develop CNT FED, with the vision to scale up for large TVs display.

The use of CNT FED has been investigated for many few years but the difficulty has been to create structure that produce adequately focused emissions as well as to achieve uniform brightness. According to Japan's R&D Association of Future Electronic Devices, "CNT FEDs tend to short, destroy quickly and degrade far faster than the tens of thousands of hours of reliable operation needed for commercial acceptability." Materials selection for field emitters is also very critical and molybdenum is one of the most common materials used today.

Technology	Research (Blue sky)	Development (Commercial prototype)	Emerging (New kid in the block)	Established in the market	On the decline
Flat panel display (FPD)	Nanodisplay-NEMS Molecular display	Carbon nanotube FED	Small OLED	LCD PDP - Plasma (Microdisplay - MMA MEMS)	CRT LCOS
Flexible display	Carbon nanotube	OLED flexible display Other Polymer display	Electrophoretics (Gyricon SmartPaper, E-Ink)		
3D display		3D holographic display			

Table 5. Technology Scan (Display Technologies)

At present, the main applications of CNT FED are mainly targeting small size colour TVs, industrial products and computers screen. FED is expected to compete with TFT-LCDs in the areas of notebook PCs or CRT monitors. Telematics applications for car navigation system and medical equipments are expected to benefit from FED in many cases. For televisions, FED is targeting mid to large size (20" to 40") television/wall display in the introductory phase. It is then expected to scale upward to very large size TV and wall displays that are more than 40".

Surface-conduction Emission Display (SED). SED uses a thin film of palladium oxide as an electron emitter instead of the spindt tip used in the FED. It has several advantages over the FED, particularly in the manufacturing stage, which uses a combination of ink-jet and silk-screen printing, requires no semiconductor technology and does not need to be performed in vacuum or special gases. Its ability to scale up with low manufacturing cost will make it attractive for large display and high definition TV. The SED also consume less power than FED. Both Canon and Toshiba have formed a joint venture to commercialise display based on this technology.

Market players. Various techniques are used by different companies to develop the CNT FED. Motorola, for instance works on nano emissive display (NED) for 50" TV display, using a method that can control the length and diameter of the CNT, and precisely place them individually on a surface material. Samsung SDI has produced several generations of FED prototypes, including a 9" colour display. Its next FED is a 30" display for digital televisions. Applied Nanotech Inc. (ANI), a subsidiary of Nano-Proprietary has demonstrated a 14" full colour TV proof-of-concept based on CNT FED in Aug 2004 and is planning to demonstrate a 25" CNT TV soon.

According to Japan's Ministry of Economy, Trade and Industry (METI), the global FED market scale is estimated to reach US\$5 billion to US\$22 billion by 2010, surpassing the PDP market. The optimistic forecast is based in part on the increasing R&D investment from companies in Japan and South Korea. The cost of 42" FED panels should stay at US\$450, lower than that of 42" PDPs, estimated to be US\$680, according to Japanese companies. Companies from Japan and South Korea have developed more advanced FED technologies and produced prototypes that run on 60 to 80 watts of power.

3.4.3 Flexible Display Development

Flexible display is a fusion of chemistry, physics, material and electronics technologies. It is fast gaining popularity as a method of producing futurist flexible screen on plastic substrate instead of on rigid glass substrate. It also holds potential to be integrated with electronics devices as plastic

electronics for on-screen circuitry, reducing overall size, complexities and cost. The market opportunities are so broad that even major electronics, plastics, and printing companies are interested in the development of these displays for consumer applications.

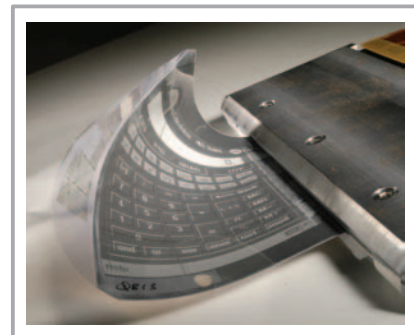


Figure 19. Flexible Display

Source: Philips Research

Flexible display will impact the way information is communicated in the future. It could be fold or roll into different shapes and sizes, suitable for portability. As electronic paper, it could save news publishers on the massive printing and distribution cost. The technology will find applications in e-books, e-newspapers, e-magazines, e-catalogues, e-maps, programmable signage, fashion/wearable, consumer products, etc. along with the digital transformation of new media era. It can be used as smart display stickers for items tagging in warehouse and supermarket. In education application, paper-based textbooks could be transformed to an all-purpose e-book, allowing students to download contents on-demand instead of bringing textbooks for classes. For business travellers, smart rollable displays provide portability and convenience to access information anytime, any place. These displays could be used as digital map for travel-guide. In the long term, flexible display could also be woven with fabric to form a part of the wearable computing system. The following highlights some of these technologies:

Smart Paper. The smart paper is actually made of two sheets of thin plastic with millions of tiny bichromal beads embedded in between. Each bead has different colour on each hemisphere and carries either positive or negative charge. The hemispheres are also charged differently. Under an electrical field, they rotate to present the image as different colour to the viewer. This image stays in place until a new voltage pattern is applied. Resolution is currently limited to 127 dots per inch, however, and the lack of colour displays is expected to limit the field of applications. Gyricon has commercialised a reusable display material like paper that is electronically writeable and erasable. The product, the SyncroSign Message Board, a battery-powered wireless-network sign incorporates a rewriteable display medium originally developed at Xerox PARC.

E-Ink. The principal components of e-ink are millions of tiny positive-charged white particles and negative-charged black particles microcapsules suspended in a clear fluid. When a negative electric field is applied, the white particles move to the top of the microcapsule where they become visible to the user. This makes the surface appear white at that spot. At the same time, an opposite electric field pulls the black particles to the bottom of the microcapsules where they are hidden. By reversing this process, the black particles appear at the top of the capsule, which now makes the surface appear dark at that spot. E-Ink, Philip and Sony have also announced the first consumer application of an e-paper display module in Sony's new e-Book reader, LIBRIé in March this year. The LIBRIé reader was designed to allow readers to download and store information to be read later, using a light, low-power display. It is expected to compete with tablet PCs and other means of displaying downloadable media.

Electro-wetting. Another approach is the use of black oil and water trapped in tiny cells to create black and white pixels developed by Philips Research. An electric charge makes the water push the black oil to the side, exposing a white surface underneath.

Organic Light Emitting Diode (OLED). These are devices that use organic materials to produce light through electrical stimulation. The term OLED includes polymer light emitting diode (PLED), small molecule organic light emitting diode (SMOLED) and dendrimer technologies. OLED is self-emitting and do not require backlighting, polariser, or diffuser, thereby greatly reduces the size and weight. In addition, they offer a wide viewing angle and low power consumption. OLED is fundamentally different from LCD in that they are made by sandwiching a layer of organic material between two electrodes. When a charge is applied to one electrode, it flows through the organic material, causing it to glow. Flexible OLED uses flexible thin substrates that significantly reduce the weight of flat panel displays and provide the ability to bend a display into any desired shape. OLED products will be used for mobile handhelds and high-end consumer electronics displays, and OLED will be further developed as flexible display for electronic books, papers, signage and on wearable textile.

The main challenge that needs to be overcome is the extreme sensitivity of OLEDs to moisture and air. Other issues include the difficulty of producing larger size OLED display with high manufacturing yield. More works need to be carried out on extending the organic material operational lifespan and efficiency. Colour versions will take more time to develop, as integrating colour filters on the top of the display is a more complicated process. Integration with wireless technologies, while at the same time, maintain its uniqueness in term of flexibility and power consumption will be a major challenge to overcome.

Polymer Light Emitting Diode (PLED). PLED is one of the more advanced OLED display technology. It uses organic polymers which emit light when stimulated electrically. The technology, discovered in Cavendish Lab at Cambridge University has major advantage of being solution processable, and can therefore be applied to substrates using techniques such as ink-jet printing to enable very low-cost manufacturing. The joint development effort between Cambridge Display Technology (CDT) and Sumitomo Chemical is expected to herald in a potentially disruptive technology for the future flat panel display market.

Small Molecule Organic Light Emitting Diode (SMOLED). SMOLED is the earliest class of OLED exploiting the light emitting property of organic chemicals. Developed by Eastman Kodak, it is more power efficient than LCD and had been successfully used in most commercial product to date, especially in mobile phones' screen. Production of small molecule OLED displays is however more complex than the polymer OLED displays. The disadvantage of requiring complex and expensive production methods such as vacuum deposition will limit its application in the small display product segment.

Dendrimers. Originally developed by Opsy, dendrimer OLED is a class of molecule featuring a high degree of branches and can be designed to offer specific performance characteristics. The technology was later acquired by CDT in 2002 as a strategic move to develop future generation of OLED display technology.

Industry Outlook. A European group, called FlexiDis, is the latest consortium formed to research, develop and demonstrate the viability of high-performance flexible displays. It is funded under the European Union's 6th Framework Program as part of the IST (Information Society Technologies) priority. The group plans to develop a flexible and low-power electronic paper display that enables mobile access to newspapers, e-mails and maps, and could eventually be rolled up to fit inside a tubular container. The group also aims to develop a 'video-photograph' which is a paper-thin robust flexible display to enable users to view full-colour video and still images.

Korea Electronics Technology Institute (KETI) has also demonstrated an electronic paper made from ordinary paper coated with thin layers of plastic electronics. The device was fabricated by coating a sheet of commercial inkjet paper with the plastic parylene to protect the paper from moisture and provide a uniform surface, then applying a second layer of parylene followed by layers of nickel, three types of organic material and a metal top layer. The method could be used to make all kinds of roll-up displays, including e-paper, e-maps, and advertising billboards.

Singapore is also at the forefront of OLED research and development. The OLED Network of Singapore (ON-Singapore) is an initiative spearheaded by the Institute of Materials Research and Engineering (IMRE), with the support from the Singapore Economic Development Board (EDB) and Agency for Science, Technology and Research (A*STAR). This network aims to bring together industries and research organisations that are interested in developing OLED technology in Singapore. Currently ON-Singapore has more than 30 local and foreign corporate members, including the major OLED manufacturers in Singapore, Innoled Pte Ltd and Ness Display.

3.4.4 3D Volumetric / Holographic Display Development

The development of 3D visual system is accelerated by the improvement of computing power and storage due to miniaturisation, material science and nanotechnology. True 3D imaging method includes floating 3D image or holographic 3D methods: by projecting lasers on a rapidly spinning screen to create a floating 3D image, or by recording the image information through the beams from the object and diffraction patterns formed by the reference beam on a special material, and projecting the reference beam onto the screen to create hologram.

The problems with graphic and visual images today are mainly restricted to displaying flat images. Sometimes images may look 3D, but these are mostly generated using 3D visualisation softwares, and not really create using holographic techniques. Normally, human visual system will perceive a flat plane of pixels when viewing images on most display systems, unless viewing a manipulated image with a special goggle.

Compared to current planar displays, 3D displays will provide a realistic presence of the subject. 3D display applications are wide-ranging, from improving industrial design to medical imagery, to virtual educational, entertainment, and many more. Real 3D imageries are critical in numerous applications such as visualising and understanding of complex data for bioinformatics and nanotech simulation purposes. Key uses for 3D displays include molecular modelling, surgical planning, collaborative design and playing games. It is expected that gaming will pave the development of 3D displays for the consumer market. In the longer future, it is not impossible to imagine future display technologies rendering true 3D objects in real-time. Perhaps, one day we will be surfing Internet in a 3D environment!

Major projects. Some projects under the EU FP6 programme include Coherent (Collaborative Holographic Environments for Networked Tasks), Holonics (Holographic and Action Capture Techniques) and Hologvision (Holographic 3D

visualisation) based on emerging optical and opto-electronic technologies. These R&D activities focus on developing next generation holographic 3D displays and inherent 3D applications.

Market development. The 3D Consortium is an important entity working on 3D display. It was founded by five Japanese manufacturers, namely Sony, Sanyo Itochu, NTT Data and Sharp. The consortium has established subcommittees to create technical and safety standards to bring 3D displays to desktops, laptops and mobile phone and also to develop new input/output devices for 3D stereographic displays and create compelling 3D content that will drive the purchase of those devices. The consortium plans to aggressively promote educational activities to encourage widespread application and expansion of 3D.

Hitachi Human Interaction Lab has reported the development of a holographic-like display called *Transpost* system in 2004. The system allows 360 degree viewing of an object rendered in light without the need to wear special glasses. The system uses a combination of mirrors and light to render the holographic image in real-time in an enclosed cylinder. Hitachi has also recently demonstrated an image transmission system, capable of imaging a human being, and transmitting this information over a broadband network to a 3D display in real-time. This could pave the way for applications such as 3D virtual conference with global business partners, remote 3D medical imaging for telematics, as well as 3D performances by artist for entertainment.

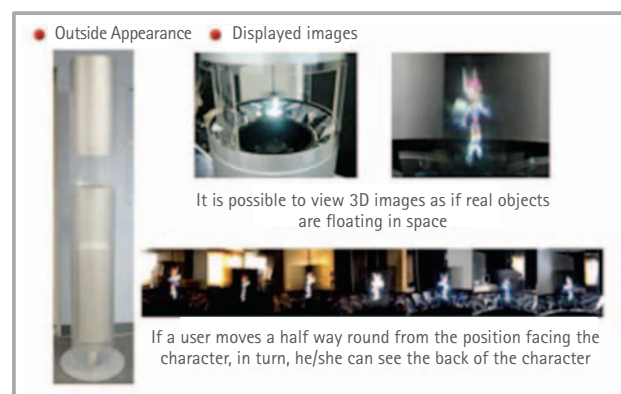


Figure 20. Holographic Display

Source: Hitachi Lab

Holografika, a Hungarian company is also developing 3D display technology. Its proprietary system, known as Hologvizio is targeting medical imaging, air traffic control, design, simulation and gaming applications. Hologvizio is based on holographic geometrical principles to reconstruct the key elements of spatial vision. The pixels, of the holographic screen emit light beams of different intensity and colour in various directions. A light-emitting surface composed of pixels will act as a digital window or hologram and will be able to show any 3D scenes.

Another company, IO₂ Technology has also commercialised 3D display. Its heliodisplay projects TV is able to stream video and computer images into free space. The heliodisplay feature a "floating touch screen" allowing interactivity.

At Chiba University and the Institute of Physical and Chemical Research (RIKEN) in Japan, researchers have developed a hologram generator prototype. The electro-holographic system consists of a special purpose computational chip and a high resolution, reflective LCD panel as a spatial light modulator. With this system, they were able to generate a high resolution hologram. The researchers believed that the technologies will be suitable for real-time 3D applications for television or medical imaging within five to ten years.

3.4.5 Virtual Retinal Display

An interesting visual system known as the Virtual Retinal Display (VRD) has been invented in University of Washington, HIT Lab. One of the unique features of the VRD is the ability to create an image directly on the retina. VRD is potentially useful for applications where hand-free visual operation is necessary and critical, such as for medical and military usages. It can also be developed for immersive infotainment applications on mobile handhelds that are limited by the size of the display screen. This is so especially for mobile devices that are limited in screen size, but require large display to present multimedia entertainment for users. It is also well-suited as head-up display to augment information for future generation cars.

In the VRD system, a coherent light source is used to scan an image directly on the retina of the viewer's eye, creating a full colour, high resolution, high brightness and wide field-of-view images. The graphic below shows the VRD projecting a laser beam carrying the video image through the pupil onto the retina. The point of laser light is scanned horizontally and vertically very quickly, creating the image point-by-point onto the back of the eye.

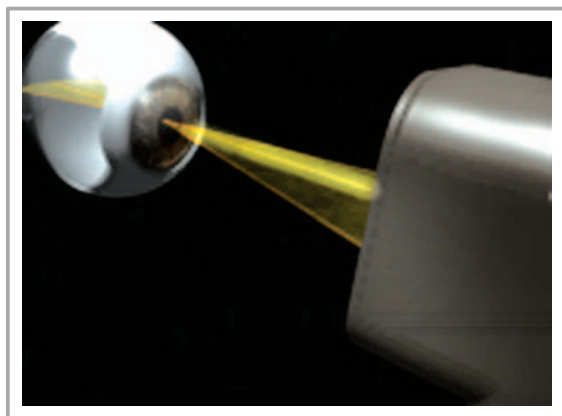


Figure 21. Virtual Retinal Display

Source: Quin Smithwick HIT Lab University of Washington

VRD system can also be further developed for 3D viewing by projecting images into both users' eyes. Each image will be created from a slightly different view point to create a stereo pair. It is also possible to vary the focus of each pixel in the image such that a true 3D image is created. Thus, the VRD has the ability to generate an inclusive, high resolution 3D visual environment in a device the size of conventional eyeglasses. It is not unthinkable that this display could be further improved into an integrated smart contact lens system in the future using nanoelectronics, nano-photonics and nanomaterials technologies. Commercial applications of the VRD are being developed at Microvision Inc.

3.5 Telecommunication System

Carbon nanotubes can also be exploited for use in future telecommunication systems. In wireless communication, nanotube field emitters have been exploited for generating microwaves, potentially improving the efficiency in transmission and sensitivity in reception. It also promises to reduce the size of communication base stations and antenna drastically. In optical transmission, nanotech can increase the tunability of lasers, and both nanoporous silicon and quantum dots hold potential. Nanoscale diffraction grating using photonics crystals can be used to switch optical wavelength. These potentials are further highlighted below:

Nanotube antenna. Nanotubes could be used as antennas to transmit and receive lightwave, using the concept of radio wave communications. Researchers at Boston College, the U.S. Army Natick Soldier Center, Mega Wave Corporation and Florida International University have recently demonstrated the light antenna effect using arrays of multi-walled carbon nanotubes. Instead of transmitting and receiving radio waves, which are at the longest end of the electromagnetic spectrum, antennas of their size pick up the nanoscale wavelengths of visible light. The method could be used to convert optical signals to electrical signals in communications equipment, to carry out optical computing, to detect different wavelengths of light including the infrared wavelengths used in telecommunications equipment.

Photonics crystals. By creating periodic nanostructures out of materials with contrast in their dielectric constants, it becomes possible to guide the flow of light through the photonic crystal material in a way similar to how electrons are directed through doped regions of semiconductors. The period of the structure is related to the wavelength of light for which a photonic crystal will exist, for instance a few hundred nanometres for visible light. These materials are a relatively new discovery, with potential applications ranging from efficient light emitting diodes, low-cost integrated optical devices to quantum computers.

Nano light emitting devices. Scientists at the U.S. Department of Energy's Brookhaven National Laboratory and IBM T.J. Watson Research Center have demonstrated that individual carbon nanotube can emit light through a process called "electron-hole recombination." that is by running an electric current through a carbon nanotube negatively charged electrons in the nanotube molecule combine with positively charged "holes." This development will be critical for future applications in electronics and photonics opto-devices.

Nano-diode. GE Global Research has also reported the development of a diode built from a carbon nanotube. The nano-diode is one of the smallest functioning devices ever made that will enable smaller and faster electronic devices with increased functionality. Under the GE Nanotechnology Advanced Technology program, this diode holds potentials for use as a highly sensitive sensor.

In long range telecommunication system, low cost microwaves amplifiers for higher frequencies operating in the range of 30 GHz to 100 GHz could be developed from carbon nanotubes. These nanotubes could be used as cold cathode, instead of today's hot thermionic cathodes, to produce a new generation of high power transmitters for ground stations and satellites transponders.

3.6 Long-Lasting Power

The previous chapters covered mainly on the infocomm technologies (hardware) enabled by nanotechnology. This section covers a peripheral technology critical to infocomm i.e. power. Without long lasting power, infocomm users will not be able to enjoy true mobile experience.

As products become more sophisticated and functionalities grow, power requirements increase accordingly. In the next few years, mobile handheld and PC makers will be adding more hardware and processing power in handsets, notebooks and PCs to support multimedia applications. Radio and TV tuners/transceivers will be added to mobile handsets to receive mobile broadcasting. These handhelds will be further integrated with application-specific

chipsets and communication hardwares for streaming video, voice recognition, cognitive capability and wireless connectivity. Most of these modules consume huge amount of power, and with the existing power technologies, the power are clearly not enough. To support a future converged intelligent mobile platforms, alternative form of power technologies are needed.

Many R&Ds are currently directed towards exploiting smart nanomaterials and nanotech. There are also long-term researches looking at various methods of harvesting energy from direct conversion and nature. Imagine a possibility of charging your iPod or mobile phone via a rechargeable jacket/clothing powered by solar-nanofibres! Table 6 below lists a landscape of available power technologies suitable for infocomm usage.

3.6.1 Micro Fuel Cell

In recent years, micro fuel cell technology has started R&D for communication systems. Prototypes of micro fuel cell are already developed for mobile devices and consumer electronics products. Due to the high energy density that it promises to deliver (about 10 times more power than existing lithium batteries), it has become an attractive energy source for infocomm products. Mobile phones, PDAs, laptops and digital cameras are expected to create demand for micro fuel cells. By exploiting nanomaterials on fuel cell membrane, even higher efficiency fuel cell could be developed. By 2015, the possibility of not tethered to the wall for power supplies could become real.

In 1990, the industry used Nickel Cadmium batteries which had a charging time of 8 hours and an energy density of 40 Watt hours per kilogram (Wh/kg). Towards the end of the decade, the Li-ion battery was introduced and is widely used in mobile devices today. It has a typical charge time of 3 hours and specific energy of 150 Wh/kg. By comparison, fuel cells can offer charging times of a few seconds and a massive 1000 Wh/kg.

Technology for Mobile/IT apps	Research (Blue sky)	Development (Commercial prototype)	Emerging (New kid in the block)	Established in the market	On the decline
Renewable (Refillable, Regenerative or rechargeable)	Electrokinetic properties of liquid carbon nanohorn & nanotubes	Ethanol Fuel Cell SOFC	Micro Fuel Cell (DMFC)	Li-ion Li-Polymer Alkaline Others Chemical batteries'	Ni-Cad NiMHd
	Energy from human (body heat, talking, breathing, nose/chest, walking, hand gesture, static) Carbon nanotube based ultra-capacitor	Thermal power Micro-batteries			
Unlimited	4th Gen biological solar cell	Multi-junctions New alloys Nano solar 3rd Gen organic solar/Dye-sensitive		Solar cell 1st, 2nd Generation	
	Biomass Nuclear (beta particles)		Wideband EM employing nanotech	Narrowband Electromagnetic conversion	

Table 6. Technology Scan (Power Technologies)

Particularly, direct methanol fuel cells (DMFC) technology holds one of the most promising candidates over other type of fuel cells. A proven technology, it has been heralded as the chemical power source of the future. Fuel cells produce electricity from potential chemical energy without combustion, through an electrochemical process that combines oxygen and hydrogen to produce electricity, heat, and water.

Unlike other types of fuel cells (like generic Polymer Electrolyte Membrane (PEM) fuel cells) which require pure hydrogen as a fuel, DMFC enables this electrochemical process without the need to reform complex hydrocarbon fuel molecules into pure hydrogen. Efficiencies of about 40 to 50% are expected, operating between 50 to 100 degree celsius.

Nanotechnology impact on fuel cells. Recently, the National Institute of Standards and Technology (NIST) under the Advanced Technology Program awarded Carbon Nanotechnologies, Motorola and Johnson Matthey Fuel Cells a US\$3.6 million grant to develop carbon nanotube electrodes for micro-fuel cells in order to meet the ever growing demand for more power and longer operation in portable electronics devices. This program aims to exploit the unique properties of single wall carbon nanotubes (SWNT) in order to achieve significant breakthroughs in fuel cell performance in term of output efficiency.

NEC is also working on carbon nanohorns (CNHs) which have the same carbon atom structure as carbon nanotubes. The main characteristic of the CNH is that it is able to aggregate into a large area of about 100 nm, suitable for use as an electrode for a fuel cell and easy for the gas and liquid to permeate to the inside. Nanohorns can also be easily prepared with high purity and thus it is expected to become a low-cost raw material, especially for fuel cells.

NEC called it the next frontier for developing nanobatteries with up to 10 times the capacity of the best lithium ion batteries. The horns can be easily developed at room temperature, and NEC can produce them with a 90% yield at a rate of 50 grams/hour. NEC is currently developing cell phone batteries fuelled by nanohorns, and Nissan Motors has invested US\$300 million in it.

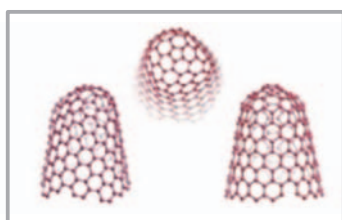


Figure 22. Carbon Nanohorns
Source: NEC

Challenges. Today the high cost of developing micro fuel cell for cost competitive small form factor IT products has not spurred enough competition in this area. Technical issues still prevail. DMFC has 'methanol crossover' effect that must be overcome before it can be used as a viable power source. This is because the polymer membrane separating the anode and cathode in the DMFC allows methanol to 'cross over' from the anode chamber into the cathode chamber. This effect causes methanol to oxidise in a competing reaction to the reduction of the protons, thus reducing the overall cell potential. Solutions to this problem of methanol crossover at the moment consist of either modifying the membrane so that it is only permeable to protons, or to modify the catalyst used at the cathode so that it is only selective to oxygen reduction and avoids oxidation of the methanol. Nanotechnology plays an important role in solving this problem.

Reducing the size and weight of the fuel cell is also a challenge that needs to be taken into account. The cell needs to function at ambient temperatures and pressures to avoid costly and bulky enclosures. The fuel itself must be easy to store as a high pressure hydrogen gas canister is not the safest item to carry in your pocket!

Besides technical hurdles, there are also regulatory hurdles that need to be addressed before DMFC fuel cells are allowed on aircrafts. Methanol is a flammable liquid and is therefore a controlled substance by the Department of Transportation (DOT). However, in Apr 2002 the DOT ruled methanol fuel cells would be permitted for air transport. However, the FAA has yet to rule on the safety of methanol in the cabin area of the aircraft. Furthermore, airlines have yet to determine if they will permit the substance on their aircraft indicating they would not permit the device if it could interfere with the aircraft handling.

Standard development. The International Electrotechnical Commission (IEC) has formed a working group to draw up standards that will ensure compatibility between micro fuel-cells. WG10 is tasked with setting an international standard to ensure compatibility between the fuel cells and their fuel cartridges. WG10 is the third working group formed as part of TC105 that is looking at micro fuel cell standardisation. The others are WG 8, which is looking at safety standards, and WG 9, which is looking at performance standards. These standardisation works will pave the deployment of micro fuel cell in music players, digital cameras, and other devices for mass deployment.



Figure 23. Fuel Cell Notebook
Source: NEC

Market development. Many R&Ds are currently directed towards DMFC. However, cost and regulatory concerns are still not favourable for mass markets adoption. Companies, notably the Japanese, such as NTT DoCoMo, Fujitsu, Hitachi, Toshiba and NEC have their development roadmap in the next few years to commercialise them. NTT DoCoMo has recently developed a prototype mobile phones battery charger with Fujitsu Lab, with the aim to commercialise it in 2006. It also expects the first mobile phone with built-in fuel cell charger could be ready by 2007. Both NEC and Toshiba have also unveiled prototype fuel cells for laptop computers in 2004, but mass commercialisation could only be viable in 2007.

A recent Allied Business Intelligence (ABI) research report: ("Micro Fuel Cells: Market Challenges and Opportunities for Cameras, Laptops, PDAs and Wireless / Mobile Devices") estimated that micro fuel cell (MFC) technology will power nearly 15% of the world's laptop computers as early as 2012. The market for fuel cell powered laptop will grow rapidly from 2008 to 2011 with 120 million laptops shipped, with a market value of US\$1.2 billion by 2012.

3.6.2 Ultracapacitor

Ultracapacitors, also known as electric double-layer capacitors are a new class of advanced batteries that hold potential for powering future electronics. Unlike traditional batteries that use chemical to deliver power to your computing gargets, it uses electrical charges to store and regenerate energy. In comparison with batteries, ultracapacitors are more compact and can supply more power for a given weight, charge in seconds instead of hours and function at more extreme temperatures. They are also more efficient and can last longer than chemical batteries. The technology works on the polarisation of an electrolyte between the high surface area electrodes, and the extremely small charge separation hold the electrics charges.

Today, ultracapacitors are mainly targeting the automobile market. A South Korea company NessCap has developed an impressive record of 5 kilofarads super capacitor to power cars and buses. Tokyo-based Ricoh Co. is using them in copier machines to store the energy needed to warm up the machines quickly, minimising time spent in the energy-wasting standby mode. Makers of high-end car stereo amplifiers are using ultracapacitors to deliver the surges of power demanded in car audio system. By exploiting better nanomaterials in the development of ultracapacitor, it is not impossible to use it to power mobile phones, PDAs and laptops devices.

The critical components behind the ultracapacitor are the selection of appropriate electrolyte with low ionic resistance and high performance electrodes. Research is ongoing on technologies that could improve the performance, while lowering the cost of the electrolyte. At MIT's electromagnetic laboratory, some projects are ongoing to investigate the use of carbon nanotubes as electrodes. The researchers are

creating materials in which the nanotubes grow out perpendicularly from a substrate. The nanotubes will become electrically charged to attract oppositely charged ions in the electrolyte. The nanotubes will be spaced to hold these ions. The advantage is that this arrangement can trap more ions, enough to raise the energy density of an ultracapacitor 100-fold, according to the researchers.

Already ultracapacitor products are available in the market for niche application. Maxwell Technologies is offering a range of small ultracapacitors for applications in toys, tools and consumer electronics products providing standby, backup and burst power. The boostcap ultracapacitors are slated to deliver up to 10 times the power, last up to 10 times as long and ability to operate in extreme temperature as compared to normal batteries. Going ahead, research works will be looking more in the integration of ultracapacitor with fuel cell technologies.

3.6.3 Solar Power

Photovoltaics (PV) are solar cells that convert sunlight into direct electrical current. PV cells are grouped into modules and arrays, which can then be used to charge batteries, operate motors, and to power mobile platforms and portable devices. PV cells generate electricity by absorbing photons from sun and direct the resulting energy to move an electron from the low energy valence band in a material to a higher energy conduction band where it is free to flow.

Development in Solar Cell Technologies. The first generation of photovoltaic cell is based on crystalline silicon. Large, high-purity single crystals are used to make high-performance cells capable of converting some 20% of incident sunlight into electricity. Recently, SunPower Corporation announced that its A-300 crystalline silicon solar cell has achieved an efficiency of 21.5%. Even higher efficiencies - roughly 30% have been demonstrated. But these types of high-end cells, which have proven to be durable in space applications, are very costly because of demanding and energy intensive crystal growth and manufacturing processes. Research are ongoing to find better ways to improve the efficiency of PV cells that can absorb and use a higher spectrum of wavelengths of sunlight from infrared to visible light to ultraviolet.

Future outlook. A recent breakthrough arising from nano research on solar cell was reported from Los Alamos Research Lab. The technology based on a phenomenon known as carrier multiplication, has achieved a conversion efficiency of more than 60% using lead selenium nanocrystal to increase cell's energy production by making each photon move two electrons. The technology is expected to be ready for commercialisation within 2 to 3 years.

The second generation of solar cells are mainly developed from thin-film semiconductor. These thin-film solar cells, with commercial availability in the mid-80s, have for several years been considered to be a promising alternative to the silicon devices. It has potential for cheaper production costs with efficiencies generally up to 20%. Thin-film solar cell based on Copper-Indium-Gallium-Diselenide (CIGS) is important for terrestrial applications because of high efficiency, stable performance and low cost potentials. The CIGS solar cells are also promising for space applications due to their excellent stability against high energy irradiation and higher power output. These cells continue to improve in efficiency at a much lower cost.

Future outlook — New Alloys. Researchers at Lawrence Berkeley National Laboratory announced that they discovered a single system of alloys incorporating zinc manganese tellurium (ZnMnTe) in such a way that a single junction of the material may be able to respond to virtually the entire solar spectrum. The researchers found that in the case of zinc-manganese-tellurium, instead of splitting the conduction band, introduced oxygen molecules formed their own band well separated from the original conduction band. The material could lead to relatively inexpensive, highly-efficient solar cells. Such cells would be much simpler than today's high-end multi-junction solar cells because the three bandgaps reside in a single material. Solar cells based on this can achieve about 50% efficiency, compared to about 30% demonstrated by conventional silicon cell today. In another development, a US start-up, Konarka Technologies has produced a flexible thin-film solar cell with conversion efficiency greater than 7%, and expecting to achieve its next milestone of 10% efficiencies.

The future of renewable power source — Toward plastic and biological power. The development of third generation solar cell, i.e. Dye Sensitive Solar Cell started mostly in 2000. Based on artificial photosynthesis system invented by Prof Michael Graetzel in Switzerland, this type of cell will be flexible, using organic or polymeric molecules as the photovoltaic active material. Recent results of about 2 to 3% efficiencies have been reported.

An innovator in developing plastic solar power technology for future embedded devices is Konarka Technologies. It has recently developed a process that coats strips of plastic film with titanium dioxide and light-absorbing dye. Power is produced when light hits the dye and the electrons in the titanium dioxide flows. Konarka expects to deliver its first commercial solar cells, designed for use with consumer electronics like laptops by end of the year.

In the longer term, solar cell will be developed based completely on biological photosynthesis process. Researchers at the MIT and the University of Tennessee in Knoxville are already working on a new type of photovoltaic cell using a protein found naturally in the green vegetable leaves. The researchers isolated these microscopic protein structures, measuring about 5 nm in size, from the plant and sandwiched them between a thin gold film attached to a sheet of electrically-conductive, transparent material on one side and an organic layer of conductive material on the other side. When the researchers directed sunlight on to the sandwich, the proteins generated electrons which passed from one layer of the sandwich to the other and produced a tiny electrical current.

The U.S military, which is funding the project through the DARPA and the Naval Research Labs, is also hoping that one day biological-based solar cells could provide power to tiny robot spy craft or even woven into soldiers' uniforms to lessen their dependency on batteries for radios and other high-tech battle suits. The following diagram summarised the development of solar technologies.

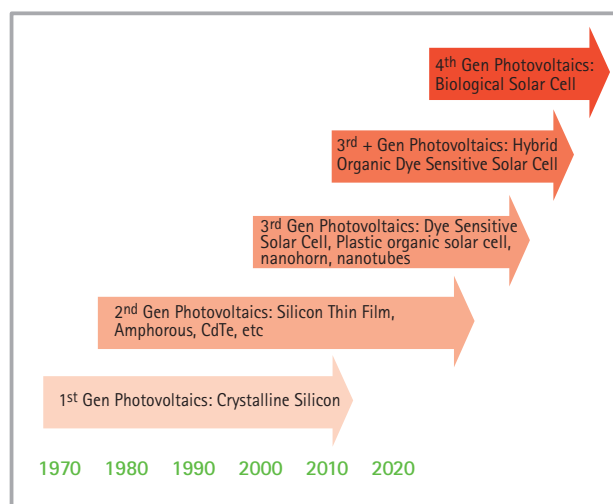


Figure 24. Solar Power Technology Development

Dye Solar Cell (DSC). DSCs are based on the mechanism of a regenerative photo-electrochemical process. It differs from classical thin-film cells where light is absorbed in a semiconductor layer, absorption occurs in dye molecules adsorbed at a highly porous structure of nano-particles of transparent TiO_2 . An efficiency of 8% has been reported.

Nano solar cells. Chemists at the University of California at Berkeley are researching on polymer solar cells flexible enough to paint onto any surface and potentially able to provide electricity for wearable computers and other low-power devices. The prototype solar cell they have created comprised of tiny nanorods dispersed in an organic polymer. These rods act like wires, absorbing light to create an electric current. Current efficiency can only achieve about 1.7%. A layer only 200 nm thick is sandwiched between electrodes, and can produce, at present, about 0.7 volt. Although nanorods solar cell technology is cost effective to manufacture, its efficiency is limited, about one tenth of current silicon solar cells technology.

Organic Solar Cell (OSC). For OSC, the organic materials mimic the photosynthesis process in plants. In plants, the absorption of sunlight by the chlorophyll dye creates a charge separation, converting carbon dioxide, water and minerals into organic compounds and oxygen. OSCs use light-sensitive polymer like polythiophene; when sunlight strikes the cell, an electron is expelled by an excited dye molecule and travels through a semi conducting material to become electrical energy. For large-scale manufacturing, key issues poised include long-term stability, maximum obtainable solar efficiency and industrial production methods. Reproducible solar efficiency of 3% has already been reported. Both DSC and OSC are new technologies with potential to enable low cost production compared to conventional silicon cell.

3.6.4 Electromagnetic Conversion

Electromagnetic conversion of EM/RF energy to electrical power a next generation direct energy conversion concept based on antenna-coupled diode technology. ITN Energy Systems is one such company that developed a high-efficiency direct conversion device (DCD) that converts available electromagnetic radiation (i.e. active emitters, solar spectrum) directly into DC electric power based on an antenna coupled diode. ITN's DCD consists of an optical antenna that efficiently absorbs incoming EM and couples the energy into a high-speed quantum tunneling diode. Unlike traditional semiconductor photovoltaic cells, ITN's DCD is not fundamentally limited, with conversion efficiencies greater than 85% theoretically possible. An efficient DCD would revolutionise world energy resources, creating new

applications in both the military and civilian sectors. Although integrating optimised components into a functioning device is challenging, current nanotechnology breakthrough in atomic layer deposition and large area nano-patterning technologies make the DCD concept feasible.

3.6.5 Thin Film Batteries

Imagine power source that are thin and flexible, and ability to integrate with electronics circuits in the same manufacturing process. These are thin-film micro-batteries that hold great potential for small-form factor electronic devices, such as RFID, tags, paper power applications. An Israeli company, Power Paper has commercialised this technology to enable the mass production of low-cost, thin and flexible energy cells capable of powering a host of applications.

The cells are composed of two non-toxic, widely-available commodities: zinc and manganese dioxide. The cathode and anode layers are fabricated from proprietary ink-like materials that can be printed onto virtually any substrate, including specialty papers. The cathode and anode are produced as different mixes of ink, so that the combination of the two creates a 1.5-volt battery that is thin and flexible.

The technology can be laminated onto smart cards and other micro-devices and replace ordinary tickets and tags. It can also be used as smart labels for diagnostic medical devices. Power paper has to-date developed a UHF RFID based on this technology.



Figure 25. Ultra Thin Paper Battery
Source: Power Paper

3.6.6 Body Driven Power

In recent years, more handheld devices were introduced onto the consumer marketplace. Almost all of these products use batteries as a power source because this is an easy, small and relatively high energy density way of powering the product. The main disadvantage of batteries is that they contain a limited amount of energy and have to be replaced or charged. From an environmental point of view; these batteries have to be disposed as chemical waste.

An alternative way to overcome these problems is the use of human energy as a power source. The human body can serve as an inexhaustible, green power source for some low power handheld devices. This can be done by using smart material technologies to harvest energy from human kinetic activities and convert them into useful power sources. Some forms of activities include walking, exhalation, arm motions, breathing band (chest), thermoelectric from body heat, blood pressure, etc.

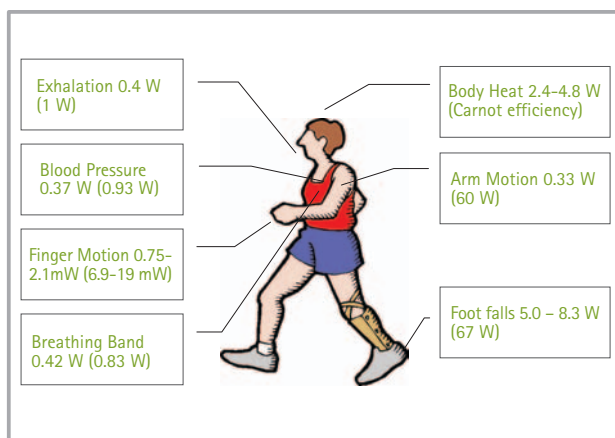


Figure 26. Body-Driven Power Sources

Source: Data from IBM Journal, Vol 35, T. Starner

Piezoelectric devices. Piezoelectric substances, like some ceramics, also generate electrical energy from mechanical strain. This technology can be used in devices that generate electricity from walking. Researchers from IBM have found about 5 to 8 watts of power could be tapped from this motion. However, a major issue that has to be overcome is the durability of these devices over prolonged periods of use. Nanomaterials research could improve the efficiency of piezoelectric devices.

Bio-synthesis. Researchers in Japan are developing a method of drawing power from blood glucose, mimicking the way the body generates energy from food. The battery is based on an enzyme capable of stripping glucose of its electrons. Such "bio-nano" generator could be used to run devices embedded in the body, or sugar-fed robots. The team at Panasonic's Nanotechnology Research Lab has so far only managed to produce a very low power device.

3.6.7 Biocatalytic Energy

Biofuel cells utilise biologically-based compounds and natural reaction (such as oxidation) to produce power along standard, miniaturised electrodes. Miniature biofuel cells are being developed which run on glucose. In these fuel cells, a catalyst such as platinum is not needed, thus reducing costs. Instead, a micro-organism or an enzyme is used to oxidise the sugar in the anodic chamber, with electrons transferred to the anode via a mediator (essentially a molecule designed to 'ferry' electrons). The lone protons then travel across the membrane into the cathode chamber where they mix with oxygen. A mediator transfers electrons from the cathode to the protons and these react with the oxygen to form water.

These cells can be implanted into the body to run implantable electronics such as pacemakers. The cell in theory would be able to withdraw glucose and oxygen from the bloodstream and return waste products carbon dioxide and water to the bloodstream.

Bio-chemical Conversion of Biomass. The plant material all around us contains hydrogen. Demonstration projects are showing that hydrogen fuels can be made from plant waste materials using enzymes, fermentation, catalysts, and algae. Many communities have wastes from sugar beet plants, food processing plants, ethanol and biodiesel facilities, and even sewage treatment plants that may in the future be used to generate hydrogen fuels.

3.6.8 Nanograss

A nanotechnology battery based on electrochemical power storage and generation has been prototyped by a joint program from Bell Labs, the R&D arm of Lucent Technologies and mPhase Technologies in Sep 04. The prototype battery is based on a Bell Labs discovery that liquid droplets of electrolyte will stay in a dormant state atop microscopic structures called "nanograss" until stimulated to flow, thereby triggering a reaction producing electricity.

The experiment proved that this super-hydrophobic effect of liquids can permit precise control and activation of the batteries on demand. Future batteries based on this technology have the potential to deliver far longer shelf life and better storage capacity than existing battery technology. Potential initial applications for this technology may include defence, industrial, healthcare and consumer electronics.

Expected to be commercially available in 12 to 15 months, mPhase plans to produce the technology packaged in various configurations. A primary development goal is to create a battery that could have a shelf life lasting decades, yet can be activated instantaneously.

3.6.9 Radioactive Power

The idea is to harness the natural decay of radioactive material and convert it into a power source, without use of a reaction such as fission or fusion. The device converts the energy stored in the radioactive material directly into motion. It could directly move the parts of a tiny machine or could generate electricity in a form more useful for many circuits than has been possible with earlier devices. This new approach creates a high-impedance source better suited to power many types of circuits.

In Oct 2002, researchers from Cornell University developed a tiny battery fuelled by the radioactive isotope nickel-63. These radioactive isotopes are suitable for powering MEMS devices that can run for at least 50 years. According to the researchers, using an isotope that emits beta radiation, the least energetic radiation associated with nuclear decay, could make it safe for implantation. This form of power source is ideally suited for future applications such as nanoelectronics, wireless sensors and miniaturised mechanical devices.

3.7 Computing with Bio

We have seen how computing will be revolutionised with nanotechnology. We shall see how it can be revolutionised also with bio-inspired computing.

Before we embark on the revolutionary technologies that are considered bio-inspired computing, let us first look at

conventional bioinformatics as we know today of how IT is applied to life science advancement. Then we will look at bio-inspired computing, which is how life science, the study of living organisms, plant organisms and swarm behaviour in nature can be applied to IT to create revolutionary computing technologies.

3.7.1 Bioinformatics

IT is essential for bioinformatics and to support the global healthcare industry such as in healthcare delivery, monitoring, diagnostics or support function areas. It also supports drug discovery, development, monitoring in clinical trials, manufacturing, supply chain management, marketing and sales, as well as drug life cycle management. IT technologies such as collaborative workspace software suites, grid computing, high performance simulation and modelling tools, are useful in many of these activities.

The global healthcare market is probably worth trillions of dollars in spending. Wireless IT services are also fast gaining popularity in healthcare services. In IBM's Pharma 2003 report, targeted treatment solutions will become the major revenue earner towards 2010-2020, during which gene based therapies will slowly emerge during this period to overtake in the very long term targeted treatment solutions. Gone would be the days for traditional healthcare products.

Some key challenges in bioinformatics for biomedical applications are the development and deployment of:

- Massively parallel computing services for computation, simulation and modelling;
- Grid computing, which will remain a core business into the year 2015 also for other non-biomedical applications such as in collaborative industrial and engineering design;
- Huge affordable bandwidth to facilitate collaborative work between researchers and companies geographically apart;
- Technologies to efficiently manage massive databases, a key issue today is still the performance of object and/or relational database technologies available;
- Security to ensure that data stored is not tampered with or changed without a user's knowledge, and also secure storage solutions;
- Semantic web technologies like ontologies for software sharing between research collaborators...

Life science research today is much focused on understanding how biological molecules and systems work, why they fail, etc. In this course of work, infocomm technologies may offer enabling tools such as those above.

Towards a new era beyond 2015, we expect other bio-inspired computing technologies to mature described in sections below. Amongst the examples, we will see evidence in the confluence of infocomm, nanotechnology, engineering, neuroscience, chemistry, biological and botanical disciplines.

3.7.2 Bio-inspired computing

3.7.2.1 Amorphous or Swarm Computing

In biological terms, the adjective 'amorphous' means having no determinate form, irregular, undefined in shape or structure. In a living organism, an undefined colony of heterogeneous cells can be controlled by a genetic programme shared by member cells to become a purposeful multi-cellular organism. In the 1940's, John von Neumann studied how biological systems processed information, which led to his theory of natural and artificial automata.

Amorphous computing is a term coined in 1999 in a MIT memorandum to refer to a new paradigm in computer programming models. Today's research scope is basically to examine how we can program in a purposeful manner an amorphous network of mass entities (systems, computers, processors, sensors, biological cells, etc) to form a determinate pattern, or accomplish a system oriented mission or functionality.

Individual entities that belong to a mass are considered time variable and unreliable that may fail during its manufacturing or in its communications with neighbouring entities. However, when one observes the way biological cells work in mass, where one or more cells may die anytime or malfunction, yet the integrity of the intended global behaviour of this group of cells is preserved. From here, we could envision a new robust but cheap computing programming paradigm to engineer smart and powerful systems that are built out of a mass of individual 'dispensable' components. This concept is particularly attractive to building robust sensor networks out of a mass number of cheap and possibly unreliable sensors, so tiny yet with processor capabilities that you can even paint in mass onto a smart wall for making embedded computing and communication interfaces.

MIT looks at inventing new programming paradigms, languages, and algorithms for controlling amorphous computing agents, as well as to investigate prototypes, both in traditional silicon technology and in molecular biology. Their direction of work includes the engineering of mix and match genetic components that can give added functionalities like signal and control, sensing and actuating, and communication.

The inspiration does not come alone from biological computing. By mimicking other natural behaviours found in nature, such as in colonies of social entities like ants, beehives, flocks of birds or schools of fish, military systems have also devised simple rules-based swarm computing to guide a mass network of unmanned aerial vehicles or tiny robots on search missions.

In fact, natural scientists studying these aggregated behaviours in nature have found that in all that is seemingly chaotic and random in behaviour, there are in fact simple rules that members of this community actually follow. In doing so, the collaboration between members results in an organised global behaviour and identity, such as being able to stay together in a flock and reform the flock when disturbed. In the case study of an insect, the coordination of legs and wings are not done via a central complex algorithm, but by local algorithms that move each part. Each part follows a simple algorithm, and the combined team effort results in a coherent movement of the legs and wings.

Simple rules can mean for example the following:

- Keep approximately 'x' distance from thy neighbour;
- Exhibit at times random behaviour at local level to see if better solutions can be found;
- Enter a room if it is empty...

Core enabling technologies in distributed artificial intelligence can be statistically based or contextual rule based. This is a case of contextual rule based artificial intelligence programming. Its applications range from rule-based decision systems to autonomous execution systems. This lends well to today's enterprise computing trends, where we see an automated management movement towards policy-based automation and optimisation to handle distributed environments.

Inspiration can also come from research in chaos theory, or in fractal formations, where there are also simple local algorithms or mathematical equations that govern global behaviour. Research in these areas shows organisation exists within the seemingly random and chaotic global behaviour.

In Singapore, the Defence Science Technology Agency (DSTA) and DSO National Laboratory are also researching into such programming models for artificial intelligence. Initial results look promising in simulation and in manipulating prototypes of robotic machines. It is possible to programme a mass of tiny unmanned robots to perform a search and rescue mission in a building filled with many rooms by spreading themselves according to simple rules. The system accuracy can also be refined with learning and training sessions. Ad hoc networks between these coordinating sensors can perform a search and destroy mission in this case.

In Australia, Mr Alex Ryan, a mathematician with DSTO (Defence Science and Technology Organisation under the Department of Defence), heads a programme to modify natural swarm behaviour of insects for developing smart communication networks. The programme looks at developing intelligent goal oriented software that is network self-adaptable to unanticipated changes and using small inexpensive drones costing about S\$24,000 each for initial applications like surveillance missions, ultimately to be equipped with weapons for battlefield usage. The programme is estimated to be about 10 to 15 years away from fruition.

Some benefits of amorphous computing are:

- **Robust & Cheap Sensors.** Today's IC world is manufactured with precise engineering and quality control, in expensive clean rooms, and low yield with little fault tolerance. With organic engineering & amorphous programming tools, we can hope to transform the microelectronic and nano-electronics industry where millions of tiny, cheap and unreliable sensors, actuators, electronics can be self-assembled and programmed into meaningful IT devices. Organic engineering can help to mass-produce identical units of nano-components. We need amorphous intelligence to programme these cheap and dumb units into useful functions with a global purpose. Biologically inspired IT systems rely only on local algorithms, local communications, local state to exhibit robust global resilience to achieve their designed goals, by virtue of redundancy in the mass number of units in the system.
- **Resolving the Software Crisis.** Software can fail with single line errors hidden in the heaps of long codes and nested calls that can render software maintenance a tedious and almost impossible task. Future software systems need not be a complex master algorithm to solve complex and distributed system problems. Distributed local algorithms working in parallel and in a teamwork fashion may do the trick, and they make full use of the availability of distributed computational resources and does not wait upon the coordination by a central entity. In future, hardware processing power, processing speed and storage will be so abundant. There is no more need to design hard-to-maintain complex software to optimise operations by hardware. A paradigm shift in designing software is timely for local algorithms and local resources, so as to optimise code simplicity. Simple codes, but sophisticated global behaviours, where hardware is cheap, abundant and highly redundant.

Amorphous programming can make IT programming of codes and software more reliable, and in much fewer lines. Software is liable to security attacks. In a flock of birds, when external interferences occur, the flock may undergo a split second of disorder but regroups into its original flock formation in no time by adhering to local intelligence. When amorphous computing matures, it may offer software programmes resilience against security attacks.

Early examples of computing with similar amorphous characteristics include Sun Microsystems' JINI and Java. JINI does not assume that the network is working at all times, just as an amorphous computer does not assume that all its components are always-on. Java allows the execution of post issuance local applets, and hence can facilitate the local peer-to-peer communication, rules portability, and local downloads, to enable swarm-like behaviours.

- **Facilitating Cluster Computing.** With the advent of cluster computing, there will be more mass networks of millions of smaller IT devices, sensors, actuators and systems to be coordinated into a collective behaviour to perform meaningful tasks. Sensor networks deployed for research, academic, scientific or engineering purposes can be made more intelligent by some systemic programming like amorphous computing.
- **Battlefield Applications.** With the growing popularity of unmanned vehicles and sensors deployed in the modern battlefield, coordinating a swarm attack, rescue or data gathering for information dominance in a group mission can be made easier with swarm computing.
- **Smarter Nanotechnology.** Nanotechnology is no doubt going to herald in the new future of IT. Amorphous computing can be used to command and control with prescribed behaviours the millions of tiny invisible nano-devices that will be embedded in chips, into our environments or even in our bodies as drug delivery capsules. Programmable materials hence can be a reality.

3.7.2.2 Brain-Computer Interface

Recently scientists have had success in making a monkey operate a robotic arm via its thoughts. Brain cells communicate by producing tiny electrical pulses that facilitate processes such as thought, memory, consciousness, and emotion. Specific nerves or muscles associated with human activities like speech or movement are of particular interest to monitor brain cell activities. Thought control or brain-computer interface technologies translate brain cell activities and recognise brain patterns into commands, for example to access a computing device or application.

One means to capture brain or neural impulse signals is to use electroencephalography, which involves the use of multiple electrodes in contact with a person's scalp. Brain signals are then detected as tiny electric currents which can be amplified and fed into the computer for processing as messages to relay a person's moods or commands to manipulate for example a word processing application. However, such methods may be deemed intrusive by some. Hence, a challenge in brain-computer interface is to devise non invasive methods to read brain patterns.

Applications of such interfaces are so far often limited to physically challenged individuals, such as coma patients or those severely handicapped to the point whereby only their brain function works. In a smart space, it would be nice if we can detect a person's mood via such intelligent interfaces provided a convenient means to detect brain signals can be devised. Meanwhile, other biometric interfaces with shorter term potential like facial or voice recognition can also be used to detect a person's mood, hence lending to our ability to design affective smart spaces and applications.

3.7.2.3 Neuro-computing

Neuro-computing contributes to the cause of creating autonomous self-learning systems in smart spaces. It refers to a computing paradigm modelled after how neurons work, or in other words, how our nervous system or the brain works. Neural networks refer to a computer networking architecture in which processing entities are linked in a manner inspired from how neurons communicate with each other with the characteristic of being able to learn by trial and error. Neuro-computing hence aims to develop self-learning and self-organising goal-oriented computing systems. This will help in turn to develop autonomous artificial intelligence systems that can lend themselves to smart sensor and sensor network systems.

In approaching neuro-computing, we deal with architectures and modelling of neural networks, methods and theories of computational learning, analysis of network dynamics, cognitive science, fuzzy logic, genetic algorithms, information theory, neurobiology and pattern recognition.

The typical underlying computational model of neuro-computing is based on one or more artificial neural networks (ANNs), already very much used in the financial industry for risk analysis software. An ANN has computational nodes (simulating biological neurons) interconnected by influencing links (or synapse, a connection between two neurons) in a particular configuration or topology to execute computations. Many ANN models exist today, not all will work well in all situations. Some people work with multi-ANN hybrids. Currently, experimentation has been playing a strong role to determine the choice and suitability of ANN models. More mathematical analysis is required to capture and code the dynamics of ANN models, so as to reduce the need for experimentation.

Neuroscience today tries to better understand the human nervous system, neuro-computing is to leverage on this understanding to build computational systems to solve real world problems. The inspiration for computational models to be built from the human brain is due to the widely recognised fact that the brain is flexible to react to novel stimuli, open to introspection, self-analysis, self-diagnosis, can draw knowledge from information, via its mysterious network of neurons working at an estimated 10^{15} operations per second (one operation per synapse per second), the computing power of a human brain.

Some benefits of neuro-computing are:

- **Robust and Self-Learning Systems.** From neuro-computing, we can make more robust and self-learning systems. We can make neuro-computers, and neuro-chips and sensors. Other application areas include signal processing, speech processing, image processing, pattern recognition, computer vision, control, robotics, optimisation, scheduling, resource allocation and financial forecasting. With advanced neuro-chips or neuro-networks, we can have automated agent negotiation, speculative execution that are more akin to how human brains function, hence towards proactive computing.
- **Unbreakable Security with Chaos Theory.** Recently, researchers from Bar Ilan University in Israel have combined chaos theory and neural networks to demonstrate the feasibility of producing a virtually unbreakable encryption code. In encryption technologies, a truly random number generator is often needed as a key component of the system to generate keys used in security algorithms. Random sources such as chaotic systems can be synchronised using a common external signal. Other random sources can be a pair of software-based neural networks that can be synchronised by training each network on the output signals from the other, and a pair of chaotic maps. In a hybrid model, the researchers successfully synchronised a pair of neural-chaotic networks by using the neural network signals as the chaotic map input, and the chaotic map output as the neural network input.

Neural Network technologies are very much used today. For example, CET Technologies in Singapore, a fully owned subsidiary of ST Electronics contributing to its Communications and Sensors Systems business group, has a patented cetrac™ Traffic Management System that is based on neural networks. The system uses advanced image-processing techniques and traffic engineering know-how to process and analyse 'live' video signals and GPS-based traffic information. Based on Neural Network, the system utilises advanced video-imaging processing techniques to extract traffic data such as speed, volume, occupancy and queue length of vehicles from an integrated network of roadside video cameras which forms a virtual loop for detection of traffic incidents.

Neural networks are also used to analyse odours in electronic sensors for industrial and medical purposes. This can be used to tell the freshness of perishables and raw ingredients, or to detect venous ulcer infection.

3.7.2.4 Organic Engineering & Computing

In chemistry terms, the word 'organic' refers to a class of chemical compounds having carbon as a basis, which is characteristic of living organisms. Au contraire, 'inorganic' means inanimate objects to the layman (for example, silicon electronics).

Organic computing and engineering leads to the fabrication of IT logic functionalities, IT circuitry, computing systems that leverage on the working of living organisms, such as by building living cells/neurons on electronics, or using viruses/living cells to make inorganic electronics in order to facilitate cheaper manufacturing processes.

By combining IT with organic engineering and molecular biology in a purposeful manner, we make smart biosensors and inorganic nanosensors. Not all future IT sensors are bio-enabled sensors, but the latter does bring about disruptive new capabilities to the world of sensing such as sensing for pathogens. There are many companies dealing in the business of biosensors.

With the future convergence of computing, communications, sensing and advances in organic engineering, we could see the emergence of highly integrated biosensors, capable of processing information and storing information at 1 terabyte per cm² with molecular memories, and a world of proactive healthcare with computer links to biological sensory organs. From an accuracy level comparable to humans today, odour and flavour sensors will improve in sensitivity to that of a dog. An obvious application would be for smart sensors to sniff out mines and pathogens. Future biological sensors could also simulate human nerves, create tactile sensors comparable to that of human sensation.

In a 2004 IEEE Technology Leaders Survey, the number one ranking with over 60% of votes goes to biomolecular

engineering as the field of science that will have a major societal impact over the next ten years. Next in line was nanotechnology, followed by megacomputing and robotics. A few of the respondents noted that system engineering at the confluence of technologies with telecommunication and sensor technologies would create even greater opportunities than each of these technologies alone.

Nevertheless, while some may think that the societal impact will be evident in the next decade, Gartner places Protein-DNA logic and molecular transistors as a processing and storage technology that is more than 10 years away from its Plateau of Productivity for the marketplace.

Organic or bio-computing has several key disruptive features for smarter computing vis-à-vis conventional IT wisdom and solutions:

- **Flexible Mission Oriented Goals versus Deterministic Processes.** Today, the computer or any application programme is but a conglomerate of algorithms waiting to be executed upon call. The computer simply executes millions of lines of algorithmic codes very rapidly, in a deterministic manner, step by step as it is programmed to, and cannot react to changes in the application that are not within its pre-programmed job description. There is a division of labour between the human who provide the creative infrastructure to architect the programme, to code the programme to achieve purposeful goals, and the machine that simply unfolds the code into a step-by-step execution.

The bottleneck appears when something happens that is not supposed to, when pre-programmed parameters need to change, when algorithms need to deviate. At that moment, human intervention occurs to analyse data, decide on the next path, by taking into account strategies, goals and the mission. Now, when this bottleneck appears, it might not always be possible for the human to intervene, as the computer runs tiny codes at millions of times faster, and sometimes parallel along multi-threads. The human brain thus cannot absorb or interact in a meaningful manner with the programme and computer.

To resolve this human brain bandwidth problem, one way is to make the computer 'human' and autonomous by giving it the mysterious biological functions of a living cell. This is to grow circuits out of bioelectronics. This can make smart sensors that are able to adapt to changing environmental conditions, to survive under different influences, in the same manner that a living cell works – goal orientation. The living cell only recognises its goal, reacts and evolves its structure to external changes so that it can constantly achieve its goal.

- **Autonomous & Self-Regenerative Systems.** Advanced R&D agencies like DARPA are also looking into self-regenerative systems through natural robustness found in biological metaphors such as self-healing. In fact, living cells possess features to synthesize, copy, reproduce, divide, shape, orientate, move, filter, sort, sense, defend, aggress and communicate in intra-cellular or inter-cellular manner. This can also be fancifully termed as self-rejuvenating software and hardware, autonomous healing and diagnosis. When smart sensors are deployed in mass, it is impossible to 'take care' of each one and autonomous self-healing bioelectronics is indeed attractive. Our smart space components are not only intelligent but more self reliant and robust.
- **Interactive Systems.** The living cell is context aware, adapts to environmental changes and interactive in that sense. Neurons grown on silicon can become a tiny replicate of our brain function that allows the sensing circuitry to perform as intelligently and highly self-interactive with the environment on behalf of its human counterpart.
- **Coping with Hardware Advances.** With the advent of hardware technologies like nanotechnology, future hardware processing units will be so fast and powerful that software, being dependable on human programming, will not be able to advance as fast. Software will need something disruptive for a change to catch up with hardware revolutions. Even IEEE listed hardware security as the next trend instead of software security. This is because hardware will get so cheap, so fast, so complex, so disposable, so small while software is increasingly being tainted with vulnerability attacks. Software without any disruptive innovation might just be increasingly replaced by hardware.

IBM also believes that we cannot keep computing as we have for years. Millions of businesses, billions of humans that compose them, and trillions of devices that they will depend upon all require the services of the IT industry to keep them running. The complexity of these systems and the way they work together creates a shortage of skilled IT workers to manage all of the systems. It is a problem that will grow exponentially, just as our dependence on technology has. We need to create a new capacity where important computing operations can run without the need for human intervention. In Oct 2001, Paul Horn, senior vice president of IBM Research suggested a solution: build computer systems that regulate themselves much in the same way our autonomic nervous system regulates and protects our bodies. Hence, autonomic computing was introduced. Molecular biology, neuro-chips and organic computing offer autonomic computing on a chip scale.

To increase its complexity handling ability, software also needs to be as parallel as it can get. Today we have multi-threading from Intel, but the most powerful parallel machine in the world is in fact the human brain. Living cells provide an incredible tour de force of parallelism, executing complex tasks in split seconds. The living cell embodies a perfect complex self-organised system of software algorithmic intelligence in a black box. Organic engineering and nanotechnology can allow the building of electronic transistors by living cells, with amorphous computing, we can build and programme living cells to achieve conventional IT functionalities. A CMOS inverter, basic IT logic building block, was demonstrated by MIT AI Laboratory using amorphous programming.

In botanical chemistry, local chemical gradients incite new growth points in plant stems, and hence the terms botanical computing and growing point languages are invented. In plant terminology, tropism is defined as the involuntary response of an organism, or part of an organism, involving orientation toward (positive tropism) or away from (negative tropism) one or more external stimuli. This involuntary movement is called a taxic movement or taxis. For instance, negative phototaxis occurs in certain protozoans that move away from light. The external stimuli can be other things than light, such as heat, electric current, moisture, gravity or chemical agents. The activation or deactivation of external stimuli can be controlled via the intelligence of local algorithms carried by member entities.

To programme organic cells in building electronic organisms or inorganic electronics, local rules can be coded in genes via genetic programming/engineering. We can then, based on negative or positive tropism, group or repel materials that we desire to form logic patterns of conducting materials to eventually build an IT circuitry. Uniform state machine can be programmed as well into the member entities to simulate the splitting, dying or joining of growing points.

With the above methods, we may one day be able to manufacture cheap wafers and smart sensors that can be painted in mass on jet engines, consumer electronics, hospital walls, traffic lamp posts, or anywhere else we want it. Would computation be 'free' one day?

The following are some reasons why organic computing and engineering can make a difference to the world of infocomm:

- **Solving Complexity.** The challenges faced by the software industry relates to information explosion in the new age of a connected world. Division of labour between humans and machines is not scalable to future needs. Today, tools for auto-generating codes are but incremental facilitations. A paradigm shift is needed to dramatically reduce the need for division of labour. By leveraging on organic cells, such as the embedded intelligence in proteins, we can solve complex problems. By the advancement of genetic and neurosciences, we can tap on genetic algorithms and neural networks to produce self-organising programmes. Reducing the need for humans to manually intervene, such concepts are also nearer to the concept of calm computing by Mark Weiser, former CTO of Xerox.

In 2002, the University of Southern California with funding from DARPA, NASA, NSF, and the Office of Naval Research successfully implemented a bio-computing system using DNA molecules to resolve a computational problem with 20 variables and more than a million possible solutions. This was a vast improvement from previous experiments that had solved problems with a maximum of nine variables. With such a fast evolution, molecular computation may one day save the software industry from succumbing to increasing complexity of IT systems in a world where machines will interact with machines by the billions, and not only with humans.

- **Cheaper Hardware.** DNA engineering on electronic circuits combined with amorphous programming of bionic cells, can lead to very low cost hardware for sensors because of fault tolerant manufacturing.
- **Smarter Systems.** Organic systems have properties of self-healing, self-organising, self-assembly. Such properties are very desirable in an IT system and are aligned to IBM's concept of autonomic computing on a micro-scale. Today, we know that genes in DNA direct protein growth to build precise living structures. Via genetic engineering, scientists can one day manufacture with precision future generations of electronics.
- **Cognitive Systems.** Living organisms can sense their environment and react accordingly. Its interactive characteristic can be used to make cognitive sensors and sensor arrays.
- **Gigantic Systems on a Tiny Grain.** Other than nanostorage and quantum storage technologies, DNA technology can store also amazing amounts of information. For instance, one gram of DNA can

accommodate up to 108 terabytes of data, which is about ten thousand times the capacity of today's largest mass storage systems. Imagine smart wearable, sensors and embedded devices that will have no issue of storage scarcity and probably also dirt-cheap. Future mega storage devices can be as thin as a film and embedded into sunglasses, a watch or a pen. This will certainly be a disruptive change to the world of IT as organically engineered circuits can reach physical dimensions that silicon cannot reach. However, this future world is still far away, the big challenge in such DNA storage systems is reducing the humongous power system, standing tall at human height in prototype systems. While we may store 'unlimited' data in DNA, the power needed to extract and process information is currently prohibitive for us to implement in mass products, let alone wearable.

- **Natural Computing – DNA General Purpose Computing.** One of the revolutionary benefits that both nanotechnology and biotechnology can bring to infocomm is the development of embedded computing entities with DNA enabled general purpose computers. It is not to replace PC boxes with bio-computers, which we do not think is strategic since bio-computers perform much slower than electronic or optical ones, as measured by some researchers today.

Rather, the disruptive and more practical usage is to enable drugs in future to have general purpose computing power that is bio-based (DNA based). Such DNA computer enabled drugs are not as invasive as embedding a hardware nanochip into our bodies to treat illnesses or to monitor personal health (imagine the backlash from society when we start embedding intrusive hardware into bodies). Allowing natural products to have IT computing power to perform smarter is what really DNA computing can promise.

This defines a new IT computing industry based on what the confluence of biotechnology, nanotechnology and infocomm will lead us to. This is more so as healthcare applications are increasingly important and relevant to society as the ageing population increases. Non invasive techniques of computing with biosensors, non invasive monitoring probes that can be fed into our body systems, combined with electronic medical record systems, and a virtualisation of healthcare applications with different stakeholder users can open up a new world of smart personalised healthcare applications. That future is still far away today.

3.8 Standards Development

It is still too early to comment on standards for bio-inspired computing as these technologies are still in research phase. However, we would see more standards work in the area of nanotechnology.

The IEEE is creating standards to facilitate the movement of nanotechnology innovations from the research phase to commercialisation, and to establish fundamental nanotechnology platforms that support accelerated growth of the sector. These standards address critical commercialisation issues such as nanoelectronics device design and characterisation, and quality and yield in high volume manufacturing. Overall, the IEEE Nanotechnology Standards Initiative seeks to identify:

- Nanoelectronics technologies likely to generate products and services having high commercial and/or societal value;
- Areas where new standards can aid rapid commercialisation, technology transfer and diffusion into the market;
- People and institutions to lead and support IEEE nanotechnology standards projects.

One such standard is IEEE P1650, "Standard Test Methods for Measurement of Electrical Properties of Carbon Nanotubes." (<http://grouper.ieee.org/groups/1650>). This standard defines the electrical testing procedures and suggests characterisation tools for carbon nanotubes. It is intended to help accelerate the emergence of nanotube based devices in transistors and other nanoelectronics components. IEEE has also recently completed IEEE 1620, "Standard for Test Methods for the Characterisation of Organic Transistors and Materials." This standard creates a uniform framework for evaluating organic field effect transistors (OFET) as a platform for high-volume manufacturing. It is now extending the OFET activities to device standards.

This activity is part of a broader nanotechnology effort at the IEEE driven by the IEEE Nanotechnology Council, a multi-disciplinary group whose purpose is to advance and coordinate work in the field of nanotechnology carried out throughout the IEEE in scientific, literary and educational areas. The Council supports the theory, design, and development of nanotechnology and its scientific, engineering, and industrial applications.

In line with this, the American National Standards Institute (ANSI) also established a Nanotechnology Standards Panel (ANSI-NSP) in Aug 2004. This is a new coordinating body formed to develop nanotech standards in the area of nomenclature/terminology; materials properties; and testing, measurement and characterisation procedures. In Nov 2004,

the ANSI-NSP a set of recommendations that identified four broad standardisation topics to be most urgent in a 12-month-or-less time frame:

- General terminology for nanoscience and technology, including definition of the term "nano," consideration of impact on intellectual property/other issues, sensitivity to existing conventions;
- Systematic terminology for materials composition and features, including composition, morphology and size;
- Toxicity effects/environmental impact/risk assessment, including environmental health and safety, reference standards for testing, controls, and testing methods for toxicity;
- Metrology/methods of analysis/standards test methods, including particle size and shape, and particle number and distribution.

The ANSI-NSP also identified manufacturing and processing as well as modelling and simulation as items of lower urgency and noted standardisation time frames of 3-5 years in these areas.

3.9 Summary: Technology Roadmap

The following summaries all the pertinent points from the previous chapters of this report as well as input from other sources i.e. websites, publications and conferences materials on plausible nano effects on the future of infocomm devices and system towards and beyond 2015.

3.9.1 Phase 1. Exploiting Material Properties (now to 2010)

The first wave for nano (in the next 5 years) impacts on IT is on magnetic storages and display, by simply exploiting material properties with nanostructures. Many companies are now using nanomaterials to enhance their existing products with new properties through nano engineering. These improved properties will benefit most infocomm products, from improving the performance in storage density to ushering a new type of flexible polymer display. Nanotubes memory based on Van der Waals forces will also commercialise during this period.

There will also be some impact of nanotechnology on power sources for computing devices in the next 5 years. New nanomaterials properties will be used to develop novel products ranging from recovering energy from mechanical motion, using nano-membrane for more efficient micro fuel cells and harvesting small amounts of ambient energy from electromagnetic radiation for smart cards and RFID tags. Nanotechnology will also improve nanomaterials' efficiency of multi-layered solar cell to more than 50%.

3.9.2 Phase 2. The Nanodevice (2010 to 2015)

Within the next 10 years there will be mass commercialisation of non-volatile memories such as magneto-resistive RAM (MRAM), phase-change RAM (PRAM) as alternatives to DRAM, SRAM and Flash memories for computers, consumer electronics and mobile devices. Molecular memories devices incorporating elements built from array of carbon nanotubes and organic molecules will start to appear for product development. Holographic storage and memories will compete with hard-disks drive in high-density storage medium space. Plastic electronics devices built from polymer and nano-imprinting offer cheaper alternative to low-cost electronics, toys and display. Some of these devices will be integrated for wearable computing applications.

Nanotechnology will also improve photonic components used in optical communication system. Better, smaller and more efficient optical add-drop multiplexer and tunable laser will be enabled by nanotechnology to deliver ultra-fast optical switching and wider spectrum photonics lasers. Photonics crystals will be able to guide, confine and emit light for used in optical switches, optical memory and laser applications. Integrated photonics chipset will also be developed during this period.

Quantum cryptography will be readied for commercialisation within a 5 year timeframe, and perhaps will reach its productivity level in 10 years. There are already several companies selling quantum encryption systems, such as MagiQ, D-Wave System, ID Quantique and BBN Technologies. Refer to accompany report on Sentient Technologies for more information.

Dye sensitive flexible solar cell using polymer/organic material with efficiency more than 10% offers alternative form of power for low-power wearable electronics will be available. 3D display based on hologram without the need to wear special glass will be built into product to offer truly immersive infotainment. Nano-light emitting bulbs will be developed, potentially disrupting LED technology.

3.9.3 Phase 3. The Nanosystem (beyond 2015)

Beyond 2015, serious difficulties scaling transistors feature size below sub-10 nm are anticipated. Coupled with the high semiconductor manufacturing cost, alternative method in designing and producing electronics will be needed to continue fuel IT growth. An approach that utilises the inherent smallness of molecules to build products from bottom-up is currently in active research. If realise, it could potentially offer low-cost production as compared to existing fab techniques. Known as molecular self-assembly, products developed from this approach are known as molecular electronics. The process is based on self-assembly which mimicks nature's growth abilities to organise matters. Molecular electronics are being developed. These are built

up of chemically assembled logic switches organised in large numbers to form a computing system or memory devices. Large number of parallel, low-power computing devices could be developed at lower cost. Product manufactured from this method will exhibit defect tolerant capabilities, mimicking nature ability to self configure for computing resources and performs self-healing functions. Molecular electronics computing devices will start mass commercialisation after 2015.

One potential long-term solution for overcoming obstacles to increased computational power is to shift the basis of computation using quantum effects. The ultimate quantum computers would need many more years to research. In fact, scientists are looking at 20 years or beyond to make general-purpose quantum computers. Perhaps in 10 to 20 years, quantum computers of 50 qubits can be designed, which would be already much better than classical computer systems.

During this phase, transistors will utilise carbon nanotubes as source to drain channel to provide ultra-fast transistors. The electrical properties of these carbon nanotubes are such that they are able to transport electrons at ballistic speed, compared to today's technology based on random motion of electrons flow from source to drain.

This phase will also see the development of power based on nature's ability to sustain itself using sunlight as source of energy. Highly efficient biological power source utilising photosynthesis process will be developed for niche commercial applications. These biological fuel cells convert the chemical energy of carbohydrates, such as sugars and alcohols, directly to electric energy. Research works at the Helsinki University of Technology in Finland have demonstrated an efficiency of more than 40% at room temperature.

	2005 to 2010 Smart Material	2010 to 2015 Flexible & Organic	Beyond 2015 Bio-inspired Systems
Advanced Display	- Extensive use of Organic LED display on mobile phones, digital cameras and CE products, offering longer-lasting power, clearer and wider viewing experience for users - Small screen carbon nanotubes field emitter display introduced, vying for market shares with LCD display	- Flexible Organic LED display gains momentum in electronic paper (digital ink), e-signage and wearable display - Entrance of large Organic LED and carbon nanotube FED for TVs and wall display	Holographic 3D display system (hologram) matures, spurring demand for augmented and virtual telepresence applications
Infocomm Storage & Memory	- Non-volatile memory using Magneto-resistive RAM, Carbon Nanotube RAM, Phase-change RAM used in products, allowing fast data access and power-up capability - Perpendicular magnetic recording (PMR) technology used on magnetic disk, offering 100 to 500 Gbit/in² area density (A*Star Tech Scan) - Emergence of holograph storage technology i.e. holographic versatile disk (HVD) with 200 GB gains pace, outpacing DVD	- Era of Storage Abundance - DRAM memory with 64 Gbit introduced (ITRS 2004). Non-volatile MRAM & PRAM memories surpass Flash memory in mobile devices - Heat assisted magnetic recording (HAMR) used in magnetic storage, offers more than 500 Gbit/in² area density (A*Star Tech Scan) - Atomic force probe storage for mobile handheld, offering 1 Tbit/in² storage (IBM millipede) 3D holographic system widely used as mass storage media, providing multi-terabytes data storage	- Atom level storage possible - Self organised magnetic arrays (SOMA) and HAMR technologies used in magnetic storage media, offering beyond 1 Tbit/in² to near 50 Tbit/in² area density (Seagate) - Molecular memory makes inroad into computers
Device Architecture	- Reaches a billion transistors on a single die, and system-on-a-chip design starts gaining pace - Cell architecture takes hold and majority of gaming consoles migrated using cell processors - Dual-core and multicore processors make inroad for desktop computers and mobile handhelds - Carbon nanotubes and semiconductor nanowires in active research as alternative for future nanoelectronics devices	- Transistors built on 25 nm process with 10 nm feature size in 2015 (ITRS 2004) - Nanowires and quantum dots transistor developed, bringing new capabilities in signal processing and sensing application - Plastic electronics widely used for low-cost RFID tags and sensor devices - Fast optical switches widely implemented using photonic crystals, replacing MEMS-based optical switches	- Era of Terahertz Computing - Silicon reaches limit in scaling as gate length hits 7 nm by 2019 (ITRS 2004). Carbon nanotube-based transistor viable - Emergence of Molecular Electronics & NEMS devices for processors and memory in computing system & sensors - Self-directed assembly technique emerges as alternative to conventional lithography, enabling low-cost manufacturing
Future Advanced Power & Others	- Micro fuel cell makes inroad on computers, phones and digital appliances, providing massive energy density of 1000 WH/kg, about 10 times more than Li-ion batteries - Solar cell used for powering handhelds and low power devices	- Micro fuel cells and Super Capacitors obsolete small electrochemical batteries - Micro fuel cell power about 15% of world's laptop computers with 120 million laptops with market value of US\$1.2 billion by 2012 (ABI Research) - Organic dye sensitive solar cell gains significant inroad for powering mobile devices and consumer electronic products	Highly efficient solar cell (>40%) based on biological process converts sunlight to electricity at lower cost

Table 7. Roadmap Summary

3.9.4 Bio-Info Roadmap (beyond 2015)

The following paragraphs describe the future for various bio-inspired computing technologies.

Amorphous/Swarm Computing – Towards Amorphous Semantic Web. Little hardware circuits and robots can be programmed as amorphous computers, but applications and services on the Web can also do likewise. Computerworld thinks amorphous computing is the next wave after grid and web services, providing the network system intelligence to coordinate resources, humans and computing devices on the World Wide Web into meaningful purposes. Web service can publish, search and connect business functions to others, what it lacks today is the automated intelligence to direct and organise a cluster of services. Grid today is but a virtualised network computer that could do more if some automated bio-inspired network intelligence can coordinate and direct the sharing of computational resources, grouping of computing devices, and tolerate unreliable nodes to achieve a mission or common goal.

Today, in the area of web artificial intelligence, we have R&D in semantic web that can make the web more machine friendly for automation. Tomorrow, we should be looking at a semantic and amorphous web. In fact, the web can be seen as a conglomerate of millions of unreliable, not-always-present devices connected together, and human behaviour affecting the operations on the web. Amorphous computing and swarm engineering will enable the web to act smart. We not only will have smart spaces, but an entirely smart Web.

Brain-Computer Interface – Towards more distinctive brain patterns. Today, Gartner estimates that we are able to recognise only five distinctive brain patterns and more is needed to formulate useful systems. Hence the technology is more than 10 years away from its Plateau of Productivity. It is a difficult science whereby multiple disciplines like neurology, neuroscience, psychology, information processing, computing, and engineering are needed.

Neuro-computing – Towards silicon-based artificial neural intelligence. Many universities around the world are researching on machine learning, neuroscience and neuro-computing. Researchers in Germany's Max Planck Institute for Biochemistry has successfully grown neuron cells from a snail onto silicon, with bilateral communication ability between the neurons themselves and with the silicon transistor. The cells were held in place by polymer 'fences' and the silicon coated with proteins to keep the cells alive. Electrical signals emitted by neurons can be detected via the transistors below the neurons. The challenge now is to develop neuron-silicon systems in thousands and millions of synapses to simulate the real brain, from a mere 20-neuron system as currently experimented.

Another key invention, by Professor Thomas DeMarse at the University of Florida's Neural Robotics and Neural Computation Laboratory and joint work with the Computational Neuroengineering Laboratory, was to have grown a mini brain via a monolayer of 25,000 rat cortical brain cells on a 1.6 mm² silicon chip that interfaces to, nurtures and controls the natural adaptation of the living neural network. In a test application, this biologically alive neural network was given only control to ten percent of the stick deviation in a F-22 flight simulator. The chip was stimulated at 64 points with a 8x8 array of gold electrodes measuring just 30 microns, spaced 200 microns apart, etched onto the chip and connected to electronics. The neural network learned how to stabilise the military fighter plane and was able to fly the plane 'true' in about 15 minutes even under simulated hurricane wind forces. In actual motion, the neuron cells began independent of each other, but on time-lapse videos, it was noticed that they sent out feelers to see what other neurons are nearby and then within 15 minutes, the cells started to self organise into an interconnected network that works towards stabilising the plane.

One of the greatest challenges to this field of computing is that neuron cells can survive from a month to two years and have to be nourished weekly, which makes it impractical for daily computer use. It hence remains still a platform to study neurological computation. However, the work proves that biological circuits for new age biologically-inspired computing is not a myth anymore and can be applied to solving real world problems via a robust self-learning system, albeit a lot of work to commercialise it. Such work will open up doors to biomedical therapies to understand and treat neurological conditions like epilepsy, not by understanding of how biological computation works, but by how they fail – by analysing why the neurological circuitry malfunctions.

Professor DeMarse is now working on extracting the rules that biological networks use to make its biological computations, so that he can create better artificial neural networks in silicon. His understanding so far is that the process is much more like an analogue circuit than a digital one (an irony when we are going into the digital age, when biology and nature brings us back to analogue in biological mechanisms that offer self-learning and self-adapting computing systems for the future).

As a matter of fact, to enable the learning function of the chip, its outputs are fed to a robotic system, whose outputs in turn become electronic signal inputs for tuning the neural network in a analogue feedback loop. The feedback signal encoding was done in an analogue language that the neurons already understand: frequency modulation. Neural pathways grow fatter if used more frequently, thereby reinforcing the effect of the feedback loop. Conversely, neural pathways used less frequently will grow thinner, thus attenuating the effect of the feedback loop.

Agent Negotiation & the Sentient Web. Another challenge in neuro-computing or neuroscience is the study of the brain as a society of agents. Negotiation and sharing of information between agents allow the brain to derive a clear understanding of the current situation. We have yet to fully understand how the agents in the brain work, but further research into this neuroscience area could yield benefits as to how we should manage and what new algorithms are suitable for distributed agent collaboration on the web. Advances in this area can lead to better proactive computing.

In 2003, Microsoft's co-founder, Paul Allen initiated the Allen Brain Atlas programme by the Allen Institute of Brain Science, a US\$100 million project over three years to unravel the genes (out of 20 000) that are responsible for mouse brain functions, what they do and where they execute operations. Future intent is to do similarly for the human brain. Results are promised in instalments on the Web for neuroscientists. The amount of data to be generated far outweighs that of the Human Genome Project and will be tantamount to petabytes.

Organic Computing – Towards bio-inspired molecular self-assembly. For now, commercialisation of initial but powerful concepts such as molecular self-assembly has begun. For example, Nanolnk, a Chicago-based start-up, commercialised dip pen nanolithography (DPN) which uses the tip of an atomic force microscope to deposit dissolved compounds. These compounds could contain DNA strands that are meant to be attached to electronic components like carbon nanotubes, quantum dots, nanowires that are in turn used to build circuits. Complementary strands of DNA will seek to bind to each other, binding also the electronic components that carry these DNA strands. This was in fact a laboratory concept conceived by Northwestern University in USA in 1996. The same researchers had paved the way for DNA scribing process, whereby single strands of DNA can be deposited in a desired pattern onto a glass substrate suitable for building circuits, and whereby nano-building blocks of circuits with complementary DNA strands can then be fixed into the pattern automatically.

Other companies also believe that self-assembly is within the commercial realm in the near term, with initial applications to build sensors onto silicon circuitry. The self-assembly process at room temperature by DNA and proteins using microbes could replace the much costlier process of making semiconductor circuitry today. Nevertheless, the future is still far where we can self assemble millions of units of nano-components.

Transistor Built by Living Cells. Today, scientists at MIT have successfully experimented with using genes in DNA and proteins to construct basic IT and computer components like a transistor, but not yet full complete devices. Using virus-facilitated process to bind metals (e.g. GaAs and InP, commonly used in high frequency wireless chips), nanoscale components with exceptional specificity can be manufactured. The trick was to leverage on a coat of proteins to interact with the molecular structure of the semiconductor material to which it is introduced, via a process called directed evolution. The primary steps are as follows:

- The two tips of the virus are genetically modified to bind gold, thus providing for the crystallisation of gold contact points for the transistor's drain and source gates;
- ZnS precursor chemical is then introduced, and the proteins on the virus react with the chemical to cause ZnS to precipitate uniformly along its shaft, forming a conducting nanowire between its tips;
- Heat is then applied to vaporise the virus, leaving behind the ZnS nanowire attached electrically to its gold source and drain gates;
- A nano-transistor is hence formed via a biological process.

MIT is moving on to research using living cells besides viruses, as the former has better advantages in making self-healing circuits, and can interact with a wider range of electronic materials used today to fabricate circuits.

So promising is this category of research that the US Army poured in US\$50 million to form the Institute of Collaborative Biotechnologies to accelerate the research of MIT and others. The US Army has plans to use bio-inspired self-assembly in areas like future sensors, displays, magnetic storage devices, energy production and information processing. The institute also sees sponsorship from Aerospace Corp., Applied Biosystems, Genencor, IBM, SAIC, and Becton, Dickinson.

The technology conceived can also be used in IT storage applications. As a matter of fact, films of magnetic quantum dots representing memory bits can be fabricated this way and lend themselves to high-density flash memories. One cm² of film area could store as much as 30 Gbytes of data. Companies interested in quantum dot storage devices include IBM, Fujitsu and Hitachi.

Some players in organic computing include:

- Semzyme (founded by MIT and UCSB) was founded in 2001 to exploit the self-assembly concept;
- Genencor formed a US\$35 million partnership with silicon materials giant Dow Corning in 2001 as well. Their long-term target products include sensors;
- DuPont is looking at short-term applications to purifying carbon nanotubes using peptides and DNA to selectively sort out semi-conducting and metallic nanotubes, which are used to make logic circuits;
- IBM established a new long term of research programme on nanoscale molecular electronics in Jan 2004, which is based on single molecule jointing with pure metal or silicon. It has replaced research on pure polymer electronics which had not been able to produce enough gain for their purpose.

Singapore Landscape

4.1 Introduction

Nanotechnology in Singapore. Singapore has recognised the importance of nanoscience and nanotech R&D as one of the key areas which it should develop as far back as in Sep 2002. Under the Economic Review Committee (ERC) recommendation, the sub-committee on manufacturing has deliberated on strategies for sustained competitive advantage for Singapore, and nanotechnology was identified as a key enabler to achieve this vision.

Many nano R&D labs, research centres and initiatives have thus been borne out of this vision, with research spanning from basic nanoscience in academia to applied R&D in the various A*STAR research institutions. These centres are supported by a sizable pool of global talented nano technologists and scientists. Two nanotech initiatives were also been established during these times – the Singapore National Nanotech Initiative at NUS and Nanoscience and Nanotech Corridor at NTU. Both are chartered to conduct cutting-edge engineering and scientific research to boost Singapore's long-term expertise and capabilities in nanoscience and nanotechnology.

Singapore has a good eco-system and infrastructure to develop a strong nanotech cluster. Its economic strength is supported by a strong presence of more than 7000 multinational companies dealing with a diverse range of businesses, and a sizable pool of local SMEs that are equipped with hi-tech precision manufacturing capabilities. There are also venture investment communities to seed major initiatives and commercialise new innovations. Together with a well established science and technology (S&T) infrastructure to support these R&D activities, it will provide an attractive place to test-bed, trial and development new and innovative product.

Biotechnology in Singapore. In our previous chapters, we have discussed organic engineering, amorphous programming of living cells, growing neurons on chips and biosensors. Biotechnology may have long term potential to create

disruptive capabilities in future lab-on-a-chip sensing devices. Singapore's biotechnology industry, manufacturing and research capabilities have taken impressive great strides since the country's strong investments in this sector as another economic pillar for growth, attracting many top industry players to Singapore and churning indigenous innovations.

One of the growth areas in biologics manufacturing has been built over the years since 1990. In particular, the A*STAR has funded one of the key players in this field, Bioprocessing Technology Institute (BTI), via its Biomedical Research Council. The institute has achieved a protein-free, chemically-defined media for growing cells that comply with regulatory guidelines (no animal-derived components in the media) and a chemical cocktail that prolong cell viability. Another key player is A-Bio Pharma Pte Ltd, wholly owned by Bio*One Capital, a subsidiary of EDB Investments Pte Ltd. It aims to be a leading biologics contract manufacturer of therapeutic proteins for major pharmaceutical and biotechnology companies. Other research institutes of A*STAR, such as the Bioinformatics Institute and the Genome Institute of Singapore are also important players in biotechnology.

4.2 Key Players in Singapore

Agency for Science, Technology and Research (A*STAR).

The key funding agency in Singapore for nanotech and nanoscience research is managed by A*STAR. It funds a rich spectrum of nano-related projects to most research institutions under its Science and Engineering Research Council (SERC) and Biomedical Research Council (BMRC). A*STAR has also convened a tech scan panel to identify the next best bets on nanotechnology and recommend strategic development in this area for Singapore. The initial study has identified three potential areas for further research and development – nanoelectronics (in molecular electronics), nanomaterials (for next generation sensors) and nanomedicine.

Singapore Economic Development Board (EDB). The Singapore EDB is another funding agency supporting industrial applications research. In particular, it funds nanotech start-ups and supports international joint ventures. In 2003, EDB partnered with NTU to establish a Nanotech Industry Application Centre at NTU. This centre, known as NanoFrontier, co-develops applications, transfers knowledge and provides equipment support to start-ups working on nanotechnologies. In creating opportunities and awareness of nanotech in Singapore, EDB has also co-organised a World Nano Economic Congress Singapore (WNEC 2004) with Cientifica in Oct 2004, drawing an attendance of more than 150 participants from around the world.

Infocomm Development Authority of Singapore (IDA). IDA is committed to growing Singapore into a dynamic global infocomm hub. IDA uses an integrated approach to developing info-communications in Singapore. This involves nurturing a competitive telecoms market as well as a conducive business environment with programmes and schemes for both local and international companies.

The Infocomm Technology Roadmap (ITR) formed one of the key technology thrusts supporting IDA's mission of beyond Connected Singapore. It aims to identify future market and technology opportunities, so as to facilitate the development of strategies and programmes by the industry, government agencies, academia, and research communities. Through this effort, it strives to promote synergy and vibrancy in the infocomm community through a shared common vision. In a departure from the five-year roadmap period in past ITRs, ITR-5 maps out a long-term vision and foresight of strategic technologies up to 2015. It tracks technology evolutions and disruptions, which could lead to strategic thrusts and programmes for the industry, government agencies, academia and research communities.

Data Storage Institute (DSI). DSI was established by A*STAR and the National University of Singapore (NUS) to conduct research and development in storage technologies. To-date, it has achieved world-class status in developing extremely high-density data storage. For example, a DSI research team has developed a world lowest Femto Slider with a 3.5 nm-flying height technology, putting Singapore alongside the US and Japan in work. With the new technology, a DVD-sized magnetic disk can hold 350 times more data than a conventional DVD. The sub-3 nm Flying/Proximity-On-Demand Pico/Femto Slider is currently in research. The institute is also directing research in areas of nano-spintronics, for magneto-resistive RAM and exploring new technologies for data storage beyond Terabit per inch² area densities.

Institute of Chemical and Engineering Science (ICES). ICES conducts research in four cluster of chemical and engineering science, namely:

- Process Science and Modelling. Covers research in molecular modelling, process modelling and characterisation and reaction engineering;
- Applied Catalysis. Research and development of novel catalysts and processes relevant to the petrochemical, fine chemical and pharmaceutical industries;
- New Synthesis Techniques and Applications. Research pertaining to the synthesis of complex organic molecules for the pharmaceutical and fine chemical industries;
- Crystallisation and Particle Science. Develop fundamental understanding of crystallisation and particle science and to apply this knowledge to industrial and academic R&D as well as existing industrial problems.

Institute of High Performance Computing (IHPC) is a research institute that conducts research in computational science and engineering. In nanotechnology, IHPC provides modelling and characterisation of molecular electronic nanostructures. IHPC aims to generate a computational efficient code that is capable of modelling and simulation of molecular electronic nanostructures using advanced computational technique and high performance parallel supercomputers to simulate molecular devices with a large number of atoms. IHPC is also investigating carbon nanotubes with desired band gaps by changing chemical structure symmetry or size. IHPC is also developing a parallel computing platform under the growth mechanisms of nanostructures, in particular self-assembling quantum dots.

Institute of Materials Research and Engineering (IMRE). Established in 1996, IMRE is a research institute focusing on the advancement of materials science. The research covers from polymers to electronics to nanomaterials. New innovations and discoveries are also being explored to help create viable knowledge-based enterprises as well as applications of advanced materials and processes. IMRE has developed the reversal imprinting technique, a new method that offers unique advantages over conventional nanoimprinting by allowing imprinting onto substrates that cannot be easily spin-coated. It has also successfully fabricated many types of organic-inorganic hybrid materials such as top-emitting OLEDs (TOLEDs), flexible OLEDs (FOLEDs) and passive matrix displays. Research on nanostructures singular ID nano-tag that is practically impossible to forge is also been developed at the institute.

Research activities undertaken by IMRE can be categorised as follow:

- Polymer science and chemistry;
- Nanomaterials;
- Advanced materials characterisation;
- Performance materials;
- Nanoparticles;
- Macromolecular chemistry;
- Surface science.

Institute of Microelectronics (IME). Formed in 1991, IME's mission is to increase value-add to the electronics industry in Singapore by engaging in relevant R&D in strategic fields of microelectronics; supporting and partnering the electronics industry; and developing skilled R&D personnel. IME helps to drive the continual growth of Singapore's electronics industries through high calibre research and development for semiconductor applications. The Institute has three research focus areas: (1) Integrated Circuits & Systems (RFIC & ASIC Design & Modelling); (2) Semiconductor Process Technologies (Advanced Interconnect, Process Modules and Silicon Micro-photonics and Devices; and (3) Microsystems, Modules & Components (MEMS, Micro-Modules, Interconnects & Integration, and Microsystems Reliability). Recent R&D efforts include: SiGe devices, 10 Gbps optical communication IC and microphotonics for optoelectronics integrated circuits. Research activities undertaken by IME include:

- Advanced packaging;
- VLSI design;
- Nanoelectronics devices;
- MEMS/NEMS;
- Semiconductor physics processing methods.

In nanotechnology, IME develops photonics devices and single electron devices based on quantum dots. IME has also built up strong capabilities in nano wafer level packaging and strained silicon and SiGe fabrication.

Institute for Infocomm Research (I²R). On the other hand, Singapore's Institute for Infocomm Research and the Department of Mechanical Engineering at the National University of Singapore are collaborating on brain-computer interface technologies with renowned BCI research Niels Birbaumer, a neuropsychologist at the University of Tuebingen in Germany. The joint research targeted at wheelchair bound patients with total paralysis is one of Asia's pioneering BCI research efforts. The patient may one day steer his wheelchair via his brain blood flow through a BCI system with magnetic resonance imaging. Mr Birbaumer's achievements included the pioneering implementation of Thought Translation Device. The latter can be used by partially paralysed patients to control a word processor.

Singapore Institute of Manufacturing Technology (SIMTech).

Officially formed in 1993, SIMTech aims to enhance the competitiveness of Singapore's industries through the generation and application of advanced manufacturing technology. Its areas of research focus include Production and Logistics, Advanced Forming and Joining Technology, Machining Technology, Mechatronics, Precision Measurement, Advanced Automation and Product Design and Development. Research activities undertaken by SIMTech include:

- Advanced automation systems;
- Control systems;
- Precision metrology;
- Robotics control systems;
- Mechatronics, systems engineering;
- Micro-manipulation technologies;
- Laser processing and design;
- Photonics;
- Optics;
- Product development life cycle management;
- Artificial intelligence applications;
- Materials processing casting technologies;
- Supply chain methods;
- Operations research.

Nanyang Technological University (NTU). The Computational Nano-Electronic Initiative in the Department of Microelectronics was established in the emerging field of nanoscale device modelling. Programmes are directed towards the computational aspects of nanoscale electronics, materials, and devices.

The Nanoelectronics and Devices Research Group in the school of electrical & electronic engineering design, synthesise and develop integrated nanoelectronics devices and systems that comprise semiconductor-related materials towards the following activities:

- Computational nanoelectronics;
- Carbon nanotubes and nanocomposites;
- Wide band gap nanostructured materials and device;
- Nanoscale semiconductor materials and devices;
- Compound semiconductor quantum dots.

The Nanoscience & Nanotechnology Corridor (NTUNNC)

(<http://ntu.edu.sg/nnc>) aims to promote inter- and multi-disciplinary nanotechnology research. It aims to draw together nano research groups within Singapore and around the world to realise nanotechnology through a common user facility. There are five core areas of focus, in particular for IT, the Nanoelectronics cluster focuses on nanoscale semiconductor material and devices, carbon nanocomposite-based material and devices, wideband gap nanomaterial and devices, semiconductor quantum dots and computational nanoelectronics. Other clusters relevant to infocomm development are in molecular devices and nanoengineering, nanomaterial systems and nanofabrication.

National University of Singapore (NUS).

The Nanoscience & Nanotechnology Initiative (NUSNNI) (<http://www.nusnni.nus.edu.sg>) aims to initiate and coordinate long-term nanoscience and engineering research to achieve fundamental discoveries of novel phenomena, processes and tools. The following areas of research are of relevance to infocomm:

- In nanoelectronics. Fabrication of CMOS memory devices using quantum dots floating gates to achieve highly scalable flash memories with high speed and low voltage characteristics. It will also explore Metal Oxide Semiconductor Field Effect Transistor (MOSFET) properties using nanowire gates. Another area of research under this category will be on self or assisted-assembly of nanosize materials, the ability to manipulate and arrange these nanomaterials into useful controlled pattern or structures;
- In nano-photonics. Focuses on photonic bandgap (PBG) or photonic crystals. The project aims to fabricate 3D photonic crystal, using self-assembly and nanolithography methods, along with characterisation and theoretical work in this area;
- In nano-magnetic. Fabrication of nanomagnetic structures, growth and characterisation of ferromagnetic metals for spintronic application, and computer modelling and theory of nanomagnetism will be investigated;
- In nanostructures & Nanomaterials. Development of novel nano-hybrid molecular/inorganic materials, which have potential for commercial applications in electronic, optoelectronic and spintronic devices;
- In molecular functionalisation, assembly & devices. Focus on bridging the molecular and micro levels with the aims to understand the fundamentals of surface forces and interactions, as well as to develop capabilities for fabrication of workable molecular devices. Focal research areas include organised molecular systems, design and control of surface properties, functionalisation, characterisation, molecular imprinting and nanopatterning and molecular and organic electronics;
- In nano/micro fabrication research involves new area of lithography such as proton beam writing on 3D structures, as well as other advanced nanolithography tools.

NUS, in collaboration with DSI have also succeeded in growing the first 2D carbon nanostructures known as carbon nanowalls. Current research has made it possible for the first time to grow carbon nanostructures with zero dimension (0D) to two dimensions (2D) in a well-controlled fashion. Nanowalls may have potential practical application in electronics components such as super capacitors batteries, gas sensors, catalysts, light emission/detection, field emission and biomedical devices. In fact, the group has found that the threshold field emission field of carbon nanowalls is

much lower than that of carbon nanotubes, which makes them very promising for field emission displays and other miniaturised electron sources.

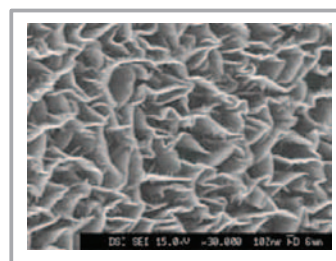


Figure 27. Nanowalls

Source: NUS, Dr Wu Yihong

NanoFrontier Pte Ltd. Spun-off from NTU, NanoFrontier is wholly own by NTU with backing from EDB. It functions as a nanotechnology application development centre (in contract research and development) and industrial resource centre (technology tracking and technology and partner search.) NanoFrontier works together with companies on joint projects to develop nanotechnology enable products, processes and services.

STMicroelectronics has set up a R&D unit called ST Nanotube Centre, on developing applications based on the unique properties of functionalised carbon nanotubes. It is collaborating with the local research institutes to exploit many other areas of nanotechnology.

Atomistix, a Danish company provides modelling software and computational tools to simulate electronic structure and charge transport processes in nanosystems. The software package called the Virtual NanoLab allows scientists and engineers to perform designs and virtual experiments on nanosystems, and to gain insight and understanding of experimental laboratory results. Atomistix has recently setup a R&D and product support centre in Singapore.

Japan's Waseda University and Olympus Corporation have set up a facility in Singapore's Biopolis to specialise in basic research and technology development on neuroscience. Other partners include Duke University from USA and NUS.

Singapore is also drawing investments in OLED manufacturing. It is one of the few countries in the world where state of the art organic light-emitting diode (OLED) displays will be made. By Q2 2005, Eastgate Technology's subsidiary Innoled will start commercial production of OLED. The company also collaborate with IMRE as well as UK Cambridge Display Technology which owns inventions, patents and patent applications related to light-emitting polymers (LEPs). Ness Display Co. Ltd, a South Korean display maker, has also invested \$66 million to set up an OLED display manufacturing plant in Singapore. According to a recent study by iSuppli/Standford Resources, the global market demand for OLED devices is expected to reach US\$3.1 billion by 2009 from about US\$129 million in 2003.

Conclusion

Nano-Bio-Info confluences are enabling technologies towards sentient spaces. We have seen in this report the following:

- The vision of nano-info and bio-info convergence in 2015;
- Computing revolutions with nano;
- Computing revolutions with bio;
- Roadmap for nano-bio-info developments in technology, standards and market trends;
- Summaries of activities in Singapore.

Singapore has recognised the vast commercial potential of nanotechnology to IT and aims to develop capabilities in this area. Over the years, it has built up strong R&D foundation, with research spanning from basic nanoscience in universities to applied nanotechnology in the various research institutions, centres and polytechnics. The institution, DSI for example has strong capability in storage research. The industry development efforts from EDB, strategic R&D programs from A*STAR and initiatives from other stakeholders endorsed a clear direction on Singapore's commitment in nanotechnology. It makes Singapore an attractive place for new business venture, ready to ride on this vision of nano-convergence.

There are opportunities for more corporate nanotech R&D to anchor in Singapore, leveraging on the inherent strength of Singapore's high IT literacy. For instance, R&D activities on advanced storage technologies are important to the economy of Singapore. The hard disk drive industry contributed significantly to the electronic sector. In 2003, the industry employed about 21,000 people, shipped over 100 million drives, constituting about 30% of the world's total hard disk drive, contributing S\$15.8 billion to the Singapore economy or 11% of total Singapore manufacturing output.

Singapore also has one of the largest concentrations of HDD manufacturers or related companies, including Seagate, Western Digital, Hitachi Global, Matsushita, Hoya, Showa Denko and others. However, there are no promises in the future that these manufacturers will continue to retain their manufacturing base in Singapore if lower cost countries such as Thailand, China and India are more cost effective. Hence, in order for Singapore to maintain an attractive base for these companies, it must move up the value chain

vis-à-vis R&D activities by developing and harnessing new capabilities from nanotech with its well established storage infrastructure.

Nanotechnology will play a key role to advance storage technologies. Singapore has competencies in storage technologies with world class research and industry players. Low-powered personal storage devices are critical for mobile users. Future mobile communication devices require exchanging and storing huge amount of multimedia files. Ultra-high density, compact size and power-efficient storage memories and disks will be found in many future mobile and computing devices. Technologies that are attractive include sub 1-inch hard disk i.e. 0.85 inch and below for consumer electronics products. These devices should be easily plug and play and with wireless networking capability. Computing devices incorporating high density non-volatile memories such as MRAM, PRAM or 3D holographic memory technology will become even more critical for fast data retrieval and instant power-up capability.

Low-cost manufacturing is strategic to maintain regional competitiveness. As the existing fabrication methods are getting more expensive to build products, the industry got to find alternative cheaper means of low-cost production. These could include developing plastic electronics capabilities in the near to mid term and advanced self-assembly manufacturing method in the long-term. However, there are still a lot of technical challenges to be solved in these approaches. These create gap that offer opportunities for investment and developing new capabilities for Singapore.

Computational tools and equipment such as mathematical modelling and simulation software are an important element in nano and bio research. These tools will help researchers and scientists discover and understand new properties of materials and molecules at nanoscale, shortening the long learning curve associated with the complexities of molecular science & engineering and quantum physics. Nanotool and equipment with 3D visualisation and haptic interface technologies are also need to practically interact with nanoscale particles. Nanometrology is another potential area where our precision engineering industry could play in this field.

Singapore's well-developed IT infrastructure and the grid computing platform that is currently being put in place will enable researchers and industry to collaborate on nano and biotech research on a global scale. Advanced data mining, recognition and patterning software/middleware will be needed to support/interoperate with this infrastructure.

By exploiting new nanomaterial properties, smart bio and chemical sensors, highly efficient solar cell and high density holographic storage, etc. could be developed. Multi-disciplinary research in material science, optical, bio and chemical engineering are therefore critical to realise the possibility of a cognitive convergent product by 2015.

In the area of bio-inspired computing, while we see initial work and development in this area, much of its promises and potential will likely to mature only beyond 2015, before its enabling technologies reach a productive level vis-à-vis its targeted audience. Nevertheless, this gives us some longer term revolution to look forward to, and more trailblazing research to do meanwhile.

Glossary

μA	microampere	CAD	Computer Aided Design
1 nm	One (1) Nanometre (or 10^{-9} of a metre)	CAGR	Compound Annual Growth Rate
10GEA	10 Gigabit Ethernet Alliance	CAST	Centre for Aging Services Technologies
1G	First Generation	CD	Compact Disc
1R	Re-amplification	CDG	Code Division Multiple Access Development Group
2.5G	Second and the Half Generation	CDM	Code Division Multiplex
2D	Two (2) Dimension	CDMA	Code Division Multiple Access
2G	Second Generation	CDMA 2000	Code Division Multiple Access 2000
2R	Re-amplification and Re-shaping	CIDR	Classless Inter-Domain Routing
3.5G	Third and the Half Generation	CIGS	Copper-Indium-Gallium-Diselenide
3D	Three (3) Dimension	CMOS	Complementary Metal Oxide Semiconductor
3G	Third Generation	CNH	Carbon Nanohorn
3GPP	Third Generation Partnership Project	CNT	Carbon Nanotube
3R	Re-amplification, Re-shaping and Re-timing	CPU	Central Processing Unit
4G	Fourth Generation	CR	Cognitive Radio
4GMF	4G Mobile Forum	CRT	Cathode Ray Tube
A*STAR	Agency for Science, Technology and Research	DAB	Digital Audio Broadcasting
AAA	Authentication, Authorization, and Accounting	DARPA	Defense Advanced Research Projects Agency
AAAC	Authentication, Authorization, Accounting and Charging	DCD	Direct Conversion Device
ADSL	Asymmetric Digital Subscriber Line	DDoS	Distributed Denial of Service
AFM	Atomic Force Microscope	DFB	Distributed Feedback
AMP	Asymmetric Multiprocessing	DiffServ	Differentiated Services
Ångstrom	10^{-10} of a metre	DMFC	Direct Methanol Fuel Cell
ANSINSP	American National Standards Institute Nanotechnology Standards Panel	DMR	Digital Modular Radio
APON	Asynchronous Transfer Mode Passive Optical Network	DNA	Deoxyribonucleic Acid
ASIC	Application-Specific Integrated Circuits	DOCSIS	Data Over Cable Service Interface Specification
ASSP	Application-Specific Standard Product	DoS	Denial of Service
ATM	Asynchronous Transfer Mode	DRAM	Dynamic Random Access Memory
B3G	Beyond 3G	DSC	Dye Solar Cell
BASP	Broadband Access Service Provider	DSI	Data Storage Institute
BCI	Brain Computer Interface	DSL	Digital Subscriber Line
BPON	Broadband Passive Optical Network	DSSS	Direct Sequence Spread Spectrum
BT	British Telecom	DTN	Delay Tolerant Networking
BTI	Bioprocessing Technology Institute	DVB-H	Digital Video Broadcasting-Handheld
BWA	Broadband Wireless Access	DVD	Digital Versatile Disk
C₆₀	Carbon 60 buckyball or Buckminster fullerene	DWDM	Dense Wavelength Division Multiplexing

EDB	Singapore Economic Development Board	HSDPA	High Speed Downlink Packet Access
EDGE	Enhanced Data Rates for GSM Evolution	HVD	Holographic Versatile Disk
eDRAM	Embedded Dynamic Random Access Memory	I/O	Input/Output
EDT	Embedded Data Technology	I²R	Institute for Infocomm Research
EEPROM	Electrically Erasable Programmable Read Only Memory	IC	Integrated Circuit
EFM	Ethernet First Mile	ICANN	Internet Corporation for Assigned Names and Numbers
ENUM	Electronic Numbering	ICT	Information and Communications Technology
EPC	Electronic Product Code	IDA	Infocomm Development Authority of Singapore
EPON	Ethernet Passive Optical Network	IE	International Enterprise Singapore
EPROM	Erasable Programmable Read Only Memory	Singapore	
ERC	Economic Review Committee	IEC	IEC International Electrotechnical Commission
ESA	European Space Agency	IEEE	Institute of Electrical and Electronics Engineers
eSRAM	Embedded Static Random Access Memory	IETF	Internet Engineering Task Force
EU	European Union	IHPC	Institute of High Performance Computing
EUDCH	Enhanced Uplink Data Channel	IME	Institute of Microelectronics
FAA	Federal Aviation Administration	IMRE	Institute of Materials Research & Engineering
FARADS	Forwarding Directives, Associations, Rendezvous, and Directory Service	IMT-2000	International Mobile Telecommunications-2000
FBO	Facilities-Based Operators	Info-MICA	Information-Multilayered Imprinted CARD
FCC	Federal Communications Commission	IntServ	Integrated Services
FDD	Frequency Division Duplex	IP	Internet Protocol
FDDI	Fibre Distributed Data Interface	IPSec	IP Security
FDMA	Frequency Division Multiple Access	IPv4	Internet Protocol version 4
FED	Field Emission Display	IPv6	Internet Protocol version 6
FeRAM	Ferroelectric Random Access Memory	IRAM	Intelligent Random Access Memory
FET	Field Effect Transistor	ISDB-T	Integrated Services Digital Broadcasting Terrestrial
FF	Form Factor	ISDN	Integrated Services Digital Network
FHSS	Frequency Hopping Spread Spectrum	ISM	Industrial, Scientific and Medical
FOLED	Flexible OLED	ISO	International Standards Organization
FOMA	Freedom of Mobile Multimedia Access	ISP	Internet Service Provider
FP	Framework Programme	IST	Information Society Technologies
FPGA	Field Programmable Gate Array	IT	Information Technology
FSO	Free Space Optics	ITR	Infocomm Technology Roadmap
FTTH	Fibre-To-The-Home	ITRS	International Technology Roadmap for Semiconductor
GB	Gigabyte	ITU	International Telecommunication Union
Gb/in²	Gigabit per square inch	ITU-R	International Telecommunication Union – Radio-communication Standardization Sector
Gbit	Gigabit	ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
or Gb		JTRS	Joint Tactical Radio System
GDP	Gross Domestic Product	KAIST	Korea Advanced Institute of Science and Technology
GHz	Gigahertz	Kbps	Kilobits per second
GNI	Gross National Income	KHz	Kilohertz
GPON	Gigabit Passive Optical Network	Lambda	Light wavelength (λ)
GPRS	General Packet Radio Service	LAN	Local Area Network
GSM	Global System for Mobile Communications		
GSMA	Global Mobile Suppliers Association		
HAMR	Heat-Assisted Magnetic Recording		
HCI	Human Computer Interface		
HDD	Hard Disk Drive		
HDTV	High Definition Television		
HFC	Hybrid Fibre Coaxial		

LBS	Location Based Services	OFCDM	Orthogonal Frequency Code Division Multiplexing
LCD	Liquid Crystal Display	OFDM	Orthogonal Frequency Division Multiplexing
LCOS	Liquid Crystal On Silicon	OFET	Organic Field Effect Transistor
LDPC	Low Density Parity Check	OLED	Organic Light Emitting Diode
Li-ion	Lithium Ion	OLT	Optical Line Terminating
Li-polymer	Lithium Polymer	ONU	Optical Network Unit
LSI	Large Scale Integration	OOO	All Optical
mA	milliampere	OS	Operating System
MAMMOS	Magnetically Amplifying MO System	OSC	Organic Solar Cell
MAN	Metropolitan Area Network	OSI	Open Systems Interconnection
Mbps	Megabits per second	OTDM	Optical Time Division Multiplexing
MBWA	Mobile Broadband Wireless Access	OUM	Ovonics Unified Memory
MEMS	Micro electro mechanical System	OXC	Optical Cross Connect
MFC	Micro Fuel Cell	P2P	Peer-to-Peer
MIMO	Multiple Input Multiple Output	PAN	Personal Area Network
mITF	Mobile IT Forum	PBG	Photonic Band Gap
ML	Markup Language	PC	Personal Computer
Moletronics	Molecular Electronics	PCF	Photonic Crystal Fibre
MOSFET	Metal Oxide Semiconductor Field Effect Transistor	PDP	Plasma Display Panel
MP3	MPEG-1 Audio Layer-3	PEDGUI	Printed Embedded Data Graphical User Interface
MPLS	Multi-Protocol Label Switching	PET	Privacy Enhancing Technology
MRAM	Magnetoresistive Random Access Memory	PHI	Public Health for the Internet
MRI	Magnetic Resonance Imaging	PHY	Physical Layer
MSRC	Modular Software-Programmable Radio Consortium	PKI	Public Key Infrastructure
MTBF	Mean Time Between Failure	PLC	Powerline Communications
mW	milliwatt	PLD	Programmable Logic Device
MWNT	Multiwall Carbon Nanotube	PLED	Polymer Light Emitting Diode
NASA	National Aeronautics and Space Administration	PMR	Perpendicular Magnetic Recording
NAT	Network Address Translation	PON	Passive Optical Network
NED	Nano Emission Display	PRAM	Phase Change Random Access Memory
NEMS	Nano Electro Mechanical System	PSTN	Public Switched Telephone Network
NGN	Next Generation Network	PV	Photovoltaics
Ni-Cad	Nickel Cadmium	PZT	Lead-Zirconium-Titanate
NiMHd	Nickel Metal Hydride	QD	Quantum Dot
NIST	National Institute of Standards & Technology	QoS	Quality of Service
NRAM	Nanotube Random Access Memory	R&D	Research & Development
ns	nanosecond	RAM	Random Access Memory
NTRC	Network Technology Research Centre	RANT	Random Access Nanotube Test
NTU	Nanyang Technological University	RAW	Reconfigurable Architecture Workstation
NTUNNC	NTU Nanoscience & Nanotechnology Corridor	RBA	Role-Based Architecture
NUS	National University of Singapore	RDF	Resource Description Framework
NUSNNI	NUS Nanoscience & Nanotechnology Initiative	redox	Reduced or Oxidised
OADM	Optical Add-Drop Multiplexer	RF	Radio Frequency
OCDM	Optical Code Division Multiplexing	RFID	Radio Frequency Identification
OECD	Organisation for Economic Co-operation and Development	RSA	Rivest, Shamir, & Adleman (public key encryption technology)
OEO	Optical Electrical Optical	RSVP	Resource ReSerVation Protocol
		RTD	Resonant Tunnelling Diode

S&T	Science & Technology	THz	Terahertz
SBO	Services-Based Operators	TiO ₂	Titanium Dioxide
SBT	Strontium-Bismuth-Tantalum oxide	TLD	Top Level Domain Names
SCA	Software Communications Architecture	TOLED	Top-emitting Organic Light Emitting Diode
SCTP	Stream Control Transmission Protocol	TV	Television
SDMA	Spatial Division Multiple Access	UDP	User Datagram Protocol
SDR	Software Defined Radio	UHF	Ultra High Frequency
SED	Surface-conduction Emission Display	UK	United Kingdom
SEM	Scanning Electron Microscopy	UMTS	Universal Mobile Telephone System
SET	Single Electron Transistor	US	United States
SHDSL	Single-Pair High-Speed Digital Subscriber Line	USB	Universal Serial Bus
Si/SiO ₂	Silicon / Silicon Dioxide	UTRA	Universal Mobile Telephone System Terrestrial Radio Access
SiGe	Silicon Germanium	UWB	Ultra-Wideband
SIMTech	Singapore Institute of Manufacturing Technology	V	Volt
SME	Small Medium Enterprise	VDSL	Very High-Speed Digital Subscriber Line
SMOLED	Small Molecule Organic Light Emitting Diode	VHF	Very High Frequency
SMP	Symmetric multiprocessing	VLSI	Very Large Scale Integration
SOA	Semiconductor Optical Amplifier	VoIP	Voice over Internet Protocol
SOC	System On the Chip	VRD	Virtual Retinal Display
SOFC	Solid Oxide Fuel Cell	VSF	Variable Spreading Factor
SOI	Silicon On Insulator	W3C	World Wide Web Consortium
SOMA	Self Organised Magnetic Arrays	WAN	Wide Area Network
SPRING	Standards, Productivity and Innovation Board	WCDMA	Wideband Code Division Multiple Access
SRAM	Static Random Access Memory	WDM	Wavelength Division Multiplexing
SSH	Secure Shell	WG	Work Group
SSL	Secure Socket Layer	Wi-Fi	Wireless Fidelity or IEEE 802.11b
STN	Super Twisted Nematic	WiMAX	Worldwide Interoperability for Microwave Access
SWNT	Single Wall Carbon Nanotube	WLAN	Wireless Local Area Network
TB	Terabyte	WMAN	Wireless Metropolitan Area Network
Tb/in ²	Terabit per square inch	WORM	Write Once Read Many
Tbit	Terabit	WPAN	Wireless Personal Area Network
TCP	Transmission Control Protocol	WRAN	Wireless Regional Area Networks
TDD	Time Division Duplex	WWiSE	World Wide Spectrum Efficiency
TDM	Time Division Multiplexing	WWRF	Wireless World Research Forum
TDMA	Time Division Multiple Access	XML	Extensible Markup Language
TD-SCDMA	Time Division Synchronous Code Division Multiple Access	ZnMnTe	Zinc Manganese Tellurium
TFT	Thin Film Transistor		

Your Feedback

Your feedback will help us improve on future reports. You can find the feedback survey form on the next page. If you have other queries on roadmap matters, technology proposals or suggestions, you can also reach us at:

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Singapore Infocomm Foresight 2015 March 2005 Release

Your feedback is valuable to us to better our future services for you. We appreciate if you could spare a few minutes to fill up the following survey.

Please return the completed questionnaire to IDA:

via Fax: +(65) 6211 2211 (Attentioned to Ms Saliza Mohd)

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Usefulness of the roadmap report	6	5	4	3	2	1
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Ease of understanding	6	5	4	3	2	1
Relevance to you or to your business strategy/ planning	6	5	4	3	2	1

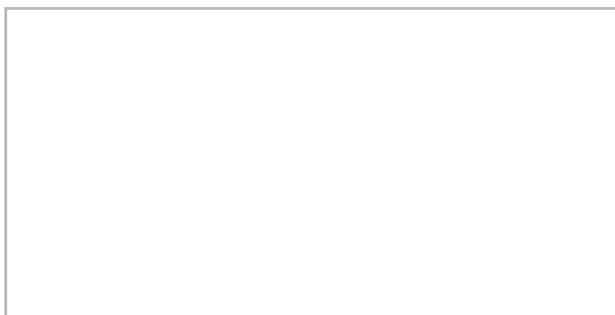
Comments (if any):

2. Please indicate the accuracy (in terms of trend & development) for the following tracks on a scale of 1 to 6.

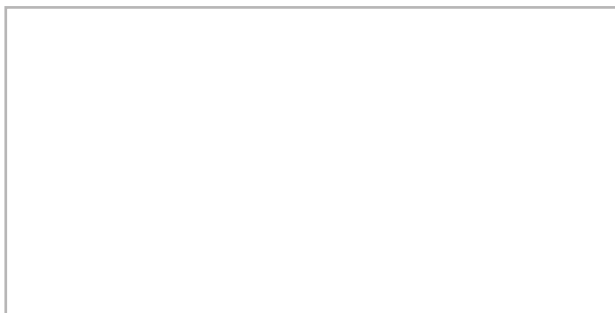
Track	Accurate					Inaccurate
Sentient Technologies	6	5	4	3	2	1
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