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A Fast Track Analysis of ICT Constraints on Evolving Physical Infrastructure

Roberta Velykiene and Cliff B. Jones

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About the authors

Roberta Velykiene is a PhD student in the ITRC project. Roberta gained her BSc in Applied Mathematics at Kaunas University of Technology, Lithuania. She continued her studies with an MSc in Mathematical Finance at the University of York, UK, for which she was awarded the degree with distinction.

Cliff B. Jones is currently Professor of Computing Science at Newcastle University. As well as his academic career, Cliff has spent over 20 years in industry. His 15 years in IBM saw among other things the creation –with colleagues in Vienna– of VDM which is one of the better known “formal methods”. Under Tony Hoare, Cliff wrote his doctoral thesis in two years. From Oxford, he moved directly to a chair at Manchester University where he built a world-class Formal Methods group which –among other projects– was the academic lead in the largest Software Engineering project funded by the Alvey programme (IPSE 2.5 created the “mural” (Formal Method) Support Systems theorem proving assistant). He is now applying research on formal methods to wider issues of dependability. Until 2007 his major research involvement was the five university IRC on “Dependability of Computer-Based Systems” of which he was overall Project Director. He is also PI on an EPSRC-funded project “AI4FM” and coordinates the “Methodology” strand of the EU-funded DEPLOY project. He also leads the ICT research in the ITRC Program Grant. Cliff is a Fellow of the Royal Academy of Engineering (FREng), ACM, BCS, and IET. He has been a member of IFIP Working Group 2.3 (Programming Methodology) since 1973 (and was Chair from 1987-96).

A Fast Track Analysis of ICT Constraints on Evolving Physical Infrastructure

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Abstract

This technical report investigates whether *Information Technology* and *Communication* (ICT) is likely to inhibit the development of physical infrastructures (energy, transport, water and waste). A brief overview of the current/future status of ICT infrastructure is provided, followed by a discussion of key issues and future risks. The report constitutes one input to a "Fast Track Analysis" being prepared by the *Infrastructure Transitions Research Consortium* (ITRC).

1 Introduction

1.1 The ITRC project

As physical infrastructures become more sophisticated and loaded to capacity they become more interdependent and rely more on ICT. The EPSRC Programme Grant *Infrastructure Transitions Research Consortium* (ITRC) was established to study these links.[1] The interactions between human (e.g. economic) and natural (e.g. climate change) factors with the national infrastructure (NI) (energy, transport, water, waste and ICT) need to be understood as well.

The project aims to identify significant vulnerabilities or capacity limitations of the NI and develop models and tools to inform analysis, planning and design of the NI.

The *Fast Track Analysis* (FTA) focuses on modelling the long-term capacity and demand for physical infrastructure services with respect to long-term infrastructure strategies under different scenarios. The ICT part of the report has a support role for physical infrastructures and aims to identify possible capacity limitations and vulnerabilities within ICT that could affect the future development of physical infrastructures.

1.2 ICT

The term ICT is used here to embrace both *Information Technology* and *Communication*. Under Information Technology (IT), both hardware and software are considered; it is also pointed out that Communications are highly dependent on IT because the switches that direct communications are computer systems. A further reason for emphasising the role of IT in ICT infrastructure is that IT systems make up significant parts of other sectors or physical infrastructures. The IT systems (e.g. smart grid, traffic control systems) can be considered large, expensive and with long development times.

As has been studied in the earlier *DIRC* Interdisciplinary Research Collaboration[2] (see Besnard et al., 2006), understanding the roles of the human participants in any complex system is crucial.

Whilst it is clear that state-of-the-art physical infrastructure systems rely on all aspects of ICT, this report provides evidence that there is ample ICT capacity so that it should not inhibit the growth of any of the physical infrastructure systems. This is by no means an argument for complacency. First, there is the opportunity to search for smarter ways to reduce wastage of, say, travel by developing further ways of using

[1] See www.itrc.org.uk
[2] See www.dirc.org.uk

ICT. More worryingly, ICT probably presents an easy target for malicious attack on the UK's NI. These future concerns, and a concern about the availability of adequate numbers of skilled system designers are explored below.

It must be emphasised that ITRC is not resourced to undertake a survey of ICT *per se*. It is the connections between ICT and the physical infrastructures that is of concern to ITRC. A study of the fast evolving ICT sector would be most valuable but is not within the scope of the ITRC project.

1.3 Future research

- The NI interdependencies add layers of complexity in demand planning, and uncertainty in risk evaluation.
- Furthermore, we recognize that the dependability of "Computer-Based Systems" (Besnard et al., 2006) relies heavily on suitable interaction with users.
- We intend to understand the various dimensions of interdependencies.
- The techniques used in studying "dependable systems" (e.g. Randell, 2000) will be used to investigate the risks of cascading failure.

2 The infrastructure system

In comparison to the physical infrastructures, ICT is a new and rapidly changing sector but it is not as clearly defined and understood. Therefore, we first aim to establish the scope of ICT for the analysis. After this, we outline some features of ICT infrastructure that are different from those in the physical sectors. Finally, most of this section aims to give an overview of the current state of ICT in the UK. This is structured by separating different constituent parts of the infrastructure.

2.1 Scope of ICT infrastructure

We consider ICT infrastructure to comprise provision of options for information-related activities. ICT infrastructure is the collection of all IT technologies, physical facilities and human systems that are operated in a coordinated way to provide these services, namely to provide for transmission, processing and storage of *information*.

ICT is a combination of communications technology and information technology (IT):

- Communications cover the whole of networks, systems and artefacts which transport and store data. These include wired and wireless networks and their components (cables, masts, satellites, etc.), as well as broadband, voice, data, positioning and broadcast services.
- Within IT, we include the software and systems that store and process the information. This is generally shared with the different sectors or infrastructures, such as transport, health, governance, etc. Examples include traffic control, smart grid, health, bank and other IT systems.
- Within both communications and IT, people must also be considered as part of the systems. These include operators, developers and other ICT specialists.

Many reports on ICT consider only the communications part of the ICT infrastructure. However, we consider IT to be part of ICT infrastructure as well, because these systems manipulate and transform the information and participate in the information routing process.

ICT is highly interdependent with physical infrastructures. Its components, especially IT systems, make up important parts of other sectors or infrastructures. For example, we consider an IT-based traffic control system to be a component of the transport infrastructure, as well as part of ICT.

The ICT sector differs significantly from physical infrastructures. The rapid growth and frequent changes of ICT sector, with continual introduction of new technologies and usage patterns, make it harder to use the methods of analysis and forecasting appropriate to the physical infrastructures. The ICT sector is mostly commercially driven and has a strong international dimension and dependence, which further increases the complexity of analysis.

ICT artefacts are generally smaller, less expensive and have shorter lifetimes, thus infrastructure expansion can mostly be made in a rapid fashion without constructing large, physical objects. However, some artefacts such as IT systems can be considered large, expensive and with long development times. Furthermore, ICT systems are subject to "generation" upgrades, development and deployment of which is also significant and costly.

2.2 Current state of ICT in the UK

The overall strength of ICT infrastructure in the UK is among the best in the global context. The evaluations differ in various reports, but the UK is ranked within the top 15 global economies. According to the ICT Development Index, the UK is 10th out of 152 world economies. The index reflects the level of network infrastructure and access to ICTs; the level of use of ICTs in society; the result/outcome of efficient and effective ICT use (ITU, 2011). The World Economic Forum ranks the UK at 15 for ICT infrastructure strength using Network Readiness Index[3] (Dutta and Mia, 2011).

Remaining competitive in the ICT industry and keeping up with the development in a global context was stated as a goal for ICT infrastructure investment strategy in the UK. It must however be remembered that having led the world in computer innovation, currently the UK has hardware companies only in niche markets and that there are very few major software manufacturers.

Table 1 provides a short overview of the current state of the ICT sector.

Table 1: Current State of ICT

Computation	The speed increase of raw computation is exponential (well described by Moore's law). **We argue that available computation power will be enough to support foreseeable developments of physical infrastructures.** The power efficiency of computation has on average doubled every 1.57 years over the period of years 1975 to 2009 (Koomey et al., 2011).
Communication	Analogue terrestrial TV and Dial-up Internet have become things of the past. Their take-up in the UK in 2011 is 4% and 2%, respectively. Fixed line telephony continues to decline: the saturated fixed-lines market has been overtaken by mobile-cellular telephony (Ofcom, 2011a). Mobile-cellular telephony has also reached saturation levels recording penetration rates of over 91% (Ofcom, 2011a). Ofcom reports an increase of fixed-broadband take-up from 3% in 2002 to 74% in 2010. Current (May 2011) average actual broadband speeds are at 6.8 Mbit/s (Ofcom, 2011a). Mobile Internet – at broadband speeds – was practically non-existent in year 2000. Now, the take-up of mobile broadband continues to rise and stands at 17%, while 7% of the population relies solely on a mobile broadband service in 2011 (Ofcom, 2011a). The UK government has allocated £830m to assist in providing the UK broadband network of at least **2Mbit/s broadband to all UK homes by 2015**. In addition, **superfast broadband should be available to 90% of people in each local authority area.**

[3]The Networked Readiness Index (NRI) featured in the report examines how prepared countries are to use ICT effectively on three dimensions: the general business, regulatory and infrastructure environment for ICT.

Radio Spectrum	The radio spectrum is used by all wireless services: mobile communications, sound and television broadcasting, satellite and others. The resource is finite and certain users (e.g. mobile communications) are at their allocation limits. The public sector is a major holder of spectrum with almost 50% of spectrum below 15GHz allocated (DCMS, 2011b). The radio spectrum allocation results in inequalities and inefficiency of spectrum use: according to some reports, less than **14% of radio spectrum is busy at any given time** (Rubenstein, 2007). The UK government is auctioning parts of public spectrum to satisfy the demand (DCMS, 2011b).
Satellite Communications	The global demand for fixed satellite services is within the available capacity, expected to be at about 79-82% of available capacity in 2011, according to various estimates (GAO, 2011). The global satellite industry posted growth of 11% in 2009 and 5% in 2010 (SIA and Futron, 2011). The growth is expected to continue. Euroconsult estimates 1145 satellites will be built and launched in the period 2011-2020, an increase of about 51% compared to the previous decade (2001-2010) (Euroconsult, 2011).
GNSS	The US-owned GPS is used most widely for navigation services but Europe's Galileo and the latest generation of Russian GLONASS systems are expected to be completed in the near future (EP, 2011; GPS World, 2011). Each system will have full global coverage and it is expected that new consumer devices will support more than one GNSS system (Amos, 2011; BBC, 2011; RAEng, 2011).
IT & Data Processing	IT is a significant component of all physical infrastructure and of government itself. Large IT projects are time consuming and expensive parts of the ICT infrastructure. In 2003, government had 100 major IT projects with a total value of £10bn (POST, 2003). Newer data shows **£16bn annual expenditure on IT in 2009**, with some IT projects being huge (e.g. £12bn NHS IT project, National Programme for IT) (Treasury, 2009). The recent emergence of cloud computing is providing greater business efficiency and lower start-up costs. Private cloud computing is being considered within the UK government (G-Cloud, which could enable £3.2bn savings (Cabinet Office, 2010a)) and academia.
Legislation & Regulation	The UK communications industries are regulated by Ofcom as well as various international bodies.

2.3 Current state of computational hardware

Modern computers are built from integrated circuits that create the equivalent of transistors on tiny areas of (mainly) silicon. The industry trends (e.g. hardware speed) are well described by Moore's law[4], which is a prediction about the feature size of micro-electronic circuits. But because the speed of light is constant, smaller circuits compute faster. Since Gordon Moore made the observation in 1965, the prediction of exponential development has held remarkably constant and has yielded exponential growth in speed computation devices and capacity of storage facilities. (There is in fact a potential future economical snag: each step in the development has cost major investment to produce high yields in what is now an extremely intricate process. A monopoly situation could arise where very few companies/countries can afford the investment to make further steps.)

While the scale of detail in circuits approaches atomic level and Moore's law slows, several options are available to prolong the exponential growth in computational power (see Section 3.2).

Another benefit of Moore's Law is that the energy consumption of circuits has decreased over time (early valve computers, and even second generation transistor machines, used prodigious amounts of electricity and

[4]Moore's law: The number of transistors that can be placed inexpensively on an integrated circuit doubles approximately every two years. (The common simplification that "computing capacity doubles every two years" is thus not quite accurate.)

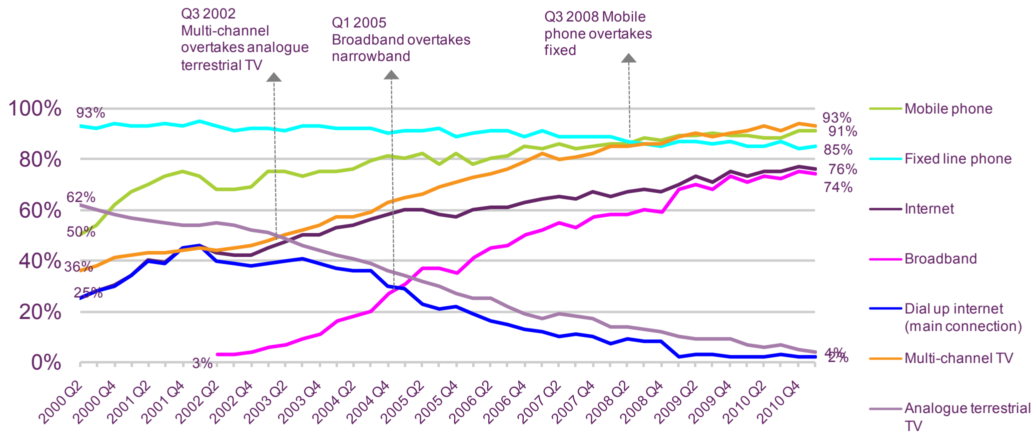

Figure 1: Take-up of communications services, 2000-2011 (Ofcom, 2011a)

cooling was a major concern). The electrical efficiency of computation (computations per kilowatt-hour) has on average doubled every 1.57 years over the period of years 1975 to 2009. Shrinking transistor size resulted in improved speed, reduced cost, and reduced power use per transistor (Koomey et al., 2011).

There is however one sense in which most computer chips are incredibly wasteful of the energy they do consume. Essentially, at each clock cycle, every single circuit is active. In contrast, there are "asynchronous" (or self-clocked) designs where computation is performed (and energy consumed) only when there is something to do. The design of asynchronous circuits is vastly more difficult than conventional clocked systems but the effort is worthwhile for mobile devices such as mobile phones where battery life is a key concern. It is likely that asynchronous circuits will be deployed more widely in the future.

With the current available computation resources, we are nowhere near needing all of the computation power available today in order to support the physical infrastructures. When computation power (or communication bandwidth) doubles that translates to being able to redo everything that has been ever done.

2.4 Current state of communication

As with silicon chips, the growth in available bandwidth has been exponential and the trends appear to continue. This is, perhaps, a more tangible resource to make the point about the "Parkinson-like" way in which this bandwidth has been absorbed. Only 20 years ago, home access to the Internet was often at 9.6Kb (Lawyer, 2007) – this made it usable mainly for e-mail (with an injunction to keep messages short). Better bandwidth made it thinkable to download CD-scale music items and today we have streaming HD television on demand. The growth in availability has created whole new expectations.

At present, analogue terrestrial TV and dial-up Internet have become things of the past. Their take-up in the UK in 2011 is 4% and 2%, respectively. Fixed line telephony continues to decline: a saturated fixed-lines market has been overtaken by mobile-cellular telephony. Mobile-cellular telephony has reached saturation levels, too, recording penetration rates of over 91% (see Figure 1).

Broadband connection is provided by different networks: fixed, wireless, mobile, etc. Ofcom reports an increase of fixed-broadband take-up from 3% in 2002 to 74% in 2010. Current (May 2011) average actual broadband speeds are at 6.8 Mbit/s (Ofcom, 2011a).

Upgrade to the next generation of super-fast fixed broadband is underway, started in 2010. This is driven by the private sector (primarily Virgin Media and BT) and the UK government. Over half of all UK households are within easy reach of super-fast[5] broadband lines, with possible speeds of 40-100Mbit/s (Ofcom, 2011a).

The UK government has allocated £830m to assist in providing the UK broadband network of at least 2Mbit/s broadband to all UK homes by 2015. In addition, superfast broadband should be available to 90%

[5]Super-fast broadband is classed as connections with headline speeds above 'up to' 24Mbit/s.

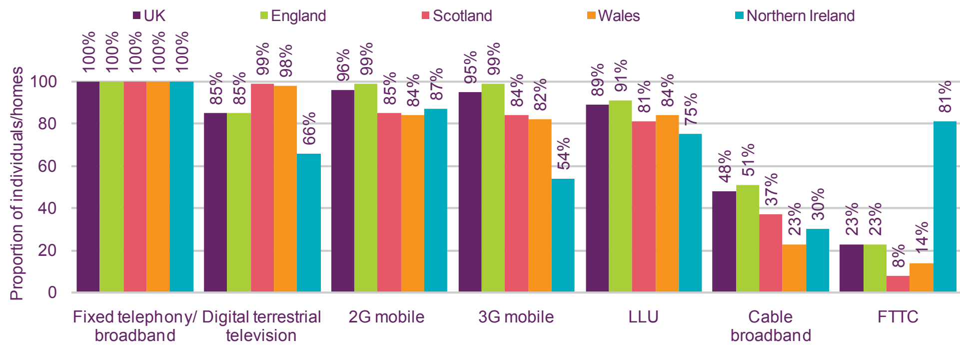

Figure 2: Communications infrastructure availability across the UK's nations by percentage of population covered (Ofcom, 2011a)

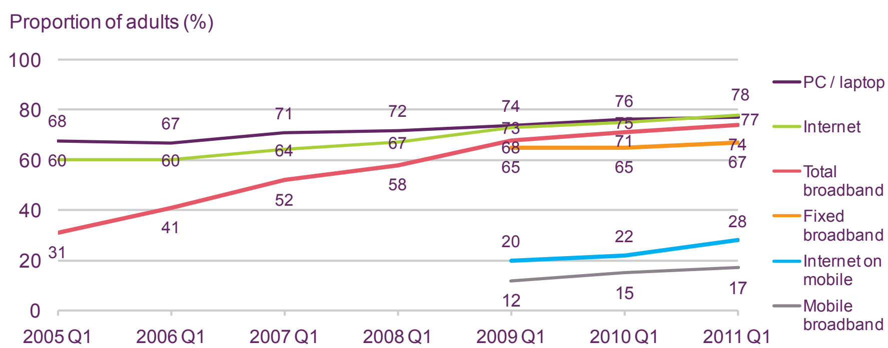

Figure 3: Household penetration of broadband (Ofcom, 2011a)

of people in each local authority area[6]. Current ICT infrastructure availability is displayed in Figure 2. The percentages show proportion of population living in postal districts where at least one operator reports at least 90% coverage.

Wireless-broadband Internet access remains the strongest growth sector. Mobile Internet – at broadband speeds – was practically non-existent in year 2000[7]. Now, the take-up of mobile broadband continues to rise and currently stands at 17%, while 7% of the population relies solely on a mobile broadband service in 2011 (Ofcom, 2011a).

Figure 3 shows increase in broadband take-up – Internet penetration now exceeds PC penetration. The use of the Internet on a mobile phone has grown substantially, driven by the growth in the smartphone market and mobile networks offering competitive mobile data packages, both allowing easier and more affordable access to mobile Internet services than before.

The demand for mobile Internet is increasing with the "smartphone revolution": 27% of UK adults now claim to own one, 32% of people use their mobiles to access the internet. Year 2010 saw a 67% increase in data transferred over the UKs mobile networks (Ofcom, 2011a). Increase in demand has shifted the strategic focus of telecoms service providers towards driving up the availability of higher-speed networks. Mobile operators are continuing to upgrade their 3G[8] networks to offer higher data speeds. Next-generation 4G[9] networks would exceed super-fast fixed broadband speeds.

[6] Recent information about investments on 14 August 2011 in Guardian: www.guardian.co.uk/business/2011/aug/14/superfast-broadband-go-uk-wide

[7] 2nd generation mobile services (2G) only provided SMS data services, but no internet (this was 2.5G).

[8] 3G specifies 100kbit/s broadband speeds.

[9] 4G specification defines 100Mbit/s speed for moving (cars, trains), 1Gbit/s for pedestrians and stationary.

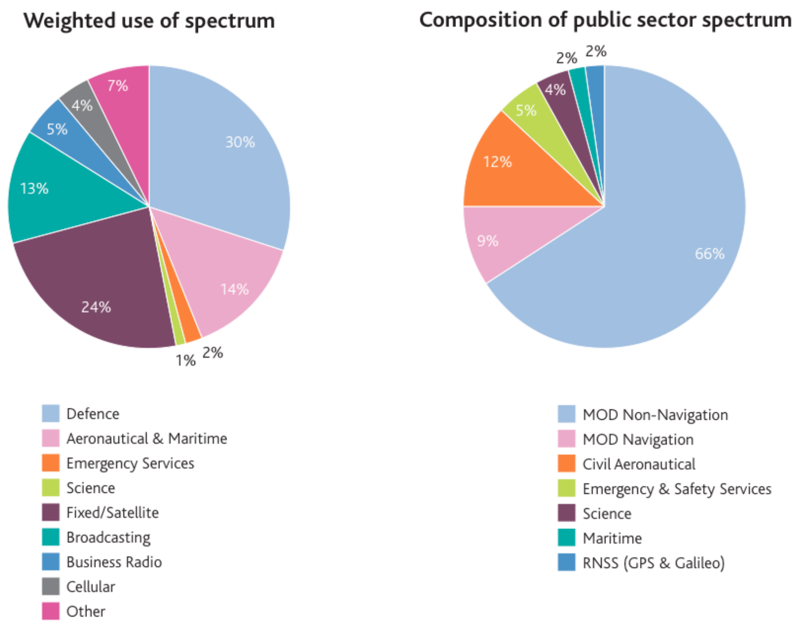

Figure 4: Weighted use of spectrum and composition of public sector spectrum holdings below 15GHz (DCMS, 2011b)

2.5 Current state of radio spectrum

Wireless communications and broadcasting infrastructure depend on available radio frequency spectrum to transfer the information. Demand for radio communications grows both in number and variety of applications: mobile communications, sound and television broadcasting, aviation, railway and maritime transport, defence, medical electronics, emergency services, remote control and monitoring, radio astronomy and space research.

The radio spectrum is a finite resource and is controlled by the government. It controls the frequency usage and sells licenses. The public sector is a major holder of spectrum with almost 50% of spectrum below 15GHz allocated to this sector (see Figure 4) (DCMS, 2011b). The historical circumstances yielded the most desirable ranges of the radio spectrum to radio and television broadcasting. Furthermore, certain parts of the spectrum work the best for certain radio applications (Rubenstein, 2007).

The radio spectrum allocation results in inequalities of spectrum use. For example, mobile-broadband technologies are limited by the available spectrum, while other applications do not use their spectrum efficiently. By some accounts less than 14% of radio spectrum is truly busy at any given time (Rubenstein, 2007).

Switchover from analogue to digital terrestrial signals in television and radio is freeing up radio spectrum allocated for these services. Switching all analogue services to digital would free up 75% of the currently occupied spectrum (BBC, 2006). Currently digital television switchover stands at 96% availability in the UK, including completed process (99%) in Wales. BBC digital audio broadcasting (DAB) network covers 92% of households, with the DAB commercial available to 85% of the UK population (it is not available in Northern Ireland) (Ofcom, 2011a). The UK digital television switchover is planned to complete in 2012, when analogue signals will be switched off (DCMS, 2011a).

The finiteness of radio spectrum availability is an important issue for wireless communications. Various options to address this, e.g. by increasing the efficiency of spectrum use via better technology or spectrum reuse, are available. See further discussion in Key issues and options (Section 3.9).

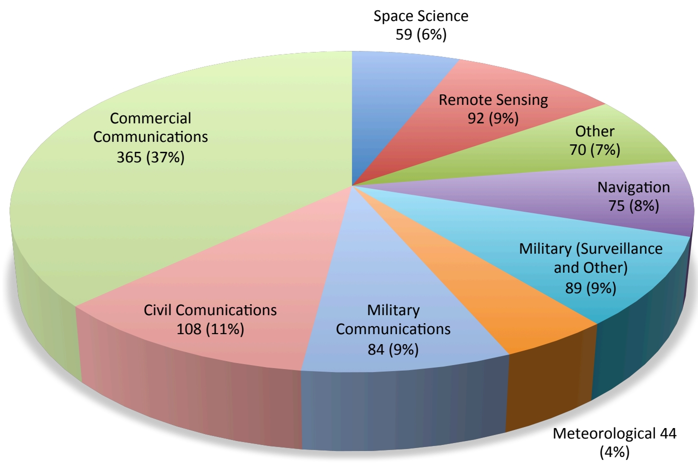

Figure 5: Operational Satellites by Function (June 2011) (SIA and Futron, 2011)

2.6 Current state of satellite communications

Satellite communications are comprised of satellites orbiting the Earth and a number of ground stations communicating with the satellites. The satellites mostly act as signal reflectors, whereas ground stations can send signals to satellite (e.g. telephones, TV broadcaster), receive the signals (e.g. telephones, TV receivers) or both (Hart, 2000).

The main advantage of satellite services is that they require little terrestrial infrastructure, thus services can be available in remote areas with poor or no communications infrastructure. The most common consumer services include satellite television, radio, broadband, telephony and positioning (SIA and Futron, 2011).

The satellite industry is a subset of both telecommunications and space industries, with very high involvement of non-commercial organisations. As shown in Figure 5, of the 986 satellites on orbit, 37% are commercial communications satellites. The industry represents only 4% of telecommunications industry revenues, and 61% of space industry revenues (SIA and Futron, 2011).

The global demand for fixed satellite services is within the available capacity, expected to be at about 79-82 percent of available capacity in 2011, according to various estimates (GAO, 2011). The global satellite industry posted growth of 11% in 2009 and 5% in 2010 (SIA and Futron, 2011). The growth is expected to continue. Euroconsult estimates 1145 satellites to be built and launched for the period 2011-2020, an increase of about 51% compared to the previous decade (2001-2010). This is fuelled by expansion of satellite services, by both government and commercial organisations (Euroconsult, 2011).

Recent advances in satellite technology allowed operators to offer satellite broadband services to residential customers at an affordable price. The service is aimed at customers in areas which are not otherwise reached by wired or wireless broadband services. The speeds are comparable to those offered by some wired broadband services, but are expected to be significantly lower than can be offered by fibre networks. Furthermore, the service is limited due to latency and noise issues, as well as limited radio spectrum (Hart, 2000; OECD, 2008). See further discussion in Key issues and options (Section 3.8).

Within the UK, satellite TV broadcasting utilises several commercial satellites and is considered to cover 98% of the UK population. Three satellites carry both a range of subscription television services (e.g. BSkyB) and the Freesat service from BBC/ITV (Ofcom, 2008).

2.7 Current state of global navigation satellite systems

Global Navigation Satellite Systems (GNSS) provide position, navigation and timing services via satellites. The original implementation of GNSS is the Global Positioning System (GPS), which is operated by the US. Alternative GNSS systems also exist or are being developed, notably the Russian GLONASS system, Galileo in Europe and Compass in China, which operate in approximately the same way (RAEng, 2011).

The navigation system consists of a control segment, at least 24 satellites and user receivers. The receivers calculate the position by comparing time signals from different satellites. The demand for and reliance on navigation systems is growing, with applications encompassing road, air, maritime and rail transport, cellular and data networks, emergency services, and others (RAEng, 2011). The high reliance on GNSS services requires improved resilience, which could be achieved with availability of multiple systems and technological upgrades. See further discussion in Key issues and options (Section 3.8).

The GNSS services to consumers are provided commercially, however commercial bodies own none of the satellites (Engel, 2011). Satellite navigation is considered a civil as well as military asset.

The US-owned GPS is used most widely for navigation services, but Europe's Galileo and the latest generation of Russian GLONASS systems are expected to be completed in the immediate future (EP, 2011; GPS World, 2011). Each system will have full global coverage: GPS had 32 satellites in service in January 2011, GLONASS - 24, Galileo will also have 24 satellites and it is expected that consumer devices will support more than one GNSS system (Amos, 2011; BBC, 2011; RAEng, 2011). For example, Galileo is designed to be inter-operable with GPS and GLONASS (ESA, 2011).

2.8 Current state of IT & data processing

Dependence on Information Technology (IT) has accelerated during the last two decades. Building upon the communication networks, information processing systems and services are taking more important roles. Effective information and technology are essential assets of government, which government employees and general public rely on. IT projects (especially large-scale ones) are emerging as significant parts of various infrastructure sectors and government itself.

Within the UK government, IT is applied in different ways: providing public services online, developing business intelligence systems to process information and assist with decisions, using business systems to support government operations, such as tax collection or benefits payments, and various back office systems to assist with day-to-day operations (e.g. finance, human resources, other systems) (CAG, 2011).

IT represents a significant investment from the UK government. In 2003, government had 100 major IT projects, with a total value of £10bn (POST, 2003). Newer data shows £16bn annual expenditure on IT in 2009, with some IT projects being very large in size (e.g. £12bn NHS IT project, National Programme for IT) (Treasury, 2009). Large-scale IT projects face difficulties in successful completion both in public and private sectors. Large IT projects are developed within UK physical infrastructure services, such as congestion charging or Oyster card services in London, which improved Transport infrastructure (Stephen et al., 2011). The next generation Energy network – Smart Grid – will have a major IT component, which the network operation will rely upon (Liebenau et al., 2009). The private sector is investing into online services and IT systems for infrastructure, such as train ticket bookings, real-time train service updates, etc.

The IT landscape is changing for other organisations and SMEs as well. The recent emergence of cloud computing is providing greater business efficiency and lower start-up costs. By using the cloud, organisations do not need to set up local ICT infrastructure and can scale their systems on demand. Private cloud computing is being considered within the UK government (G-Cloud, which could enable £3.2bn savings (Cabinet Office, 2010a)) and academia (e.g. e-Science Central).

2.9 Current state of ICT legislation and regulation

Ofcom is the independent organisation that regulates the UK communications industries, with responsibilities across telecommunications, wireless communications services, television and radio.

The ICT sector has strong international presence and is subject to regulation by various international bodies. Such agreements may have the force of international treaties and can take many years to change (DCMS, 2011b). Furthermore, certain legislation and regulation regarding ICT by the EU (e.g. European Commission) is binding to the UK.

The use of ICT services and digital information in the UK is governed by several laws, such as the Data Protection Act (1998), Computer Misuse Act (1990), Freedom of Information Act (2000), various non ICT-specific legislation, and others. The global network and the Internet allow ICT services to be provided by organisations in foreign countries, which are bound by laws in their respective countries. This has various implications, especially for data storage – see further discussion in Key issues and options (Section 3.6).

3 Key issues and options

This section outlines the main issues appearing within the ICT sector. The sector has witnessed rapid change and a number of issues relate to keeping up with the change and growth for the upcoming years. Some of the options given for the issues are already being put in place, or are in the future plans. Within ICT, the majority of options are technological - this comes from the fact that ICT is highly privately driven. Furthermore, reports advise against policy options, instead encouraging creating economic pull-through. The government cannot drive the sector – government decisions should be driven by the requirements/developments in the ICT sector (Horrocks et al., 2010).

3.1 Increasing dependability of/dependence on ICT

It is informative to look backwards 50 years in the 1960s a (huge) mainframe was supported by a team of on-site hardware engineers. Today, a small laptop has n times the storage and is m times as fast – and we expect it to run without failure for years!

On the software side, all programs were bespoke and the programmers were on call – today, commodity operating systems, programming languages, database management systems communications software and GUI builders make it relatively easy and quick to develop applications that were unthinkable five decades ago.

It is however essential to note that as "dependability" has increased, so has dependence. Many computers are deployed in systems that are financially, militarily or safety critical. Computer failures can stop a bank functioning (seen most rapidly in the loss of ATM support to customers); the primary protection systems of nuclear power reactors are commonly computers running software designed to protect safety; modern cars contain tens to hundreds of embedded computers that control things as crucial as their braking systems.

Any complex system can fail but today the failure can come from other than the obvious physical components such as turbines and motors; system failure can be caused by embedded control systems. This can be hardware (although this is the easiest thing to protect by redundancy), software or malicious attack. A dramatic example of software failure contributing to a major power outage was the US Northeast Blackout of 2003.

Randell et al. (Randell, 2000) gives both a detailed analysis of "faults/errors/failures" and ways of mitigating their impact.

As computers have become smaller and less expensive, they have become more pervasive. Fifty years ago, they were only operated by trained experts – today they are on everyone's desk and few tasks can be completed without them. This has led to an increasing reliance on the interaction between the people involved in an overall system and the design of dependable computer systems – this goes far deeper than what is known as "HCI" issues. The (EPSRC-funded) "Interdisciplinary Research Collaboration on Dependability" (DIRC) studied such issues (see Besnard et al., 2006).

3.2 Hardware (computation)

Computational capacity follows "Moore's law" and has grown exponentially. However, a limit is appearing as circuits approach atomic levels. Alternatives are being developed to replace silicon in semiconductors and would allow Moore's law to continue to hold for longer (Radisavljevic et al., 2011). Another option is to produce "3D" wafers (performance declines dramatically with "off wafer" connections which are by necessity longer – any way of getting more processor power on a wafer will retain the speed that results from the speed of light covering minute distances).

While the alternative materials are being explored, the current trend to circumvent the computation power limits is moving to multi-core. This way multiple processors perform computations in parallel. For hardware designers, this is an easy way forward but it poses significant challenges for software designers. Whilst it is true that there are specific algorithms that lend themselves to parallelism, designing such programs in general is far more challenging than (standard) sequential programming. Gene Amdahl also has a "law" named after him, which suggests that there is a diminishing return on extra parallelism. Some find his observation too pessimistic – but it is certainly true that parallel programming requires more care and skill.

3.3 Rapid development

ICT components (especially end-user ones) have short lifetimes and are frequently updated and refined to meet changing needs. However, certain components are planned for longer lifetime (e.g. networks, cables/masts, data centres, etc.). To accommodate the rapid growth, each generation of networks is planned with exponential growth in capacity.

3.4 Resilience of communications infrastructure

ICT performance under stress (and human performance when the technology does fail) can be unpredictable and it is subject to node failure in which damage or compromise of a key element (a node, router, switch or exchange) causes a service failure to multiple users. Risks of failure increase where ICT network systems are working close to capacity (i.e. above 40%) (CST, 2009).

The resilience of ICT networks is improved by their nature and availability: multiple networks and/or ICT services (e.g. wired or wireless) are available to switch between, networks can utilise multiple links simultaneously and re-route dynamically in real time. Still, link failures can be of high severity, causing stress on bottlenecks in the network and producing a cascading failure (Horrocks et al., 2010). The ripple would affect a large number of users due to shared ICT infrastructures (e.g. several providers share the same cables or masts), outsourced data and computation (clouds, data centres), which require high connectivity, etc.

The issues of communications infrastructure resilience are being recognised in academia, government and industry. Involved parties commit to and act to maintain and improve resilience, as well as react quickly to failures and reassess ICT infrastructure provision (Horrocks et al., 2010). The legislation to improve security and resilience in the communications sector is being developed within EU as well as UK government offices (Cabinet Office, 2011b).

3.5 Supplier and international dependencies

The ICT infrastructure is almost exclusively commercially driven. While this improves resilience with multiple suppliers (and thus solutions) available, recent trends show that it is increasingly dependent upon a small number of major suppliers of component subsystems (Microsoft, Google, Cisco and Intel) (CST, 2009). Massive investments necessary for next generation improvements in the sector may result in the reduction of the number of providers in the future, and therefore pose dependency (lock-in) issues.

IT system supplier dependencies are also significant. While tailor-made IT systems are usually fully owned by the customer eventually, a number off-the-shelf systems are proprietary. For example, Microsoft Office systems are very popular, however the file formats are proprietary and specifications are not available. The issues have been recognised by the industry and current trends show a move towards more openness and interoperation, e.g. by certification of data exchange formats as international (e.g. ISO) standards, using open-source systems, etc.

The international presence of the ICT sector makes it susceptible to foreign laws and international dependencies. Most ICT hardware is manufactured abroad, a large amount of IT services are based in foreign countries as well. Changes in international relations could have an impact on the provision of these ICT components. A significant issue is using public data centre services, e.g. for data storage, which are located in a foreign countries. In many cases, laws within the country would apply to that data, e.g. USA PATRIOT act of 2001, which would allow US government agents to access sensitive data stored in data centres on US soil.

3.6 IT

Large IT projects are prone to cost and time overruns, or even failures. The Chaos report in 1995 (Standish Group, 1995) gives statistics of average IT projects approximately doubling the cost and tripling the time needed to deliver. A recent study reports that while the majority of projects perform reasonably well (27% cost, 55% schedule overrun), one in six IT projects become “black swans”, with 200% cost and 70% schedule overruns (Budzier and Flyvbjerg, 2011). The report claims that IT projects can be 20 times more likely to run out of control than standard risk management models predict (Lomas, 2011).

A number of UK government IT projects have found difficulties in keeping within costs, schedule, and delivering the required service. Projects such as the National Programme for IT, the Single Payment Scheme for the Rural Payments Agency, the National Offender Management Services C-NOMIS project and ID cards, all had delivery timelines of multiple years and in some cases ended up being scrapped or radically stripped back.

To address this issue, UK government has set up a Major Projects Agency to oversee critical infrastructure projects, including large scale IT systems. New government policies aim at limiting project costs, and do not approve projects of very large scale (e.g. valued over £100 million). Instead, the focus turns to smaller projects, agile development and increased interoperability between systems (Cabinet Office, 2011a).

3.7 Security

The role of ICT has been increasing within the national infrastructure and general usage, making it a more important target for various threats, such as hackers, viruses, identity thieves, etc. The general threat of hacking and cyber espionage (e.g. banking fraud and identity theft) has been a persistent concern for general public and organisations. Cyber-crime has been estimated to cost as much as $1 trillion per year globally (Cabinet Office, 2010b). Furthermore, a recent example of the Stuxnet virus[10] shows that cyber attacks have become sophisticated, and can be stealthy, directed and able to disrupt critical infrastructure around the world. Cyber security has been identified by the UK Government as a high priority risk (Cornish et al., 2011).

New challenges for cyber security appear, with ICT usage trending towards information mobility and cloud computing: the data needs to be readily accessible yet secured. The points of attacks can be small and plenty, and the vulnerabilities often go unrecognised within the wider supply chain. The growth of such attacks has triggered reports from organisations that the volume and sophistication of cyber threats are outstripping their capacity to respond (Cornish et al., 2011).

An important issue with tacking cyber security threats is that the response is usually fractured and uncertain. The organisations are "doing the best they can", but the development of standards of best practice, continuity planning and risk management are much needed. While it is recognised that unexpected threats cannot be eliminated completely, response mechanisms within organisations or government must contain high levels of communication, capability and agility to successfully address these risks (Cornish et al., 2011).

The UK Government has allocated £650 million to the National Cyber Security Programme in 2010. Furthermore, recent attacks have prompted increased awareness of cyber dependencies and vulnerabilities within the private sector as well (Cornish et al., 2011).

3.8 Satellite communications and GNSS

Satellite communications have a number of vulnerabilities that can impact signal strength and service availability. Satellite signals have to travel great distances, and their strength can be reduced by terrestrial weather conditions (e.g. rain), as well as events in space, such as solar flares or scintillation (Rooker, 2008).

A prominent problem in satellite communications is signal interference. The signal is vulnerable to accidental interference, or intentional signal jamming, spoofing and other attacks. Accidental interference can appear when multiple ground stations are transmitting to the satellite on the same frequency. The operators are taking the initiative to reduce such interferences and identify them more quickly with the introduction of carrier ID and appropriate training and quality control (Jarrold, 2011).

Jamming is the simplest form of attack, when a noise signal of the correct frequency is used to overpower the actual signal. This could be applied to both uplink and downlink signals. The GNSS service is in particular vulnerable to this issue, where jammers are available for a very low price, and has shown to be very effective in small areas. The issue could be alleviated by adaptive antennas and signal content filters, but more sophisticated jammers appear that can work around these (RAEng, 2011).

[10]Stuxnet virus was designed to target Iran's nuclear power plants directly and succeeded in disrupting operation of a nuclear power plant for months (Nicol, 2011).

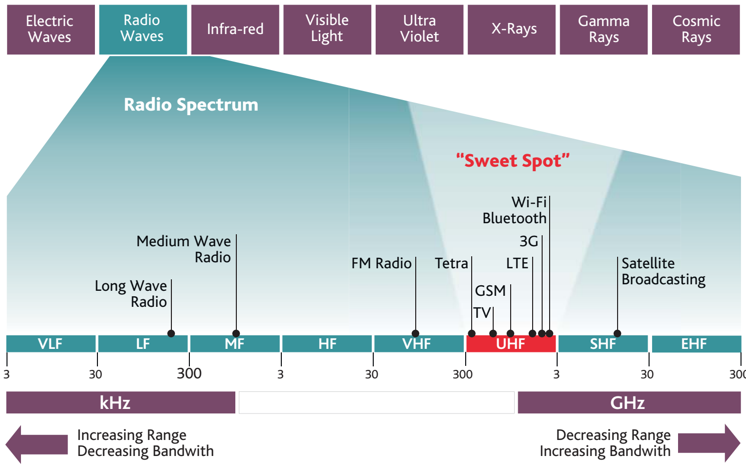

Figure 6: Spectrum usage (DCMS, 2011b)

GNSS service precision is dependent on correct satellite positions, clocks and other system components. New generation GNSS systems (e.g. Galileo) will come with quality and integrity guarantees, which should improve the resilience of the system (ESA, 2011).

The availability of GNSS (GPS) has led to over-reliance on the system. A study by the Royal Academy of Engineering has identified that no alternative or back-up systems are in place when GNSS is used (e.g. paper maps). With increasing use of GNSS in life critical systems, its integrity is insufficient for these applications, if inadequate alternatives or backups are available (ESA, 2011). This is in particular important when considering that GNSS can be jammed easily (see above).

Widespread use of satellite broadband faces issues arising from the nature of the signal. While the network is useful for remote areas, incorporating satellites into terrestrial networks is hindered by several issues (Hart, 2000):

- Latency (propagation delay): increased duration for data transmission via a satellite signal is significant in comparison to high-speed terrestrial networks, where packets need to be exchanged quickly.
- Poor bandwidth: satellite communications have a limited allocation of radio spectrum, therefore the amount of bandwidth is limited (see below for further discussions on radio frequency limitations).
- Noise: the signal becomes weak after travelling the long distances between the satellite and ground stations. This problem could be addressed by appropriate error correction techniques.

3.9 Radio spectrum

The radio spectrum is a finite resource – bands below 15GHz are considered the most valuable part of the radio spectrum due to the technical characteristics used by various applications. For mobile communications, frequencies below about 4GHz are used, with the prime bands being in 300MHz-3GHz area (see Figure 6) (DCMS, 2011b).

Mobile communications have been the fastest growing market that utilises the radio spectrum. While wired-broadband can be expended (theoretically) unlimitedly, the quality and speed of mobile-broadband connectivity relies on the available spectrum. The limited amount of spectrum means a limited amount of bandwidth, and hence speed (ITU, 2011). The demand for mobile bandwidth has been surging with the increase of smartphones, tablet and mobile computing devices. Cisco expects the mobile data traffic to have a compound annual growth (CAR) rate of 91% in 2010-2015 (see Figure 7) (DCMS, 2011b). Furthermore, the move to HD television will also increase demand for a similar radio spectrum range.

Several options have been proposed to address the so-called "spectrum crisis", including technological and governmental actions. Service providers are investigating more efficient use of the available spectrum.

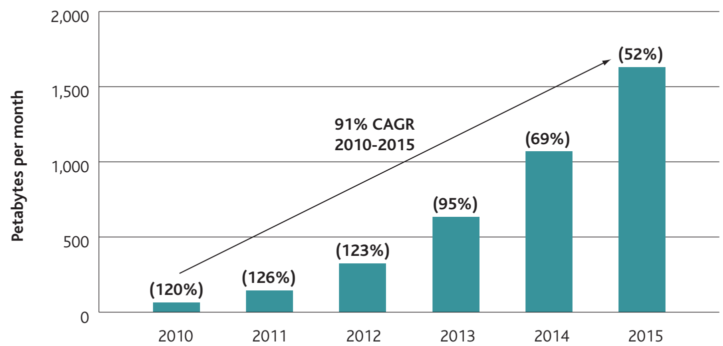

Figure 7: Mobile data traffic forecast - Western Europe (2010-15) (DCMS, 2011b)

Moving to digital signal (e.g. for TV or radio broadcast) could save three quarters of the bandwidth, next-generation networks (e.g. 4G, LTE-Advanced) also aim to reduce the bandwidth required for signals (BBC, 2006). Cognitive radio techniques (e.g. software radio, "white space" wireless broadband) would allow devices to utilise assigned but unused spectrum areas (Ofcom, 2011b).

Furthermore, large ranges (close to 50%) of radio spectrum are allocated to public sector use, especially military (Figure 4). These bands are not effectively used; therefore the UK government aims to release significant amounts of this spectrum to commercial use, especially for mobile bandwidth. The current government plans consider releasing at least 500MHz of public sector spectrum below 5GHz within the next 10 years (DCMS, 2011b).

3.10 People

The role of people in ICT systems is often underestimated. This section draws attention to three aspects that could have significant impact on the future deployment of ICT. As computers have evolved from the "mainframe" era to portable and even embedded devices, the contact between hardware/software and users has become more and more important. The move to look at "computer-based systems" emphasizes the importance of considering the role of users in the design of any system in which computers play a part. Some examples of considerations that might be overlooked include:

- Trust is a very delicate commodity. Automated systems can develop a reputation for being unreliable ("broken") based on either a small number of failures or even misunderstandings. Developers must bear in mind the fragility of trust; those who decide to deploy systems should ensure that appropriate preparations and support are available; and there should always be appropriate feedback mechanisms.
- The converse of (lack of) trust is over-reliance. All systems will fail some time. If, for example, air traffic were to be completely reliant on GPS then there could be a disaster when GPS fails. Fortunately, this is not the case but there are well-documented experiences of systems that were designed as back-up leading users to put complete trust in their correct behaviour and essentially forgetting all of their own cross checks. To a certain extent, this can be seen in the reactions of all car drivers who just push a car with safety features closer to its (new) limits.
- Exposure to subversion is another risk with computer systems. The enormous growth of crimes such as credit card fraud shows all too clearly how systems that are designed for people's convenience can be undermined by attackers. The common incentive to automate systems is to reduce staff costs but this inevitably removes human checks and balances that have evolved often over long periods; computers lose the flexibility of humans to be suspicious and even to react somewhat randomly – they thus become a static target against which those with negative intent can hone their attacks.

Without taking a position on any of the issues, the example of the scare about mobile phones damaging the brain is a classic "Luddite" reaction. One only need think what would happen if there were a widely believed rumour about potential human damage from WiFi waves to see that there are bound to be risks in the progress of technology (O'Brien and Danzico, 2011).

Perhaps the most pressing potential brake on the deployment of new ICT systems is a shortage of qualified IT professionals. Any design process needs qualified professionals so the following comments could apply to hardware and software. It is however the case that hardware designs tend to be produced as large numbers of general-purpose systems whereas the bespoke nature of deployed computer systems is normally achieved by software. The focus here then is on the availability of staff who can analyse, design and program computer software. There are very large numbers of computer professionals – some estimates put the number close to a million in the UK alone. The frequency with which large computer projects overrun their budgets and/or fail to deliver usable systems should make it clear that the skill level to create such systems needs to be of the highest engineering standards. One should therefore certainly not make the assumption that because adequate computer and communications hardware is available for say an intelligent transport system that the creation of such a system is risk free.

3.11 Grid capacity/power shortage

- The power grid capacity is at limits in some places. There are places where new data centres are not allowed (e.g. Canary Wharf).
- Dependence of ICT on energy is limiting vulnerability. We are expecting exponential growth in ICT – could it be limited by availability of power?
- Companies are building data/cloud centres in areas where energy is cheap and plentiful (to a lesser extent, the same is true of cooling). Research and development into low-power processors could limit increase in energy consumption (Poess and Nambiar, 2008).
- Data centres using less energy than predicted: The rapid rates of growth in data centre electricity use that prevailed from 2000 to 2005 slowed significantly from 2005 to 2010, yielding total electricity use by data centres in 2010 of about 1.3% of all electricity use for the world, and 2% of all electricity use for the US (Koomey, 2011).

3.12 IP addresses

Internet Protocol (IP) addresses are assigned to devices participating in a computer network, which utilises Internet Protocol for communication. They are important parts of the Internet infrastructure. Originally designed to be 32-bit numbers (known as IPv4), the available address space is depleting due to the enormous growth of the Internet. The last available address ranges were allocated from the central pool in early 2011 (ICANN, 2011).

While not prohibiting the current Internet usage, the address exhaustion may limit growth, because end-to-end connectivity will not be universally available, as required by certain applications.

The next generation IP addresses infrastructure (IPv6) will expand the address space in response to the needs for far more users, past the four billion addresses of IPv4 by many orders of magnitude. This is an example of ICT planning for future demand growth: IPv6 address space supports 2^{128} addresses. By comparison, this amounts to approximately 5×10^{28} addresses for each of the 6.8 billion people alive in 2010.

Unfortunately, migration to IPv6 is very slow. Its rollout started in June 2006, however in early 2011 only 16-26% of computers were latent IPv6 capable (Huston, 2011), and only 0.15% of the top million websites are IPv6 accessible (Kühne, 2009).

4 Future risks

4.1 Climate change

The impacts of climate change on the ICT sector are likely to be at most minor ones. While specific incidents (e.g. floods, winds) may impact certain components, we have not found substantial empirical data evidence to indicate more significant effects.

Furthermore, international design standards for ICT components also aid mitigation of climate change effects, where components are designed to operate in extreme heat or cold (i.e. the same kit may be used in different climate areas); for example, for this reason heat and drought are not considered an issue by ICT network operators (Cabinet Office, 2011b).

4.2 Lack of investment

Economic recession may reduce investment into infrastructure, e.g. replacing copper wires with fibre optic; upgrading to next generation of wireless networks; etc. However, the highly competitive market would put pressure to invest to keep clients, because end user upgrade and migration is quite easy between networks. Only mobile operator contracts usually have two years lock-in, but then users would move to a "better" network.

4.3 Increasing role of software

Software controls are taking an increasing role in various technologies. Several examples from the automotive industry:

- Cost of electronics as a percentage of vehicle cost[11]: 5% in 1970s, 15% in 2005 (45% for hybrids), predictions estimate the amounts to be 50% and 80% within 10 years, for conventional vehicles and hybrids, respectively;
- 50-70% of the development costs of the software/hardware systems in the automotive industry are software costs (Broy, 2006);
- There is an estimation that, per year, about 5% of the cost "migrates" from hardware to software (Pretschner et al., 2007).

5 Review of previous quantified assessments

The ICT sector covers various means of communication and different IT spheres. The existing quantified assessments focus on some subsectors, such as radio spectrum, telecommunications, etc. In this section we provide an overview of several reports that aim to assess future demand of ICT services and perform some analysis of strategies to address that demand.

Spectrum demand for non-government services 2005-2025. A study about spectrum demand in the UK has been produced for Independent Audit of Spectrum Holdings team in 2005 (Analysys and Mason, 2005). The study forecasts demand for radio frequency spectrum for years 2005-2025, with a particular focus on the 2005-2015 period. The report analyses three scenarios – high, medium and low growth, where applicable – for individual commercial wireless services: cellular, fixed-links, broadband wireless access, satellite and terrestrial television broadcasting. The results are eventually accumulated to produce overall demand forecast, which predicts available commercial spectrum running out in 2008 (high growth scenario) to 2015 (low growth).

The study makes a wide range of assumptions, in particular on take-up, usage levels and technologies used within various services. The authors do not distinguish between usage demand and capacity growth in the scenarios – it is assumed that if capacity becomes available, it will be used. Finally, the authors admit that breakthroughs in new technologies or take-up of alternative technologies would significantly alter the forecasts (Analysys and Mason, 2005).

[11] http://spectrum.ieee.org/green-tech/advanced-cars/this-car-runs-on-code

US GAO: competition, capacity, and costs in the fixed satellite services industry. The US Government Accountability Office (GAO) report in September 2011 analysed the satellite industry and provided demand and capacity forecasts for the years 2009-2019 (GAO, 2011). The authors expect the overall demand for satellite services to grow, fueled by increasing use of satellites for broadband Internet access, growth in corporate networks, increase in satellite television (including HDTV) channels, as well as growth in military usage. The growth in terrestrial fibre optic networks and better technologies may reduce the demand, but overall growth is still expected.

The study references estimates by Futron (Futron, 2010) about average growth in demand for satellite service of 4% annually from 2010 to 2019. It is expected that the growth will be faster in emerging markets than in western markets. The study estimates that the global capacity will not be exceeded by the growing demand (Futron, 2010).

GAO offers several options of increasing capacity, including launching additional satellite capacity, moving the satellites or hosting additional capacity in other satellites (Futron, 2010).

OECD: infrastructure to 2030. An OECD report was published in 2006, which analyses the demand and future trends of telecoms infrastructure (among others) in OECD countries (Futron, 2010). The report does not distinguish data from the UK from the rest of OECD countries; therefore the analysis is of a larger scale than preferred for the UK infrastructure review. Finally, the demand trends are analysed in global context, including markets of developing countries, etc.

Within the ICT infrastructure, the study focuses on fixed & mobile telephony and data, as well as wireless broadband. The study recognises that the market is driven by demand, and defines a single scenario, taking into account different factors that are likely to influence demand in the future. The forecast outlines an explosion in global ICT infrastructure growth, with increasing income, decreasing service costs and tariffs, and technology developments. Finally, the study outlines trends in various ICT services, which illustrate increasing dependence on and prevalence of communications, mobility, accessibility and information consumption (OECD, 2006).

AEA: adapting the ICT sector to the impacts of climate change. A study by AEA Technology in 2009 analysed the state of the ICT sector and impacts of climate change to the sector, and provided recommendations how to adapt to them (Horrocks et al., 2010). The report also contains general ideas about future trends within the ICT sector up to year 2100. Several quantified case studies are provided about the impact of climate change (e.g. floods, temperature changes) on elements of the ICT sector, such as data centres or communication lines.

6 Initial conclusions and discussion

Whilst ICT capacity will not limit the growth of the physical infrastructures, there are significant issues beyond the immediate position.

The progress of ICT opens up new possibilities (e.g. air traffic control systems make it possible to fly more aircraft safely through the same airspace). The dependability of such systems and what to do as backup when there are failures has to be studied.

The danger of "cascade failures" can be magnified by the use of algorithms in place of human judgement. ITRC will study such chains of failures and make proposals as to how the risks can be reduced. The human issues need more study (see Section 3). Specifying a system that ends up either being very hard to use or puts unrealisable demands on human players is all too easy.

The danger of malicious attack on infrastructures like energy via ICT is serious (cf. Iranian story (Nicol, 2011)). Within the ITRC, Newcastle intend to study the "dimensions of interdependence". It is too easy to say that ICT needs power and power distribution/generation relies on ICT. There are different aspects of the interdependence. For example, distributed generation of electricity can only work with elaborate billing (and possibly prediction) systems. These take time to build and need a better rate of success than many public ICT systems developments). So it is more likely that software development will hold up progress than the limitations of computation or communication.

References

Jonathan Amos. Europe's galileo sat-nav in big cash boost, 2011. URL http://www.bbc.co.uk/news/science-environment-13871198.

Analysys and Mason. Spectrum demand for non-government services 2005-2025. Technical report, Final Report for the Independent Audit of Spectrum Holdings, Analysys, London, UK, September 2005.

BBC. The spectrum and its uses. Technical report, BBC, 2006.

BBC. Russia launches satellite for global navigation system, 2011. URL http://www.bbc.co.uk/news/world-europe-12587238.

Denis Besnard, Cristina Gacek, and Cliff B. Jones, editors. *Structure for Dependability: Computer-Based Systems from an Interdisciplinary Perspective*. Springer, 2006. ISBN 978-1-84628-110-5. doi: 10.1007/b138838. URL http://www.springer.com/computer/book/978-1-84628-110-5.

Manfred Broy. Challenges in automotive software engineering. In *Proceedings of the 28th international conference on Software engineering*, pages 33–42, New York, NY, USA, 2006. ACM.

Alexander Budzier and Bent Flyvbjerg. Double whammy -how ICT projects are fooled by ran- domness and screwed by political intent. Technical report, University of Oxford, August 2011.

Cabinet Office. Government ICT strategy: Smarter, cheaper, greener. Technical report, Cabinet Office, London, UK, 2010a.

Cabinet Office. A strong britain in an age of uncertainty: The national security strategy. Technical report, TSO (The Stationery Office), London, UK, October 2010b. URL http://www.official-documents.gov.uk/document/cm79/7953/7953.asp.

Cabinet Office. Government ICT strategy. Technical report, Cabinet Office, 2011a.

Cabinet Office. A summary of the: Sector resilience plans for critical infrastructure 2010/2011. Technical report, Cabinet Office, May 2011b.

CAG. Information and communications technology in government: Landscape review. Technical report, National Audit Office, London, UK, February 2011.

Paul Cornish, David Livingstone, Dave Clemente, and Claire Yorke. Cyber security and the UK's critical national infrastructure: Threats and responses. Technical report, Chatham House (The Royal Institute of International Affairs), London, UK, 2011.

CST. A national infrastructure for the 21st century. Technical report, Council for Science and Technology, June 2009.

DCMS. Digital television, 2011a. URL http://www.digitaltelevision.gov.uk/.

DCMS. Enabling UK growth - releasing public spectrum: Making 500 mhz of spectrum available by 2020. Technical report, DCMS, March 2011b.

Soumitra Dutta and Irene Mia. The global information technology report 2010-2011. Technical report, World Economic Forum, Geneva, 2011.

Max Engel. The split personality of satellite navigation, 2011. URL http://www.satellitetoday.com/via/satellitegetspersonal/37146.html.

EP. Galileo satellite navigation for defence and security services, 2011. URL http://www.europarl.europa.eu/en/pressroom/content/20110913IPR26450/html/Galileo-satellite-navigation-for-defence-and-security-services.

ESA. What is galileo?, 2011. URL http://www.esa.int/esaNA/galileo.html.

Euroconsult. Satellites to be built & launched by 2020, world market survey. Technical report, Euroconsult, 2011. URL http://www.euroconsult-ec.com/news/press-release-33-1/48.html.

Futron. 2010 Futron forecast of global satellite services demand, executive summary. Technical report, Futron Corporation, Maryland, USA, 2010.

GAO. Competition, capacity, and costs in the fixed satellite services industry. Technical report, United States Government Accountability Office, September 2011.

GPS World. Glonass-m satellite successfully launched, 2011. URL http://www.gpsworld.com/gnss-system/glonass/news/glonass-m-satellite-successfully-launched-12116.

David Hart. Satellite communications. Technical report, 2000.

L Horrocks, J Beckford, N Hodgson, C Downing, R Davey, and A. O'Sullivan. Adapting the ICT sector to the impacts of climate change – final report. Technical report, AEA group, published by Defra, London, August 2010.

Geoff Huston. Testing teredo. Technical report, Asia Pacific Network Information Centre (APNIC), 2011.

ICANN. Available pool of unallocated ipv4 internet addresses now completely emptied. Technical report, ICANN, February 2011.

ITU. Measuring the information society. Technical report, International Telecommunication Union, Geneva, 2011.

Martin Jarrold. Satellite interference: The counter-offensive, 2011. URL `http://www.satellitemarkets.com/events/satellite-interference-counter-offensive`.

J.G. Koomey. Growth in data center electricity use 2005 to 2010. Technical report, Stanford University, 2011. URL `http://www.analyticspress.com/datacenters.html`.

J.G. Koomey, S. Berard, M. Sanchez, and H. Wong. Implications of historical trends in the electrical efficiency of computing. *Annals of the History of Computing, IEEE*, 33(3):46–54, 2011. doi: 10.1109/MAHC.2010.28.

Mirjam Kühne. Ipv6 measurements - a compilation, 2009. URL `http://labs.ripe.net/Members/mirjam/content-ipv6-measurement-compilation`.

David S. Lawyer. Modem-howto, 2007. URL `http://tldp.org/HOWTO/Modem-HOWTO.html`.

Jonathan Liebenau, Robert Atkinson, Patrik Kärrberg, Daniel Castro, and Stephen Ezell. The UK's digital road to recovery. Technical report, LSE Enterprise LTD. & The Information Technology and Innovation Foundation, 2009.

Natasha Lomas. Five ways to stop your IT projects spiralling out of control and overbudget, 2011. URL `http://www.silicon.com/technology/it-services/2011/08/22/five-ways-to-stop-your-it-projects-spiralling-out-of-control-and-overbudget-39747844/`.

David M. Nicol. Hacking the lights out. *Scientific American*, pages 54–59, July 2011.

Jane O'Brien and Matt Danzico. 'wi-fi refugees' shelter in west virginia mountains, 2011. URL `http://www.bbc.co.uk/news/world-us-canada-14887428`.

OECD. Infrastructure to 2030: Telecom, land transport, water and electricity. Technical report, Organisation for Economic Cooperation and Development, 2006.

OECD. Convergence and next generation networks. Technical report, Organisation for Economic Cooperation and Development, Seoul, Korea, 2008.

Ofcom. The communications market 2008. Technical report, Ofcom, 2008.

Ofcom. Communications market report: UK. Technical Report August, Ofcom, 2011a.

Ofcom. Ofcom progresses with new wireless technology, 2011b. URL `http://media.ofcom.org.uk/2011/09/01/ofcom-progresses-with-new-wireless-technology/`.

Meikel Poess and Raghunath Othayoth Nambiar. Energy cost, the key challenge of today's data centers: a power consumption analysis of TPC-C results. *Proc. VLDB Endow.*, 1(2):1229–1240, 2008. doi: http://dx.doi.org/10.1145/1454159.1454162. URL `http://dx.doi.org/10.1145/1454159.1454162`.

POST. Government IT projects. Technical Report 200, Parliamentary Office of Science and Technology, London, UK, 2003.

Alexander Pretschner, Manfred Broy, Ingolf H. Kruger, and Thomas Stauner. Software engineering for automotive systems: A roadmap. In *2007 Future of Software Engineering*, pages 55–71. IEEE Computer Society, 2007. doi: 10.1109/FOSE.2007.22. URL `http://dx.doi.org/10.1109/FOSE.2007.22`.

B. Radisavljevic, A. Radenovic, J. Brivio, V. Giacometti, and Kis A. Single-layer mos2 transistors. *Nat Nano*, 6(3):147–150, 2011. doi: 10.1038/nnano.2010.279. URL `http://www.nature.com/nnano/journal/v6/n3/full/nnano.2010.279.html`.

RAEng. Global navigation space systems: Reliance and vulnerabilities. Technical report, The Royal Academy of Engineering, London, UK, 2011. URL `http://bit.ly/feFB2i`.

Brian Randell. Facing up to faults. *The Computer Journal*, 43(2):95–106, 2000.

J.W. Rooker. Satellite vulnerabilities. Technical report, VA, USA, 2008.

Roy Rubenstein. Radios get smart. *IEEE Spectrum*, 2007. URL `http://spectrum.ieee.org/consumer-electronics/standards/radios-get-smart`.

SIA and Futron. State of the satellite industry report. Technical report, SIA and Futron Corporation, 2011.

Standish Group. Chaos report. Technical report, The Standish Group, 1995.

Justine Stephen, James Page, Jerrett Myers, Adrian Brown, David Watson, and Ian Magee. System error - fixing the flaws in government IT. Technical report, The Institute for Government, London, UK, 2011.

Treasury. Operational efficiency programme: Final report. Technical report, HM Treasury, April 2009.