OFFICE OF COMMUNICATIONS

Tomorrow's Wireless World

Ofcom's Technology Research Programme 2007/08

Research

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Foreword

Welcome to this, Ofcom's third report on our Technology Research Programme. This report and our annual Technology Research Symposium are excellent opportunities for us to disseminate the key outcomes of our work to stakeholders. In previous years, our activities have been influenced by the requirement for us to undertake research under the Spectrum Efficiency Scheme. The work detailed in this report, however, marks a move towards diversifying the technology research conducted within Ofcom, to better reflect the breadth of our regulatory duties.

Wireless and spectrum-related research is, naturally, still a vital part of our programme. However, this year we have also undertaken a research project investigating capacity limits of the copper network used to deliver broadband to the majority of homes in the UK. We have also undertaken two large studies into telecommunications trends within two important sectors of society; healthcare and transportation. The research programme planned for the coming year also reflects this diversification.

We have recently realigned our reporting period with Ofcom's financial year and, consequently, this report covers a period of around 18 months. We welcome comments and input to the research reported, and on the scope and direction of our future plans for further research next year. Your feedback can be directed by email to gary.clemo@ofcom.org.uk, or to any other member of my Research team[1].

Ofcom does not conduct technology research in-house; rather, we engage the services of a wide range of consultancies, public bodies and academic institutions to conduct research on our behalf. Once again, I have been impressed at the quality of research conducted in the past 18 months. I also welcome the significant level of stakeholder involvement in our projects, particularly evident within the healthcare and transportation sector studies. We gratefully acknowledge the work of the consortia on these projects and the help received from many of the consortia members in compiling this report.

Peter Ingram

Chief Technology Officer

[1] Details of Ofcom's Technology R&D team can be found at http://www.ofcom.org.uk/research/technology/members/

Executive Summary

Introduction

This report provides an overview of the technology research programme at Ofcom during 2007/08. It presents key findings and outlines the conclusions and implications that Ofcom has drawn from this work. It is worth emphasising that all of the activities described here are *research* projects; by their very nature they are speculative and describe visions of the future telecommunications landscape, rather than current regulatory policy.

This is Ofcom's third Technology Research Report. Ofcom publishes an overview of technology research on an annual basis to inform stakeholders of findings and to gather feedback on both the results and the future direction of the programme.

Context

Ofcom is the regulator for the UK communications industries with responsibilities across television, radio, telecommunications and wireless communications services. By understanding potential future technology developments, Ofcom can determine how technologies and services might develop and shape regulatory policy accordingly.

Key findings

Technology within the information and communication technologies sector continues to develop rapidly and continually open new opportunities. Breakthroughs leading to fundamental shifts in the underlying science are rare. Continuous development is more common and can be just as valuable in the evolution of services and applications.

Last year, we concluded that a breakthrough in communication technologies was unlikely within the next 10 years. Further horizon scanning, through our Technology Watch programme, leads us to make the same comment this year. This has great importance to a number of our policies, such as decisions as to whether to set spectrum aside for an "innovation reserve" – based on the conclusions here such an approach would be inappropriate. However, given a typical 10 year time lag from research to commercial deployment, continued monitoring of the technology horizon is prudent.

Breakthroughs aside, we note that the general pace of technology advancement, both within industry and academia, is very strong indeed. Wireless sensor networks are moving from the military to the civilian domain, attracting a significant amount of interest within the research community. However, their widespread deployment is still some way off and we conclude that no additional spectrum or regulation is necessary at this time. In the wired domain, the technologies underpinning copper telephone networks may progressively be enhanced to achieve higher data rates.

The sectoral studies into the health and transport sectors show that application of new and emerging technologies could have a major effect on the way we live our lives and the services that are delivered. Simply applying cellular communications, GPS positioning and short-range wireless to the car, for example, could revolutionise the way we conduct our journeys and safety levels on the roads. These studies make it clear that developing a new technology is generally simpler than introducing it into commercial use, especially where there are a number of inter-related parties or where Government plays a key role. Indeed, it is clear that delivering these services will require Government intervention and our studies have suggested that there may be a need within relevant Government departments for a team to identify and lead the delivery of these projects.

Overall, the research reported here suggests that no major changes to our regulatory policies are needed at this time. There may be a requirement to help identify incremental spectrum allocations, predominantly for licence-exempt usage, and copper networks may provide data rates that can compare with those currently being deployed in cabled systems. However, no dramatic changes requiring the review of regulation are presently foreseen.

The remainder of this Executive Summary provides an overview of the projects we have undertaken. More detail on these projects is provided in the body of this report and detailed reports on each of the projects can be found on our website[2].

Sectoral studies

Ofcom has undertaken research to examine particular sectors of society to predict the likely evolution of communications technology. We can use this information to assess whether there are any regulatory actions required to assist and stimulate development. The healthcare and transport sectors were selected as having particularly strong drivers for change in their use of communications. Moreover, both feature the possibility of massive change brought about by the widespread application of technologies that are generally already available today. These changes could bring substantial benefits to citizens and consumers. Underpinning our research into these two sectors was a study into macroeconomic trends covering the next 20 years.

The healthcare sector, and therefore the members of the public accessing healthcare services, is expected to benefit from the widespread deployment of information and communications technologies. For example, a home hub could be used to analyse a patient's blood samples, dispense the correct dose of medication and link to the local GP to automatically book an appointment when needed. Body area networks could monitor vital signs and automatically change drug dosage. The use of technology could empower the individual to take more responsibility in maintaining their health, freeing up resources within the NHS for other, higher priority uses. Many of the applications could be deployed over existing local area or cellular networks, requiring no further regulatory action. In such cases the challenge relates more to the fusion and presentation of healthcare information from disparate sources, rather than the physical means to create an underlying network. However, some applications were identified that may require future investigation and, if necessary, regulatory attention:

- body area networks may be used to interconnect implanted medical devices. The safety critical nature of this application suggests a requirement for dedicated spectrum. Depending on the deployment of such networks, the existing allocation of spectrum at around 400MHz may need to be monitored and, if necessary, reviewed;

- local area networks may be used to interconnect medical equipment or to bridge between diagnostic units and implanted body area networks. Conventional wireless local area network spectrum is available but safety critical data streams should be supported by dedicated spectrum. There is currently no allocation for such applications in the UK; and

[2] http://www.ofcom.org.uk/research/technology/

- social and emergency alarms already use dedicated spectrum. However, increased deployment in the future may lead to congestion in these bands.

The transport sector, similarly, features many future applications that can be deployed over existing (typically cellular) networks. These might include the provision of congestion and tolling information, automatic braking when the car in front stops unexpectedly or route planning across multiple types of public transport, including ticketing and real-time updates. The combination of these services will provide the consumer with the means to ensure their journey, however executed, meets their requirements in terms of cost, speed, safety and environmental impact. Again, there is a significant challenge in bringing together information from the various transport systems in order to provide the citizen with an integrated, intermodal journey. We also identified some applications that may require regulatory attention:

- spectrum is already allocated for very short-range communications systems such as radio frequency identification (RFID). The allocation is currently sufficient, but may need to be reviewed if deployment densities increase significantly. However, we expect any increase to be relatively modest;

- a number of transport applications already use, or are expected to use, licence exempt spectrum, e.g. WiFi or Real Time Location Systems (RTLS). We expect to see an increase in the use of WiFi at 2.4GHz in the coming years. The increase in congestion in this band will stimulate a move to use the 5GHz licence exempt spectrum band. Similarly, expected increases in deployment densities of RTLS devices will lead to congestion in current bands;

- intelligent road transport systems will require an allocation of dedicated spectrum, given their safety critical nature. There is already a European Union proposal for 50MHz of spectrum at 5.9GHz, in addition to an existing allocation at 63GHz. Spectrum for safety critical systems will require international harmonisation and utilisation of the spectrum will need to be monitored to see whether any additional allocations are required;

- spectrum is needed create a *wireless corridor* to provide data and voice capacity along railway lines. This could be used both to support operational requirements and to provide commercial services; and

- people will expect to be able to use broadband services whilst travelling by air and sea. This is likely to require additional capacity for satellite communications.

Research into technologies

Ofcom has undertaken research into a number of new and emerging technologies in order to understand their potential, gauge whether regulatory change is needed and further their development where appropriate.

Dynamic spectrum access (DSA) describes a concept that enables a user (or, more likely, their handset) to receive up-to-date quality of service information relating to wireless communications networks. They can then use that information to communicate in the most effective (i.e. cheapest, fastest, highest quality etc.) way. We have previously reported on a candidate architecture to support DSA. We have now concluded that the DSA architecture is viable, as simulations have shown that there is a minimal increase in signalling overhead and that proposed dynamic pricing algorithms are stable. The prospects for the introduction of DSA rest mainly on the identification of a suitable business case.

In the UK, broadband penetration has increased dramatically over the last six years from 7% in 2002 to 57% in Q4 2007, driven in part by fierce competition amongst local loop unbundlers (LLUOs): almost 80% of these broadband connections are delivered across the copper local loop with the rest over cable. Consumers are benefiting from the choice that infrastructure competition is delivering and they appear relatively happy with the headline broadband speeds – if discontented when the reality does not meet the headline. Whilst there are no definitive indications of whether consumers will want significantly higher speeds, we are seeing evidence of increasing use of IPTV and other bandwidth hungry audio visual applications. This begs the question of when the current copper network would be unlikely to meet the expectations of the majority of UK consumers.

In practice, the answer to this question depends not only on the types of services consumers require but how technologies evolve: it is difficult to predict either accurately as there are many factors which effect both. To give some insight, we commissioned a study based on an idealised environment that does not reflect all the complexities of the current underlying network. This abstraction enabled us consider **the theoretical capacity limits of copper networks** and set an upper bound for broadband data rates that could be achievable across copper. Given the important relationship of distance to data rate, we based our model on information on cable lengths from a real network. We concluded that, in our idealised environment, capacities can further improve, compared to today's deployments. We found that if the upstream modem is hosted in the exchange, households within 2km of the exchange (approximately 18% of the total number of households) could, in theory, receive data rates above 50Mbit/s. If the upstream modem is moved closer to the customer premises and into the street cabinet, then almost 100% of households are within 2km of the street cabinet and could, theoretically, expect a data rate of 50Mbit/s.

These results are theoretical and do not reflect what could be achieved in practise. Data rates experienced by end users depend not only on the distance between the customer premises and the exchange but also on home wiring and interference at the exchange, cabinet and in the home. In the real world there are different providers with different equipment sharing the exchange, and perhaps the cabinet, and therefore impacting performance. Nevertheless the real value of this study is to suggest an upper limit, given all technical progress possible, of 50Mbit/s, with fibre to the cabinet.

Wireless sensor networks are receiving an increasing amount of attention in the research community. Networks of sensors could be a fundamental technology to underpin some of the future applications discussed within the healthcare and transport sectors. They could be used, for example, to monitor the vital signs of a patient or construct a road safety system. We conducted a study to understand the key enablers of, and barriers to, the deployment of sensor systems and to estimate their likely spectrum requirements. We observed that the technologies are maturing and an increasing number of industry players are devoting their attentions to applications, rather than just on component sensor technologies. The benefits to the consumer or citizen will become increasingly clear as these applications are identified. However, we concluded that there is unlikely to be a major demand on spectrum, given predicted future deployments. We also concluded that there is no evident *killer application* at present.

Better management of the radio spectrum

One of Ofcom's major responsibilities is the management of the radio spectrum. Better spectrum management leads to more efficient utilisation and an increase in value for all stakeholders. The consumer, increasingly dependent on wireless and mobile communications, also indirectly benefits from our work in this area. By improving our knowledge of how various parts of the spectrum are actually used we can take steps to ensure that the services to which they subscribe meet the standards of quality they expect –

and have paid for. This year our work was divided into three areas – enhancing our understanding of propagation, examining whether certain applications can be moved to higher frequency bands and providing better information about spectrum usage.

Enhancing our understanding of propagation. There is an ongoing need to extend our expertise in understanding radio propagation, for example, to assist our new licensing approach of Spectrum Usage Rights (SURs) which relies on accurate underlying models for verification. We also need to understand better the effect of new network topographies, for which little propagation data exists:

- Despite the increasing use of wireless systems in and around buildings, there is no widely accepted model for radio propagation involving the passing into or out of buildings. We commissioned a study to produce a model suitable for regulatory purposes. Data generated by the model produced a wealth of useful information.

- Wind farms have been proposed as an ecologically sound method to generate electricity. However, concerns have been raised about the effects of wind farms on radio communications systems. We have commissioned a measurement study to better understand the effects of wind farms on fixed link and scanning telemetry systems. This report discusses the relevant interference effects and the approach of the measurement campaign. We will report on the outcomes of the measurement campaign in the next annual technology research report.

- Ofcom has previously commissioned a Generic Radio Modelling Tool (GRMT), which can undertake assessment of the potential for interference in a liberalised spectrum environment. During this year the GRMT has been further developed, including the ability to undertake a technical examination of whether a new or changed licence application should be approved.

- The increasing use of “micro-cells” in mobile radio systems and the possible extensive use of mesh networks highlighted a need for a general-purpose propagation model appropriate for making coverage and interference predictions where both terminals in a link are at low height. We have previously commissioned a measurement campaign to enable us to better understand this propagation environment. The results obtained in this reporting period highlighted the limitations of existing, accepted models that have not explicitly been developed for such environments.

Applications moving to higher frequency bands. Market mechanisms tend to move many applications to ever higher frequencies but may not always be effective in demonstrating what is possible. As a result, we conducted work on selected applications to understand the potential for their use of higher frequencies.

- If greater use of fixed links in the bands above 60GHz could occur then this would provide a useful increase in the spectrum available for new services at lower frequencies. We commissioned research into the feasibility of combined millimetre wave and free space optical communications links for use in place of lower frequency fixed links. Our trial demonstrated the robustness of these combined links in the presence of various weather conditions, with over 99% availability.

- Wireless television cameras are already used extensively for electronic news gathering and outside broadcast purposes and their usage is growing. Their usage is particularly applicable for sporting events, such as the Olympic Games. Existing cameras operate in highly desirable spectrum that might alternatively be used for mobile applications. We commissioned research to examine the feasibility of moving wireless cameras to a higher frequency of operation. We concluded that operation at 7.5GHz is feasible but the propagation characteristics of 60GHz spectrum means that this frequency is only suited for line of sight applications.

Providing better information about spectrum usage. In the same way that it is difficult to manage a company without management information, it is difficult to manage the spectrum well without information on its usage and quality. Ofcom has previously commissioned the development of the Autonomous Interference Monitoring System (AIMS), a multi-functional tool for monitoring the quality of spectrum. Since we last reported we have conducted an extensive field measurement campaign, including:

- A study of licence exempt band utilisation, and;
- Measurement of the characteristics of man-made noise, the outcomes of which have been submitted to ITU-R.

The coming year's research

Over the past six months, we have consulted widely, both within Ofcom and externally, on suitable topics for the 2008/09 research programme. At the time of writing, eight projects have started:

- **Estimating the value of spectrum.** An increasing amount of spectrum is allocated through market-driven approaches. However, this requires a good understanding of the real value of the offered spectrum. This project may assist trading markets by setting price expectations appropriately and help those who are interested in acquiring spectrum in understanding the likely amount that they might have to pay. We are proposing a study that will build a model that will enable us to estimate value across as much of the UK spectrum allocation as possible. The model will take a number of factors into account, such as the frequency and bandwidth, and will provide important information to drive the spectrum marketplace.

- **Capture of spectrum utilisation information using moving vehicles.** The use of spectrum in different parts of the country and across different frequency bands can vary quite dramatically. It is important that we are aware of such variations to enable us, for example, to determine whether additional licence exempt spectrum is needed or to build up a better picture of local interference. We propose to investigate a system comprising a number of vehicle-mounted nodes. Measurements would be taken as the vehicle moved, with the data stored locally until such time that it could conveniently be uploaded to a central database. Over a period of time the database will grow, building a detailed picture of spectrum use in key frequency bands across much of the country.

- **Socio-economic study of the entertainment sector.** Entertainment within and to the home is undoubtedly an enormous market. We anticipate that the manner in which video and audio is distributed, stored and subsequently consumed will have a major impact on the underlying communications infrastructure. We are proposing a study that will enable us to assess the changing entertainment sector in order to determine the impact on the regulatory environment. The study will develop scenarios describing a view of the future entertainment sector over periods of 10 and 20 years. These scenarios will then be examined to determine the technological developments required and the likely impact on spectrum and network demands.

- **Quality of service on the Internet and the implications for IPTV and other services.** The entertainment study discussed above will address an entire sector of society and will therefore be broad in scope. We are also proposing to conduct a narrower study that specifically investigates the technological and economic barriers to providing high quality television services over the Internet (known as Internet Protocol Television, or IPTV). One of the major reasons for poor quality of service over the Internet is congestion, i.e. too much data being carried at the same time, leading to some data being lost or severely delayed. In this study, we will seek to understand the various reasons why congestion occurs, the impact it has and whether we can take any regulatory measures to improve the situation.

- **Estimating the use of key licence-exempt spectrum.** Licence-exempt spectrum is important for delivering applications that generate significant consumer value, such as Bluetooth and WiFi. However, as the number of devices that support these technologies increases, so does the possibility of congestion, which can lead to degradation in quality or performance. Understanding the actual levels of congestion and the associated trends will assist us in making better-informed spectrum management decisions. Unfortunately, getting a good understanding of congestion is very difficult – congestion may only occur in a small area, such as in the centre of a shopping centre but not at the periphery, or it may only occur at certain peak periods of the day. We propose a study to seek out congested areas and measure levels of congestion.

- **Understanding the environmental impact of communications systems.** Communications systems in general might have two different environmental effects. On the one hand, transmitters and receivers consume energy and building mast sites can involve substantial activity and affect the landscape. On the other hand, effective communications, such as video conferencing, might save journeys and hence have a positive environmental impact. We propose to conduct a study to assess the relative energy consumption and environmental impact of a range of different networks as well as understanding how the benefits might vary according to network type.

- **Predicting areas of spectrum shortage.** There is a long-term view of spectrum use, in which networks are efficiently deployed in all places and at all times and there is sufficient spectrum available for a variety of demanding services. However, as we move towards that situation, the demand for spectrum may grow more quickly than the available supply. Hence, in the interim there may be areas of spectrum shortage, which may lead to poor coverage, dropped calls or low data rates. We propose a study that will enable us to model both spectrum demand and the ability of networks to respond to that demand. Potential areas of spectrum shortage can therefore be identified and, if necessary, regulatory action planned.

- **Wide-range propagation model.** Propagation tools are vital to understand the physical environment in which wireless and mobile systems operate. However, it is becoming apparent that existing propagation methods and tools will require updating, as use of the radio spectrum becomes more innovative and liberalised. We propose a study to develop a new model that will predict coverage and interference between radio networks operating in a liberalised spectrum environment.

The activities and outcomes of these projects will be presented in the next annual research report.

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Section 1

Technology research at Ofcom

1.1 Technical research to help shape the regulatory environment

Technology underpins many of the valuable services that we use today, such as our mobile phones, our broadband connections and the broadcast content we consume on television and radio. Most visions of the future foresee dramatic increases in the amount of information sent both through wired and wireless systems and forecast a range of innovative new services based on exploiting ever faster access and ever cheaper electronic equipment. Understanding how communications technology and services are likely to evolve and the implications for the regulatory environment is critical in ensuring that regulation assists innovation rather than hinders it.

Broadly, Ofcom's technology research programme is focussed around understanding and furthering new technologies and services. We also have specific duties to ensure efficient use of the radio spectrum. Therefore, some of our research activities are directed at technologies and algorithms that facilitate better use of the spectrum.

Under the overall objective of maintaining a clear understanding of technology trends and regulatory implications, and encouraging best use of the radio spectrum, our technical research programme covers a number of key strands:

- performing investigations into how two sectors of society, namely healthcare and transportation, will develop over the next 10 to 20 years. Such long term research will enable Ofcom to anticipate future impacts on the underlying communications infrastructure and quantify any requirements for changes to regulation in general and spectrum allocation in particular;

- performing investigations into emerging technologies, for both wired and wireless applications, to understand the impacts they may have on the future regulatory environment, and;

- improving our understanding of how the spectrum is utilised and then using this information to manage the spectrum more effectively.

1.2 The technical research programme in overview

In the year to April 2008, Ofcom's technical research programme comprised eight major projects and a number of smaller activities. Ofcom does not conduct research in-house but makes use of external resources. During the year, our projects involved 12 separate organisations, including private commercial organisations, university departments and government funded research institutions, all of which are based in the UK. As well as ensuring the best possible team is available to conduct the research, this facilitates an exchange of information and networking across the technical community around the country. Broadly, Ofcom owns the intellectual property arising from the projects it funds and makes all output freely via our website.

This report focuses on a subset of our studies that have produced material of particular interest. Most of these projects both commenced and concluded within the timeframe covered by this report. The report also covers several projects that concluded prior to April 2007, whose conclusions were not captured in the last report. Final reports of all studies undertaken are available on the Ofcom website[3] and the complete list of the studies that make up the Ofcom R&D programme can be found in Annex 1.

The strands and key projects that we are reporting on here are:

- **Sector studies**. These broadly-scoped investigations predict how selected sectors of society will develop in the next 10 or 20 years and, therefore, assist us in understanding future impacts on and requirements for spectrum and communications infrastructure. Two such studies were conducted in this reporting period, addressing:
    - the healthcare sector, and;
    - the transportation sector.

  A macroeconomic study, concentrating on similar timescales, was also performed to provide an economic context to the sector studies.

- **Research into technologies**. Keeping abreast of emerging technologies enables Ofcom to anticipate impacts on our regulatory responsibilities. This year we report on:
    - the evaluation of an architecture to enable Dynamic Spectrum Access (DSA), a proposal for improving open competition for services in a simple and usable manner. DSA can also promote the efficient utilisation of radio spectrum through the introduction of market forces;
    - the investigation of the emerging wireless sensor network (WSN) area, from both a technical and a market perspective;
    - a study to determine the theoretical capacity limits of the copper cables used to deliver broadband connectivity to the home;
    - a review of emerging technologies that we expect will impact communications devices and networks in the longer term.

- **Better management of the radio spectrum**. Improving the information on the utilisation of spectrum helps Ofcom improve its approaches to managing this scarce and valuable resource. This year we report on:
    - the final phases of the Autonomous Interference Monitoring System (AIMS). This system provides valuable data on the quality of spectrum across a very wide band. Earlier phases of this project have been detailed in previous annual reports;
    - a study to investigate the feasibility of increasing the operational frequency of wireless television cameras to higher frequency bands. This would free up the existing frequency bands to potentially be used for mobile applications;
    - the initial phases of a study on the effects of wind farms on communications systems, particularly fixed links and scanning telemetry; and

[3] http://www.ofcom.org.uk/research/technology/

- o a number of propagation projects, aiming to improve the tools available for radio planning. These include studies to better understand the performance of devices when they move from outdoors to indoors and on understanding the propagation environment for devices at low heights.

1.3 The structure of this report

The bulk of this report is structured according to the segmentation set out above, with the projects grouped together in strands. In each section an overview of the research projects is given. The final chapter draws together the different strands and looks at future research activities.

This report presents the findings of the consortia of industry, consultants and academic institutions that have undertaken the technical work on Ofcom’s behalf. It also contains conclusions and implications that we have made from those findings. The full details of the consortium findings for each project can be found in the detailed final reports on each project available on the Ofcom website. The consortia that have been engaged in research for Ofcom are listed in Annex 1.

Section 2

Sectoral studies

2.1 Introduction

The idea of sectoral studies is to examine a particular sector of society in some detail to predict the likely evolution of communications technology and from that to make an assessment as to whether there are any activities that the regulator could undertake in order to assist and stimulate developments. In particular, these might include assistance in enabling access to any spectrum that might be needed. This differs from the approach of considering the evolution of a particular technology and its effect in that sectoral studies effectively look at “demand pull” whereas technology studies are more about “technology push”. Of course, it is never as clear cut as this, and technology developments are often needed before application demand can be met. Hence, we see studies in both technology and sectoral needs as complimenting each other.

In deciding which sectors to study we were primarily interested in those with specific communications needs, or which might have major influence on the overall communications environment. In our view the three sectors that clearly meet these criteria are health, transport and entertainment. That is not to say that other sectors do not have communications requirements, but that we believed that these could be met within the overall developments in communications already taking place. For example, the education sector is likely to make widespread and effective use of communications but broadly is able to do so with a mix of broadband connections to educational establishments and licence-exempt wireless within the establishment, both of which are either in place, or will be delivered as a result of general communications needs. This year we examined health and transportation and in the coming year we will look at entertainment.

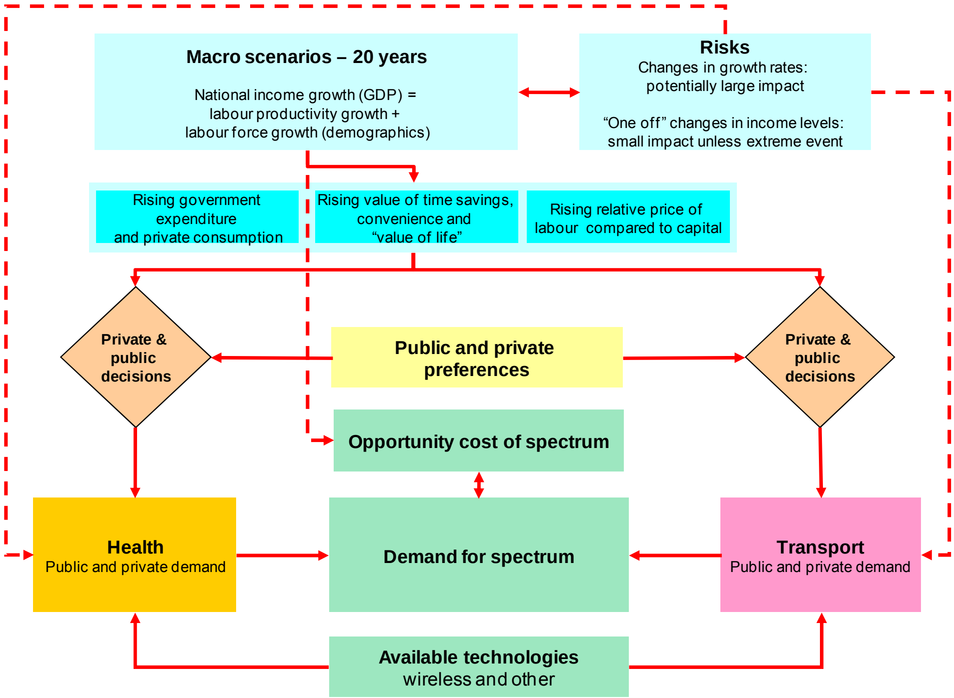
Broadly our conclusions were that for both these sectors there was the possibility of massive change brought about by the widespread application of technologies that were generally already available today. These changes could bring substantial benefits to individuals and society. For the most part, these applications did not require regulatory change or additional spectrum. Most could be supported either over existing networks such as the public cellular systems or using current technologies in existing licence-exempt allocations, for example WiFi.

In order to study these sectors the teams needed a common economic baseline, covering macroeconomic data such as gross domestic product (GDP) growth, changes in life expectancy and oil prices. Hence, we start our description of the sectoral studies with a brief look at our assumptions as to the underlying macroeconomic trends.

2.2 Macroeconomic modelling to 2025

The objective of the macroeconomic modelling is to provide a top down view of wider economic developments, which underlie the trends predicted in the sectoral studies. Figure 1 provides an overview of the inter-relationships.

Figure 1: Inter-relationships between macroeconomic scenarios and sectoral studies



Based on the long run historical trend rate of labour productivity growth of 2% and labour force projections, national income growth is estimated to be 56% or £883 billion in real terms when compounded over 20 years, whilst per capita income is projected to grow 37% or £7,864 (Table 1).

Table 1: Projected growth of GDP over 20 years

	UK GDP (£bn, 2006 prices)	GDP growth	GDP per capita (2006 prices)	Real GDP increase per capita (£bn, 2006 prices)	Percentage increase in real GDP per capita
2006 (Actual)	1,290	-	21,311	-	-
2025	2,008	55.6%	29,155	7,864	36.9%

Income is a key driver of supply and demand for health and transportation services as follows:

- government health funding increases with rising incomes (public supply dominates overall health expenditure);
- private expenditure for transport services increases with rising incomes (private transport expenditure dominates overall transport expenditure);
- income growth raises the value of time savings and convenience, and willingness to pay to reduce the risk of accidents. Income growth will therefore drive demand

for better and more convenient service in health and transportation. In turn, this may increase the private share of health expenditure in future, and may increase or decrease the private share of transport expenditure depending on whether congestion or convenience dominates in relation to private transport; and

- income growth involves a rise in the relative price of labour compared to capital, which will create an incentive to shift towards more capital intensive production of health and transport services and/or create expenditure pressure in relation to relatively labour intensive services such as health care.

In relation to risks, we identify two distinct categories:

- risks that impact on the rate of productivity and income growth:
  - i) information communications technology (ICT) golden age – a potential positive impact;
  - ii) inefficient approaches to greenhouse gas mitigation; and
  - iii) protectionism.
- risks that impact on the level of income via one-off effects:
  - i) asset price shock;
  - ii) oil price shock;
  - iii) influenza pandemic; and
  - iv) natural or man-made disaster.

The former – growth rate shocks – are likely to be far more important over a 20 year timeframe since their impact on income growth is cumulative. The latter are generally found to be negligible in their impact over 20 years, though extreme natural or man-made disasters could potentially have a material impact (a large asteroid impact or regional nuclear war are the two examples considered).

Some risks would also have direct impacts on health and transport, for example, an influenza pandemic.

2.3 Health technology scenarios development

Overview

Technology could bring major changes to the health sector. Sensors worn on or around the body could monitor vital signs and record these or forward them to via a personal gateway into the general health network. Wireless systems in an ambulance could extend coverage to accident or disaster areas allowing medical workers to access important information and could communicate with hospitals allowing them to prepare for the arrival of patients. Home wireless local area network (LAN) systems could link together health monitoring devices in the home able to perform routine measurement and diagnostic tasks and would include a gateway to the Internet. Within hospitals and GP surgeries wireless LANs and radio frequency identification (RFID) devices will enable connectivity with people and with mobile health equipment enabling, for example, rapid access to patient health records.

This section starts by setting out our predictions for the delivery of healthcare in the future using a scenario by way of illustration. It then considers in more detail the applications mentioned in the scenario, analysing where they are likely to be used and the timescales for their introduction. Based on these two sections the requirements for spectrum are then developed.

A scenario

During the study a range of scenarios were derived based upon factors such as GDP growth and public acceptance of new technology. Here we explore the most optimistic scenario, which is the one with the greatest need for communications. As it turns out, the other scenarios have generally rather similar needs.

This scenario assumes that over the next 20 years economic growth will be high at a level of 2.25% per annum and an increasing share of GDP will be invested in healthcare - 10.3% of GDP for health and long term care. This results in spending on health and long term care increasing by 108% to £215 billion by 2025. This high economic growth has precipitated conditions where the rate of technological progress has accelerated. The technology sector experiences a period of high growth, and increasing research and development resulting in the introduction of numerous breakthrough products to the health market. Standards and protocols are widely adopted within the technology community, facilitating deployment of new technologies and stimulating a global market for e-health equipment and services. Furthermore supplier relationships within the health service are simplified, encouraging companies to develop medical technologies.

Within the National Health Service (NHS) there have also been significant developments in the deployment of technology. The NHS still remains the largest employer in Europe and the potentially explosive effect of high income growth on the wage bill has been prevented with the exploitation of technologies that increase efficiency and, in some cases, substitute for labour. The increasing share of GDP being invested into the NHS means that there is more funding available for technology investment, and as a result technology and innovation lie at the forefront of NHS spending policy. This leads to significant developments in all areas of technology as well as a shift in culture within the healthcare system towards an acceptance that risk is sometimes necessary for progress to be made. In addition, NHS staff and patients not only accept technology but also have come to expect it to be used within all stages of healthcare delivery. Trust in technologies is no longer a problem as their reliability and security have improved. Additionally user interfaces have become highly intuitive, and clinical and administrative staff are able to use numerous new technologies with minimal formal training.

Large scale, secure and safe information sharing has been enabled by the implementation and success of information systems, such as the National Programme for IT, and communication systems, such as the fibre optic N3 project. It is commonplace for health information to be collected in real time, collated and analysed, transforming it from information to actionable knowledge (both at the level of individual patient and at the aggregated level where information provides evidence of the effectiveness of alternative interventions to promote health, prevent illness and tackle ill-health). Vast amounts of information is available for clinicians but the quantity of information they receive is tightly regulated and the provenance understood. Use of patient-accessible information systems is commonplace, providing patients with a wealth of information about their health.

The public rely on technology within all areas of their life. Thanks both to high economic growth and significant developments in ICT products and services, people spend a larger proportion of their income on technology. Increasingly, ICT is seen as a necessity rather than a luxury and concerns about safety and privacy have been largely overcome. As people become accustomed to using particular ICTs, in particular web applications, in other parts of their lives, they come to expect similar services and applications within the health service. Peer-to-peer networks are a big area of growth further increasing the “consumer power” within the health service.

Within this scenario personal responsibility is moderate, but increasing over the 20 years. High economic growth means that people are generally wealthier, resulting in a continued upward trend in lifestyle related illnesses such as obesity. However, within the next 20 years as health information becomes more accessible and people begin to see the effects of poor health first hand there is a shift in responsibility from the healthcare system to the individual. This transfer towards the individual represents a change where the public have become more socially responsible and are willing to make sacrifices to prevent illnesses developing later in life. Developments in screening technologies and genetics, in particular, have increased the rate of early detection of illnesses, allowing early intervention and freeing up resources. Furthermore, people have a high level of disposable income, which they can spend on discretionary healthcare products. The government and the Department of Health still have an influential role enabling people to make the right decisions and achieve this by improving the choices available, not only within the health system but also within areas such as nutrition and exercise.

The health service has become highly reformed; primary care increasingly takes place within the home, whilst polyclinics and specialist “super-hospitals” are reducing the role of traditional secondary care. High economic growth in this scenario has ensured that the necessary funding is available for the transitional costs needed to make changes to such a large system. Furthermore, within this scenario, health and social care have implemented systems that run in parallel to one another, enabling easy transfer of information and providing a seamless service to the public. The role of the private provider within healthcare delivery has become more prominent, resulting in a more competitive and efficient service. The health service has become highly personalised and doctors are able to spend longer with each individual case.

Overall, people are living longer, healthier lives resulting in lower morbidity rates. High levels of funding have resulted in universal access to high quality healthcare and health inequalities have been reduced. There have been a number of breakthroughs in medical technology and new drugs and new drug treatments have been introduced to the market, which have made dramatic improvements in a number of previously chronic diseases. Drug therapy has become more targeted allowing morbidity to be managed more effectively. Developments in genetics mean that many illnesses can be identified earlier facilitating early intervention and preventing conditions from deteriorating. Developments in ICT allow people with chronic diseases to closely monitor their condition and prevent deterioration, reducing the burden on primary and secondary care. There is an overall shift towards preventative rather than reactive care, which has been facilitated by significant developments in health technologies as well as increased personal responsibility.

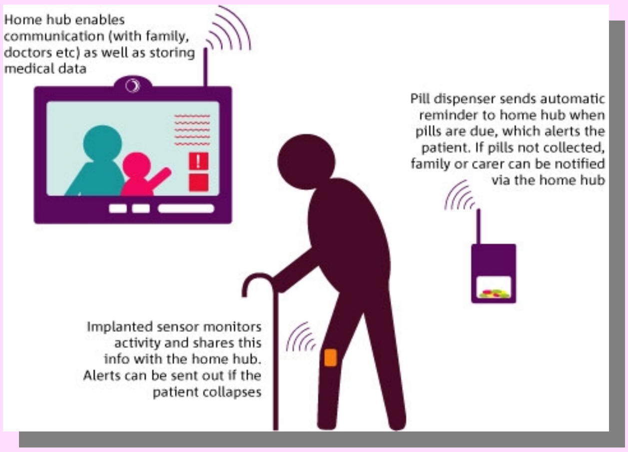


Illustration: Assisted living

Stephen has recently had a hip replacement operation. He lives some distance away from his family and is keen to remain independent and involved in his local community during his recovery period.

During the operation, an implanted sensor was fitted to Stephen's hip and temporary monitors were attached to his knees. These sensors monitor his movements and transmit this information to his home hub, so that doctors are able to follow his recovery process.

Stephen's house has been enabled for assisted living, allowing him to remain in contact with his family, as well as with doctors and carers, via a home hub in his living room. This allows Stephen to contact his family using video conferencing, enabling them to see, as well as hear, that he is feeling well. Stephen's home has also been fitted with an automatic pill dispenser, which senses if the pill box has been opened at the correct time and if not, sends a signal to the home hub. An alarm then sounds to remind Stephen to take his medication. If Stephen ignores this alarm, his family or carer can be notified so that someone can stop by to check that he is ok.

Health ICT applications

A number of applications were mentioned in the scenario above. This section provides descriptions of these applications. All applications could potentially use wireless technologies. Some of them would use wireless from 'end to end' whilst others might use wireless to connect to a wired network.

We have organised the applications according to location:

- individual/anywhere (i.e. applications related to the individual, wherever they are);
- ambulance;
- home; and
- hospital or general practice (GP) surgery.

In the diagrams that follow, we have shown the applications in each location, mapped by their approximate size and stage of development or likelihood.

Figure 2: Applications at the level of the individual (applications that could be used anywhere, e.g. at home, in the hospital, in an ambulance or “out of home”)

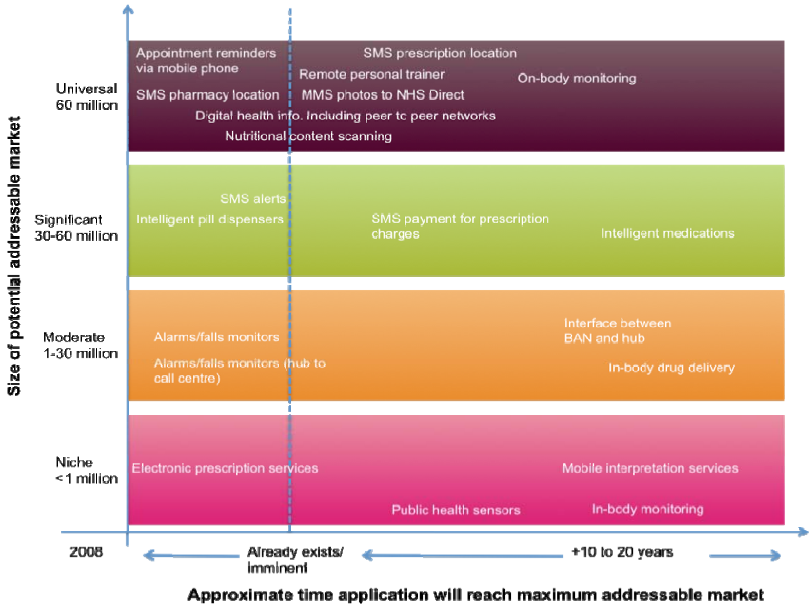


Figure 3: Applications in the ambulance

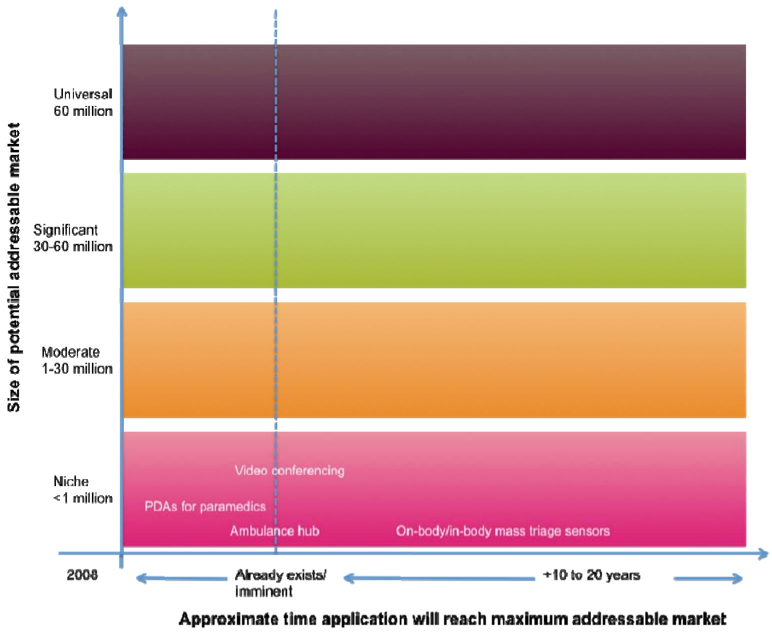


Figure 4: Applications in the home

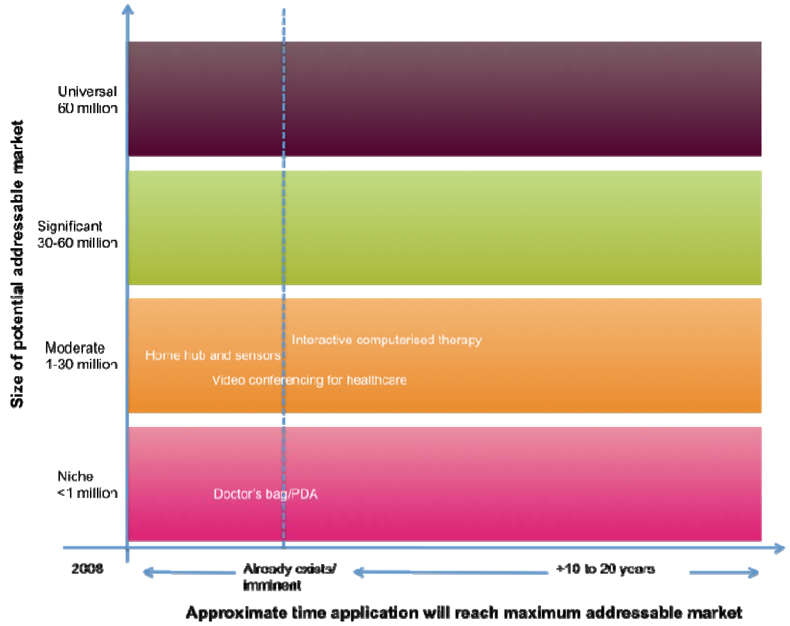
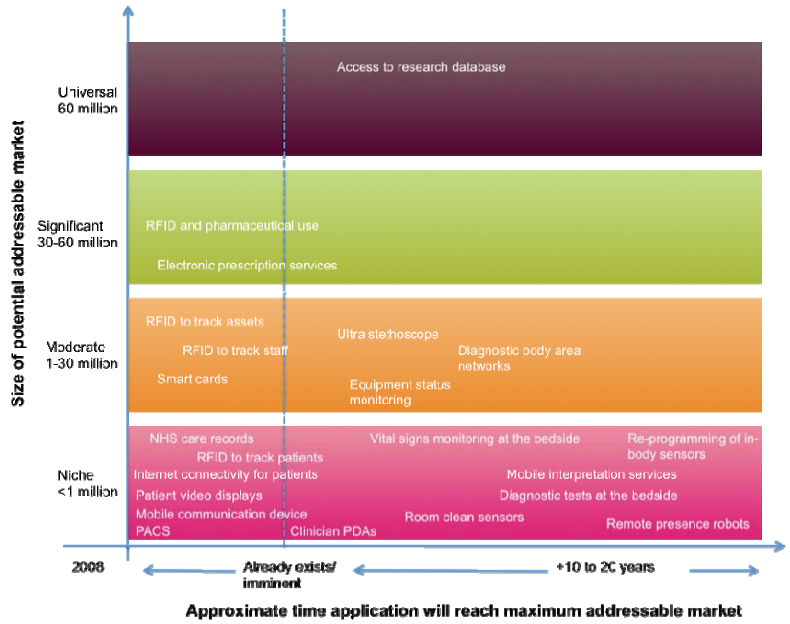


Figure 5: Applications within the hospital or GP surgery setting



All applications we considered have the potential to use wireless technologies for all or part of their journey across networks. When identifying the relevance of wireless technologies to each application a number of aspects have been considered, including:

- the need for mobility;
- the user's expectation of convenience;
- the availability of public and private third-party networks (both wired and wireless); and
- the greater appropriateness of wired connections in critical static situations.

We next describe the network architectures that could be used to support the use of ICT applications in each of the four locations. Drawings are used to illustrate the applications and some of the possible network architectures that may support them.

Individual/anywhere applications analysis. Within applications that relate to the individual and which could be used anywhere, there are four types of communication that need to be addressed:

- the wide area exchange of non-critical information e.g. appointment reminders. This would be likely to be supported by public wireless networks such as cellular, WiFi, WiMAX and beyond;

- the body area exchange of critical information e.g. in-body drug delivery. This would be likely to be supported by a wireless body area network using specific and appropriate frequencies;

- the wide area exchange of critical information e.g. alarm to monitoring centre. This will likely need an interface between the body area network and public wireless networks. Given the potentially critical nature of such information exchange it is appropriate that alternative access to public wireless networks be provided; and

- the availability of a patient’s record.

A number of architectures could support the above requirement with different degrees of integration between the various ICT systems involved. However it is possible to envisage an architecture based on a body area network and a personal hub or gateway which provides an interface between a body area network (BAN) and a wide area network (WAN) and could potentially contain processing power and electronic storage relating to the control and monitoring of in-body and out-of-body medical devices. Such a personal gateway could also hold a patient’s record although other technologies (e.g. RFID) are possible for basic medical records in a hospital environment. As noted above the BAN to WAN interface should support a number of connection types (cellular, wireless LAN, Bluetooth, ultra-wide band and frequencies specific to healthcare, e.g. social alarms).

Ambulance applications. We see three communication aspects to this situation:

- the gathering of data from on-body / in-body mass triage sensors. Such a network of sensors may be pre-wired or it may be wireless;

- the interfacing of data from the above along with videoconferencing, personal digital assistants (PDAs) and other wireless equipment to a distant location (e.g. hospital);

- the interfacing of a patient’s record and/or existing BAN (through its personal hub / gateway) to equipment associated with the ambulance or onwards to a distant location (e.g. hospital).

A possible architecture to support the above requirements would be based on an ambulance having its own wireless LAN which interfaces through its hub/gateway to the national network which supports public safety services (i.e. Airwave).

The three aspects identified above would connect to the ambulance wireless LAN and in the case of the mass triage sensors these could either connect individually, through their own gateway or through the patient’s existing BAN hub/gateway.

In addition to ambulances on the ground, helicopter ambulances are also used. There are not many air ambulances available at present and their use is infrequent. This situation might change in the future particularly with respect to scenarios that reflect high economic growth. When on the ground, air ambulances can be regarded as equivalent to an ordinary ambulance and the comments above regarding possible network architecture would apply. In the air, however, air traffic control and very high frequency (VHF) channels to connect to other services are used and multiple handsets for the different mobile networks are carried to ensure connectivity in all locations. In the event that air ambulances become more widespread a review of their connectivity requirements could be appropriate.

At home applications. Given the timeframe that this study is addressing it is assumed that in most cases the home will have a broadband connection and its own LAN which may or may not be wireless. The additional applications would be accommodated over the broadband connection via a wired and/or wireless LAN, and the other applications associated with an individual (especially the BAN hub/gateway) would also interface to the broadband connection wirelessly or, where this is not available, over the public cellular network. An alternative architecture might use femtocells should these develop into a ubiquitous technology.

Similarly, if a GP were to visit a patient’s home, it might be expected that the doctor’s “electronic bag” or PDA would interface to home broadband connection wirelessly or, where this is not available, over the public cellular network.

Hospital and primary care applications. The potential ICT infrastructure across a hospital site to support the above applications can be characterised as follows:

- an RFID infrastructure for the tracking/labelling of all assets – equipment, drugs, staff and patients;
- a wireless infrastructure (e.g. wireless LAN access points) for connecting staff and patients (voice and data) and to allow diagnostic equipment to be made fully mobile;
- wireless sensors potentially interfacing with the wireless infrastructure identified immediately above; and
- facilities to interface the BANs of individuals with diagnostic equipment (and potentially to the wireless infrastructure identified above).

In summary, the wireless networking sub-systems that might be expected to develop in order to support these applications are:

i) BANs including a personal gateway (including interfaces to public networks, ambulance network, hospital network, home network);

ii) ambulance wireless LAN including a gateway to public safety network (e.g. Airwave);

iii) home wireless LAN including a gateway to broadband connection (wired or future public wide area wireless system);

iv) hospital wide (& GP surgeries/polyclinics) wireless LAN with gateway to wired infrastructure;

v) hospital wide (& GP surgeries/polyclinics) RFID system – extent of requirement depends partly on whether patients' records are held on personal RFIDs or are associated with the BAN gateway.

Implications for Spectrum

This section describes the networks and spectrum required to support the ICT applications that are described above.

Role of public and private third party networks. Most of requirements for wireless connectivity could be supported by public and private third party networks. The key networks are as follows:

- cellular networks, which will readily transfer general information and support transactions between individuals (including their body area networks), doctors and health centres. In the longer term, taking account of the possible introduction of WiMAX and the Long Term Evolution (LTE) system, it is anticipated that video of sufficient[4] quality will be supported;

- the Airwave TETRA network has been provided for the exclusive use of emergency and public safety organisations and personnel. The current network provides voice and relatively low bit rate data capabilities and there are no publicly available plans as to how the network would evolve to accommodate the data rates associated with high quality video within the spectrum currently available. Therefore it is possible that a dedicated WiMAX or LTE network might be required to support the sharing of video between ambulances and hospitals. While it is always possible to increase the density of base stations in order to increase capacity, it is probable that any significant demand for video will have an impact on spectrum requirements, bearing in mind that current processes only deal with the transfer of small amounts of data;

- wireless LANs operating in the 2.4 and/or 5GHz bands. These could provide wireless infrastructure in several locations including hospitals, around ambulances and in individuals' homes. The 2.4GHz band continues to be popular, leaving the extensive spectrum at 5GHz sparsely used;

- Bluetooth and Ultra Wide Band (UWB) are relatively short-range technologies but will still provide useful links between the various sub-networks that will exist in the future. For example, connectivity between a body area network and a wide area cellular network would be satisfied efficiently by a Bluetooth or UWB link between an individual's body area network gateway/hub and their mobile phone;

- RFIDs are specifically provided for in the 865 to 868MHz band (15 channels) and in the centre of the 2.4GHz industrial, scientific and medical (ISM) band[5]. Operation in these bands is at a relatively high power and there are some controls on the duty cycle. RFIDs could be used to track and hold information about a wide range of assets – drugs, equipment, patients and staff. It should be noted however that it is not the only technology that provides location awareness but today it is probably the most standardised.

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[4] Sufficient quality should be taken to mean the provision of video containing enough detail to make accurate diagnostic judgements.

[5] Numerous other non-specific bands are available but RFID operation in these is generally limited to much lower power levels and therefore mainly appropriate to very localised operations.

In terms of the spectrum used by third parties (i.e. network operators) it can be noted that there is a knock-on effect from the systems deployed by the health sector. In particular, if video is to be used extensively at scenes attended by ambulances then there will clearly be an additional burden on the network connecting an ambulance to a hospital. The requirement for additional spectrum to support this will depend on a number of factors outside the control of the health sector. It can be expected that the network operators themselves will obtain any additional spectrum that might be required through the usual channels.

Finally, with regard to systems that use spectrum commons (e.g. RFIDs and wireless LANs), it is possible that there will be congestion. In the case of RFIDs the technology has not been widely deployed and in those cases where it is used in other sectors (e.g. the retail supply chain) there have been mixed reports regarding interference. It is not known whether the interference is due to congestion or poor system deployment. If congestion is the cause, then a significant deployment within the health sector would be expected to suffer the same problem. Resolution of this problem, if real and widespread in other sectors, by way of additional spectrum would probably occur at international level, i.e. through the European Telecommunications Standards Institute (ETSI) and the European Conference of Postal and Telecommunications Administrations (known as CEPT).

Systems that require dedicated spectrum. When considering whether new and exclusive spectrum should be provided, it is necessary to address the justification as to why such provision should be made. The main (and arguably sole) reason that exclusive spectrum should be made available is for those cases where communication link failure due to interference puts a patient's life at risk and, in particular, for situations where time is of the essence. Of all the applications considered in preceding sections there are only a few which fall into this category:

- **LANs supporting links with BANs**. Links between body area networks and other equipment, where this other equipment takes on the responsibility for monitoring vital signs and/or administering drugs. This could be in hospital intensive care or related to ambulance equipment at the scene of an accident;

- **body area networks** when monitoring vital signs and/or administering drugs;

- **social alarms for monitoring** activities of daily living in isolated or socially excluded groups (the most common use-case is alarms to monitor falls of older people). This could be extended to the remote monitoring of body area networks but the backhaul is likely to be carried by a public network (i.e. only the local radio link would be supported by exclusive spectrum).

It should be noted that there is one application where the risk to the patient's life is so great that a wired solution is arguably most appropriate, namely remote controlled robotic operations.

Local area networks (both hospital- and ambulance-based) are the supporting links between body area networks and diagnostic equipment, and/or between diagnostic equipment and communications gateways. It is possible that these could be provided by conventional Wireless LAN technology at 2.4 or 5GHz as noted above. However, there is a risk of interference to these networks which, for the more critical telemetry streams could be potentially life threatening. Even if the clinical environment seeks to control the interference within their buildings and vehicles, it could still be problematic for ambulances creating wireless LANs outside of their vehicle, for example at a road traffic accident. We recommend, therefore, that the more critical telemetry streams should be supported by dedicated spectrum. The Federal Communications Commission (FCC) Wireless Medical

Telemetry Service (WMTS) uses the bands 608 to 614MHz, 1395 to 1400MHz and 1427 to 1432MHz. There is no equivalent allocation at the CEPT level or in the UK.

In terms of the future provision of new, dedicated spectrum within the UK the highest priority will be the wireless local area network application for hospitals and ambulances. Critical communication links (e.g. vital signs monitoring) will require new, dedicated spectrum to reduce the possibility of interference that might be experienced if licence-exempt wireless LAN spectrum were to be used.

In terms of new dedicated spectrum there are three possibilities that can be considered:

- harmonisation with the US frequencies;
- a band or bands at or near the 2.4 and 5GHz wireless LAN frequencies given that much of this equipment already has tuning ranges of 2.3 to 2.5GHz and 4.9 to 5.85GHz; and
- a band or bands elsewhere in the spectrum.

In the case of the first two options the amount of spectrum is largely determined by the degree of harmonisation involved. In the case of identifying an allocation elsewhere in the spectrum it can be noted that the bandwidth required is relatively small as the requirement is for low bit rate telemetry and the provision of a few narrow band radio channels to support multiple devices or individuals in an area (e.g. hospital ward). If the critical applications go beyond low bit rate telemetry to, for example, the use of ultrasound stethoscopes providing moving images for diagnostic purposes (both hospital and ambulance based), then the provision of dedicated spectrum might have to be more extensive than a few narrowband radio channels.

Less critical communication links can still use licence-exempt wireless LAN spectrum and, taking account of the availability of 5GHz wireless LAN spectrum, it is not foreseen that there will be a shortage of spectrum for these less critical communication links.

Body area networks supporting implanted devices are sometimes used to deliver accurate doses of drug therapy directly into the patient. The criticality of this function means that dedicated spectrum is required; interference could cause errors that, in some cases, prove to be fatal.

Within the UK there is no requirement to allocate new spectrum to medical implants, as there is already a CEPT allocation for medical implants at 402 to 405MHz, which the UK has implemented, and is the same as the FCC Medical Implant Communications Service (MICS) allocation in the US. The CEPT allocation has recently been extended by 1MHz at either end of the existing band. It is thought that this extension is due to “apparent” congestion caused by competing technologies rather than inherent congestion due to current or foreseen demand. It is apparent that this allocation will be sufficient to cover foreseeable new applications. However, the situation should be kept under review.

Social alarms are well established and, because provision is already made at a CEPT level (and reflected in UK allocations) near 170MHz and near 870MHz, there is no requirement for new dedicated spectrum. Four channels are nominally available, two of which are for exclusive use, and the maximum power level and duty cycle are low. Given the emergency nature of these devices and their controlled power level/duty cycle, the likelihood of congestion is low. This is especially so since they tend to be used in residential areas where the density of use is low.

However, Ofcom or an appropriate body within the health sector should monitor the situation to determine when congestion might occur. In the event that additional spectrum is required it is likely to be in small amounts, although if the requirement is for contiguous spectrum (with respect to existing allocations), it may be more difficult to make provision without displacing existing users.

Conclusions and Recommendations

Having assessed the use of applications within each scenario we were able to identify the different network infrastructures required for the applications. When considering whether any of these require designation of exclusive spectrum we concluded that exclusive spectrum should only be sought in cases where communication link failure due to interference puts a patient's life at risk and, in particular, for situations where time is of the essence. The three types of applications that fall into this category are shown in Table 2.

Table 2: Applications requiring dedicated spectrum

Application / network area requiring dedicated spectrum	Dedicated spectrum requirements / details
Body area networks supporting implanted devices	There is already a CEPT allocation for medical implants at 402 to 405MHz, which the UK has implemented. The CEPT allocation has recently been extended by 1MHz at either end of the existing band. This allocation should be adequate for the foreseeable future but kept under review.
Local area networks supporting links between body area networks and diagnostic equipment and / or between diagnostic equipment and communications gateways	It is possible that this could be supported using conventional wireless LAN technology at 2.4 or 5GHz. However, more critical telemetry streams should be supported by dedicated spectrum. The FCC WMTS uses the bands 608 to 614MHz, 1395 to 1400MHz and 1427 to 1432MHz. There is no equivalent allocation at the CEPT level or in the UK.
Social alarms	These are already well established and provision is already made at a CEPT level near 170MHz and near 870MHz. Given the emergency nature of these devices and their controlled power level/duty cycle the likelihood of congestion is low. However, Ofcom or an appropriate body within the health sector should monitor the situation.

In order to realise the benefits of ICTs, the health sector (public and private providers and patient-representation) and the technology and telecommunications industry must work closely together. There may be a case for a task force to bring together the stakeholders, to monitor use of health ICTs and spread “best-practice” examples of its use, and to collaborate to overcome the barriers that may hold back the sector's technology development.

We recommend that the Department of Health should take more active responsibility for the use and management of radio spectrum by the health sector (and particularly by the NHS). This could involve the establishment of an organisation within the Department of Health or the NHS to oversee and co-ordinate the use of spectrum, and more widely, all information and communications technologies. Such an organisation would represent the NHS's (and ultimately of course, the patient's) interests in order to bring about the optimal use of wireless technologies.

2.4 Socio-economic study of transport

Overview

Technology could also bring major changes to transportation. In the rail sector, wireless communications will enable trains to be run closer together, improving capacity and a wireless corridor will provide high bandwidth services to travellers and enable applications such as closed high definition circuit television (CCTV). For buses, wireless positioning systems will allow traffic flow systems to speed their passage while information gathered on passenger loading will enable route optimisation. For both railways and buses, wireless e-ticketing and passenger information will make journeys simpler. On aircraft, users will be able to wirelessly access communications and entertainment systems. Security systems will be much enhanced, but less intrusive and widespread use of wireless systems will enhance the logistics of aircraft at the gate. Passengers on ships will have access to the same communications as they do on land and wireless systems will enable monitoring of cargo and containers. Wireless communication to cars could alert drivers to congestion or incidents ahead, be used for navigation and alerting the emergency services in an accident.

This section starts by setting out our predictions for transport across each of the different *modes* of the transport sector, e.g. road, rail, air etc. It then considers in more detail the key applications mentioned in the predictions, analysing where they are likely to be used and the timescales for their introduction. Based on these two sections the requirements for spectrum are then developed.

Transport Visions

Railways

In 20 years time, the railways will be more efficient than today, with reduced costs and increased throughput. More passengers and freight will be carried over the existing rail network. Improved radio communications with trains and with trackside staff will be an essential part of the intelligent infrastructure used to bring this about.

ERTMS (European Railway Traffic Management System) will have been introduced on most lines. Since instructions to the train will be sent by GSM-R[6], it will be possible to phase out unreliable trackside signals, saving capital and maintenance costs. Eventually, on-board navigation equipment will track train position and the current fixed block signalling will be superseded by moving block signalling. This system will be more akin to air traffic control, where trains know exactly where they are and navigate with respect to other train positions. Under this regime, trains will need to be supplied with accurate, up-to-date digital maps broadcast from the trackside.

Improved real-time train location data and speed profiling will enable 'just-in-time' delivery of trains, improving punctuality and throughput. By cutting out unnecessary stopping and starting, energy costs will be reduced, especially for long and heavy freight trains.

Intelligent infrastructure will enable proactive maintenance. For example, trains that exert excessive force on points or pantographs will be swiftly identified before real damage is done

[6] A variant of Global System for Mobile communications (GSM), developed for railway communications.

and repair schedules sent on to the depot. Train and trackside staff will be connected for voice and data, allowing them to be more flexible and efficient.

To support these operational requirements, further wireless capacity will have to be provided along the track to form a wireless corridor. Even wider bandwidths will support live, high definition CCTV monitoring for improved safety and security, and commercial applications including passenger entertainment and Internet access. At stations, reliable, high-speed wireless communications will support the needs of both the railway and retailers. Railway property values and revenues will increase. The consequent improvements to the travelling environment will persuade more people to use the railways where the opportunity exists.

Buses

Considerable growth in bus transport may be anticipated over the next 20 years, given the rising cost of fuel and a desire that public transport shall account for a greater proportion of passenger miles travelled (trains can only support a small part of this growth).

An evolution in bus services may be expected with a growth in bus priority schemes. This may include guided buses and bus lanes but in most cases buses will continue to share the road with other users. Bus priority will be maintained by carefully managing traffic flows and signals, depending on the precise position of the bus at any time.

Bus loading will be monitored, with the objective of achieving greater punctuality, reliability and efficiency and providing information to passengers in the bus and at bus stops. Where connections are involved, up-to-date information will be available to passengers on connecting buses and trains. The availability and extent of these services will vary from authority to authority and between urban and rural environments. In urban areas, some buses will take advantage of metropolitan wireless networks, where they exist, whereas in suburban and rural areas a reduced set of services will be available carried by private mobile radio (trunked or non-trunked) or public cellular networks. The means of delivery will be transparent to passengers. Most of these will be using their mobile phone/organiser, automatically connected to the in-bus WiFi system.

E-ticketing and information

In 20 years time, most people will carry a smart card electronic ticket (e-ticket) with them, similar to the Oyster card currently used for public transport in central London. E-tickets will be valid across most modes of public transport, across different carriers in some regions and right across the UK railway network.

E-tickets will be available in different forms – pre-pay and post-pay, and including season tickets that provide reduced rate fares for regular travellers.

The means of access to transport will be as at present. Cards will be swiped across, or near, a pad on entering and leaving the bus or railway station. The cost of the journey will automatically be deducted from the pre-pay balance, or charged to a monthly statement or direct debit in the case of post-pay customers.

By this time the e-ticket system will be integrated with the individual's personal travel account and planner. The passenger will be able to store recurring journeys and destinations under his web account (for example 'Work'). The result will be that when the passenger uses his e-ticket to board the bus, he will be recognised and the time and platform number for the next train home sent to him as the bus approaches the mainline station. The alert will be sent to his mobile phone or organiser as appropriate.

Some mobile phones may work directly as an e-ticket. The smart card may be built-in or, alternatively, a near-field device will provide e-ticketing based on the mobile phone's own SIM card.

While at home, in the office or on the move, the mobile phone or Mobile Internet Device (MID) will provide the passenger with information including live and future timetable data. Individuals will be able to make a booking or simply to ask for the quickest route from the current location to the desired destination.

Roads

In 20 years' time, vehicles will be more efficient and environmentally friendly due to new fuel technology. Road transport will still be a key enabler of a successful UK economy. However, congestion will be a thing of the past, and travellers will have accepted the fact that travelling at peak times and on peak routes is expensive. In line with incentives, employers will have helped the situation by adopting flexible working practices. The UK road network will have remained largely unchanged, although some very targeted capacity improvements will have been made. The UK will have agreed an architecture for the deployment of Intelligent Transport Systems, which will have proven to be the greatest market enabler.

Travellers will have far more information at their disposal in order to be able to plan their journeys and will have the ability to make modifications in real time, whenever and wherever necessary. The travel decision will likely be based on a combination of journey time and cost, which may vary throughout the day. Such information can be accessed via the web at home or in many public places and is also delivered to everyone's Mobile Internet Device (MID). The MID, which looks a little like mobile phones of old, is affordable, is easy to use, is capable of representing detailed information and is always best connected to the Internet, either by WiFi, third or fourth generation networks, personal networks, or whatever is available. Travel information is fully intermodal, enabling the traveller to take a totally joined-up view of the travel options available. With such travel information, for example, a car driver could choose to make or continue a journey by rail if the situation at that time on that day favours this, including being directed to the nearest free car park near the rail station in an unfamiliar city. The MID also contains an electronic wallet so that small charges can be paid quickly, such as in car parks and for e-tickets.

Cultural shifts have led to a massive increase in online shopping. The growth of UK based heavy goods traffic has continued to be flat, but the prevalence of light, local deliveries has increased dramatically. Van drivers take advantage of all the available travel information as they make their deliveries direct to homes. RFID has meant that lost parcels are a thing of the past and the vans can always be efficiently loaded, so helping reduce unnecessary journeys and emissions.

Roads are now much safer. The old aim of merely reducing accidents has been replaced with an aim of zero accidents, which now looks realistic for the first time due to improved technology and communications. Roads are now safer for all users and this has led to an increase in the number of people using alternatives to cars for short journeys, such as walking or using two-wheeled transport. Many safety services require speedy communications, such as Electronic Brake Lights, which warn following drivers instantly of hard braking, perhaps several vehicles ahead. A diverse collection of safety related, fast-acting applications have been realised and this has driven the adoption of dedicated safety-related spectrum in the European Union (EU), which is harmonised with the rest of the world. The introduction of the new safety systems has increased costs for manufacturers, but the industry has been able to copy the earlier success story of antilock braking systems (ABS), which began as an optional fit, but quickly became a standard fit, since they were highly valued by drivers.

The deployment of roadside sensors to detect traffic and road conditions has been supplanted by the use of vehicles themselves as sensors. Such probe vehicles can report whether traffic is stationary and even whether the road condition is poor due to potholes or other imperfections. Vehicles provide this information anonymously to the road operators, who can spot problems and take remedial action much more efficiently.

Such is the popularity of traveller information systems and safety systems, most travellers are now connected via a mix of local or dedicated networks and the cellular network. Travellers using private or public transport as well as cyclists and pedestrians are equally well connected. Entertainment services are also delivered across these networks and have been a major enabler for the business proposition in each case. But whilst it is the higher demand of entertainment services which have driven the network expansion and guaranteed the revenue, the safety and information systems have been key success factors in the whole solution, due to a strong pull from customers and encouragement via incentives from a government seeking to realise societal benefits.

Aviation

The air traveller of 2025 will find many similarities with today. Aircraft will look much the same, indeed the older aircraft still flying, such as the Airbus 380 and the Boeing 787, will enter service in around 2007 to 2009. People will travel to the same airports as today and the busiest airports will still be Heathrow, Gatwick and Stansted in the south east, although regional airports will be handling a greater proportion of long haul journeys than they do today. Aggregate aircraft fuel efficiency will have improved but the “carbon” cost of air travel will have led to a noticeable increase in prices. Despite this the numbers of passengers will have grown steadily over the previous 20 years.

However, significant changes will have taken place both within the aircraft cabin and the airport terminal and, less visibly, behind the scenes. As would be expected, the changes will have been introduced over time and will only be fully implemented at the major airports by 2025.

The introduction of the single integrated air traffic management system will have been completed, with aircraft flying more direct routes, saving time and fuel. The real time scheduling of flights and routing will ensure that aircraft take off on time and seldom suffer delays in flight, further improving fuel efficiency. Analogue VHF communications will at last begin the switch over to the more effective and reliable digital system developed in the first decade of the century, and microwave landing systems (first designed in the 1970s) will have become commonplace allowing high densities of landing aircraft to be handled even in poor weather conditions.

The biggest change in air traffic management, however, will have come about as the result of security concerns. All aircraft registered after 2015 will be fitted with high speed telemetry systems. These will allow the air traffic controllers to view the aircraft interiors (cabins and cockpits) at all times, although taking control of the aircraft in the event of hijack is still unlikely.

The continuing pressure of competition will make onboard facilities a key area of differentiation for airline operators. Cabin interiors will be rapidly reconfigurable, since almost all wires carrying public announcements and entertainment to passengers will be replaced with wireless. Passengers will be offered a bewildering array of in-flight services, many of which will have to be paid for, while the remainder will include a significant proportion of advertising material. There will also be a communication system linking any seat with any other, allowing passengers in different parts of the aircraft to talk to each other or to cabin crew.

Passengers will be able to use their mobile Internet device (now a complete phone, personal organiser, and entertainment system) just as they do while travelling on the ground. Laptops will be connected wirelessly into the World Wide Web using the 2025 version of WiFi.

Ground handling operations will also have changed substantially, to save time and greenhouse gas emissions, and in the interests of security.

Much of the documentation associated with flight preparation will now be handled in electronic form. Flight plans, weather reports, maps, passenger manifests and air traffic instructions will all be uploaded directly to the pilots in the aircraft by wireless. Similarly, ground handling services such as catering and refuelling will use wireless data links to receive orders and confirm delivery, communicating both with aircraft crew and their controllers through an integrated airport communications system.

The biggest change, however, will come about in the interests of security. All personnel and vehicles operating airside will be equipped with RFID devices that allow their movements to be continuously tracked and monitored. Alarms will automatically be raised if personnel or vehicles approach aircraft or enter areas where they are not expected to be.

The most notable change from the point of view of the passenger will be the reduction in arrival and departure formalities. All air tickets will now be issued in electronic form, either as an e-ticket or sent to the passenger’s mobile phone. On arrival at the airport, the passenger will simply swipe their e-ticket as they enter the departure lounge and check-in, while emigration control is done automatically. Security checks will be carried out by the passenger walking quickly through high sensitivity scanners that operate at the upper GHz frequencies. Within the terminal building, the passenger will be guided to the departure gate by means of personalised announcements sent to their phone or e-ticket.

All luggage will be required to be fitted with e-tags that identify the owner and the itinerary. Since most buses and trains will handle passenger luggage on behalf of the passenger, most luggage will have been checked in at an earlier stage in the journey and will be transferred without passenger intervention direct from the incoming transport to the airport system and onto the aircraft. Alternatively, the passenger will simply place their luggage onto one of several luggage ports, which will scan it for dangerous goods and materials and move it into the totally automated airport luggage handling system.

Passengers arriving by air will receive a similarly slick service. Immigration and customs control will be handled electronically as passengers swipe their e-ticket, passing the gate into the arrivals hall. Luggage arrival halls will still exist, and some passengers will collect their luggage this way, but the majority of luggage will be transferred automatically to whichever transport the passenger is going to take next.

Since 2007 all planning permission for expansion and rebuilding of airport facilities has imposed an obligation on the developers to provide high quality access links that make the use of public transport easy, convenient and comfortable. The Crossrail link will have been finally completed, doubling the frequency of trains between Heathrow and London, and similar improvements will have been made at the majority of airports handling significant numbers of passengers.

Air freight will still account for only a relatively small proportion (by weight) of goods entering or leaving the country. Air freight is valuable and the investment in automated handling systems will be justified, speeding up the transfer of goods through airports. The above changes to flight operations and ground handling will also have been introduced for air freight.

Maritime

By 2025, the great bulk of goods and freight will still enter and leave the UK by sea. The overall tonnage of non-containerised traffic (coal, crude oil and oil products, liquefied gas, steel, ores and vehicles etc.) will remain fairly static although the imports of liquefied natural gas will grow by 300% over the period. Containerised traffic will double over the same period. Ports, in particular those specialising in container traffic, will become highly automated and tightly integrated with the inland transport system.

There will still be a thriving ferry industry carrying lorries and cars to and from elsewhere in Europe. However, with the shift in freight traffic from road to rail that will occur, a significant proportion of these “lorries” will be special purpose trailers that simply carry containers between the ferries and the port side rail terminals. In addition, there will be further growth in the amount of domestic freight carried by ship and more freight will be delivered to ports closer to the final destination (diverting some traffic away from the major ports in the south-east to more northern ports).

By 2025, the International Maritime Organisation will have mandated e-navigation capability on all SOLAS (Safety Of Life At Sea) vessels. Navigation will be based almost entirely on the use of satellite navigation systems with enhanced long-range navigation (LORAN) available as a back-up across the seas around Europe. Galileo will be operational, the Global Positioning System (GPS) will have been modernised, and AIS (Automatic Identification System) based aids to navigation will have been extensively deployed in the approaches to ports and other high risk locations. As a result berth-to-berth navigation will be almost entirely based on electronic aids.

Continuing concerns over safety and protection of the environment, and particularly over security (led by the USA), will have led to the mandatory tracking of all commercial shipping within European waters and of all shipping destined for European ports. On the high seas this will be based on the International Maritime Organisation (IMO) standardised Long Range Tracking and Identification System enhanced with additional facilities developed through European research projects. Closer to shore, it will rely on the exchange of data via a supplementary AIS data service.

Ship to shore communications will also expand significantly over the next two decades. Nearly all passenger ships will be equipped with onboard mobile networks enabling most subscribers to use their Mobile Internet Devices, even in the middle of the ocean. Many of the more enlightened cargo ship operators will install onboard mobile phone networks for the benefit of their employees. Ship to shore links will also expand in support of other services, including web access for passengers and crew, real time updating of electronic charts and other navigation information, cargo status monitoring and “at sea” customs facilities. Some of these services will be provided by the relevant authorities but others are offered by commercial service providers.

The almost ubiquitous use of wireless to provide local connectivity on land will be mirrored onboard ship. Although their metal structure will remain a major limitation to propagation within vessels, this will be offset to a large extent by the very low cost of wireless equipment. Onboard wireless will be used to provide wireless LAN, cordless telephony and links to CCTV cameras (often installed in the interest of greater security). In addition, on the latest cruise liners passenger e-tickets will also act as cabin keys and a pass to facilities to which they are entitled. On container ships, some container e-tags will be interrogated remotely allowing continuous monitoring of valuable or high risk cargo.

With the growth in the size of vessels, particularly container and cruise ships, safe and accurate manoeuvring of ships into and out of port will become even more critical and major ports will have adopted sophisticated vessel traffic management and information systems (VTMIS). In order to maximise compatibility with the international shipping fleet, these systems will have been built around the facilities mandated by e-navigation. These will enable the traffic control centre to identify all vessels within the area of interest, their position, heading and speed. Combining this information with that on the weather, local tides and currents, channel depths and available berths the management system will identify the optimum route for each vessel to follow. Indeed, the route into port will normally have been transmitted to each vessel well before it reaches the port, although the ability to change it in real time is maintained so that unforeseen incidents and changes can be accommodated. A continuous data link between the VTMIS and a vessel will mean that the shore based controller and the ship’s captain (or the pilot) both will see the vessel’s track and intended route plotted on the same chart. The same system will also provide the necessary information for coordination with tugs and pilots where these are required. A number of ports handling the largest vessels will have install radar based automatic berthing systems to minimise the chance of damage to vessels and quays.

Security will be a major concern within ports and all craft operating within waters defined as under the control of the port authorities will, by 2025, be required to carry a minimum set of e-navigation equipment so that they can at all times be identified and tracked by the harbour authorities. In response to the financial incentives to reduce greenhouse gas emissions and to improve efficiency, many of these same craft will have shifted to the use of alternative fuels. For the same reason, many of the shore side vehicles and equipment will be electrically powered.

Again for security reasons, all personnel and vehicles operating within the port confines will be equipped with devices supporting RTLS (Real Time Location Services), allowing their movements to be tracked and monitored, and causing alarms should they enter any areas prohibited to them.

Passenger handling, including vehicle drivers and their passengers, will be handled in a very similar way to air travellers. Again, their e-tickets will be swiped to complete check-in and customs formalities. Vehicles and luggage will be e-tagged.

To enhance the safety of shipping, the UK and France will, by 2025, have cooperated to introduce a vessel traffic management system in the Straits of Dover. It will use radar and AIS to track vessels and data messaging backed up by voice communications to warn vessels of any potentially dangerous situations. However, the additional wireless traffic will be accommodated within the existing maritime and satellite bands.

By 2025, the Global Maritime Distress and Safety System will have been more closely integrated with electronic navigation aids and will make greater use of data transmission. The use of data in place of speech for some communications and the use of more efficient data formats means that the updated system will continue to use the same frequencies.

Environment

We have assumed that the introduction of information and communications technologies (ICTs) will bring clear benefits in terms of safety, efficiency and environmental aspects. In fact, the case for the ‘greenness’ of ICT is not necessarily so clear, since manufacturing costs and running costs can be high; for example, half of the power consumed by ICT is for cooling. We note that there are moves to improve this situation in the future, such as locating data processing centres away from urban hotspots and adjacent to renewable energy sources. Overall, we expect that the environmental concerns of ICT will be raised as an issue in the future, but there will be ways to address it, at least in part.

Inter-modality

We believe that there is a strong need for intermodality in the transportation sector, bringing together the various modes of transport already described. However, we no not believe that this drives a need for new wireless communications, beyond that which is already driven by the per-mode scenario elements of road, rail air and sea. If we wish to join up intelligent car travel with intelligent train travel, then we need to work at the back end of the system, meaning that processing power must be harnessed to unify the car and train data. In other words, we do need wireless to make the independent road and train systems work, and indeed these should also include information publishing channels such as the web and the cellular network for example, but we do not need additional wireless to join them together and hence enable intermodality.

However we do think that, when the intermodality ball starts rolling with the first two modes, whichever they are, it may quicken the process of including all the remaining modes. We expect that the availability of intermodal information will be attractive to many users and will drive further use of each modal information system.

Illustration: Intermodal e-ticketing

Mark lives in a suburban area about 30 miles away from the main city and his journey into work involves three different modes of transport. He starts his journey by taking a bus from the end of his road to the train station a few miles away. From there, he gets a train into the city. As the right train only passes through Mark's station every 20 minutes, it is important that he makes it to the station on time. Upon arrival, Mark gets the tube from the station to his office, which is only a short walk from the underground station.

As a result of new technology, Mark is now able to use one smart card electronic ticket (e-ticket), similar to the Oyster card currently available in London, on all public transport. This means that he no longer needs to fumble around in his bag to find the right ticket, or carry the exact change for the bus. As Mark is a regular traveller, he has a season ticket which saves him money and time waiting in queues at the station, but pre-pay e-tickets, where you top-up your account regularly, and post-pay e-tickets, where you are billed or pay by direct debit for the fare, are also available.

Mark's e-ticket is integrated with his personal travel planner, a portable device which he carries with him when travelling. He has saved his route to work on this as one of his listed 'favourites'. Whenever Mark uses his e-ticket to board the bus, this is recognised on his personal travel planner and the time and platform number for the next train going in to the city is sent to him as the bus approaches the mainline station. An alert is then sent to his personal travel planner, or mobile phone, to inform him of where he needs to go, ensuring that he is always at the right platform and knows exactly when the next train will be.

Applications and roadmaps

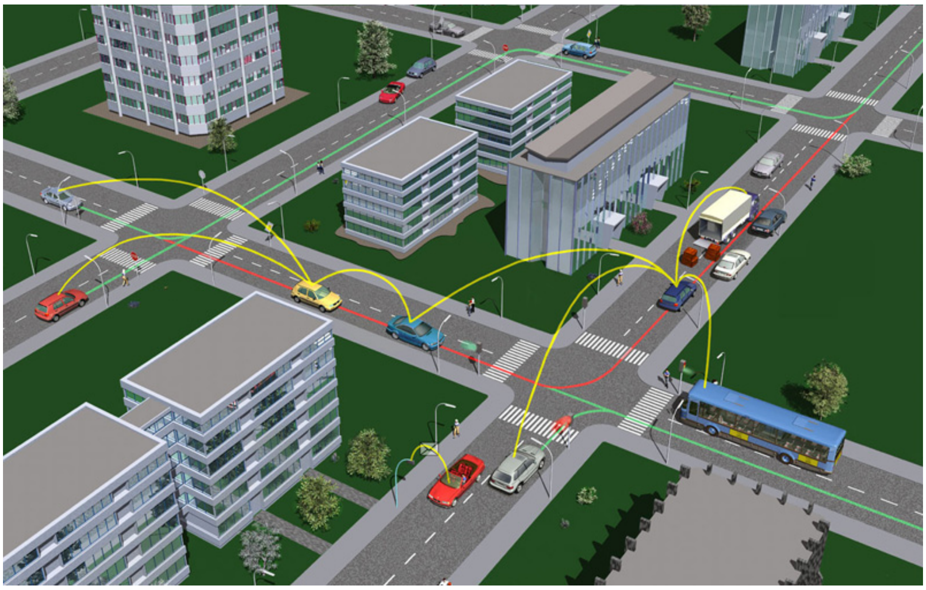
The applications from our wireless scenarios that are most likely to have spectrum requirements were:

- road safety;
- wireless corridor for rail;
- broadband connectivity in aircraft; and
- broadband connectivity at sea.

Road Safety

In the future we expect there will be provision to warn individual vehicle drivers of any potential adverse interaction between their real time driving behaviour and any upcoming road infrastructure feature. Examples of this would be advance warnings of red traffic lights or a dangerous bend that is being approached too quickly. Such a scheme using short-range wireless might look as shown in Figure 6.

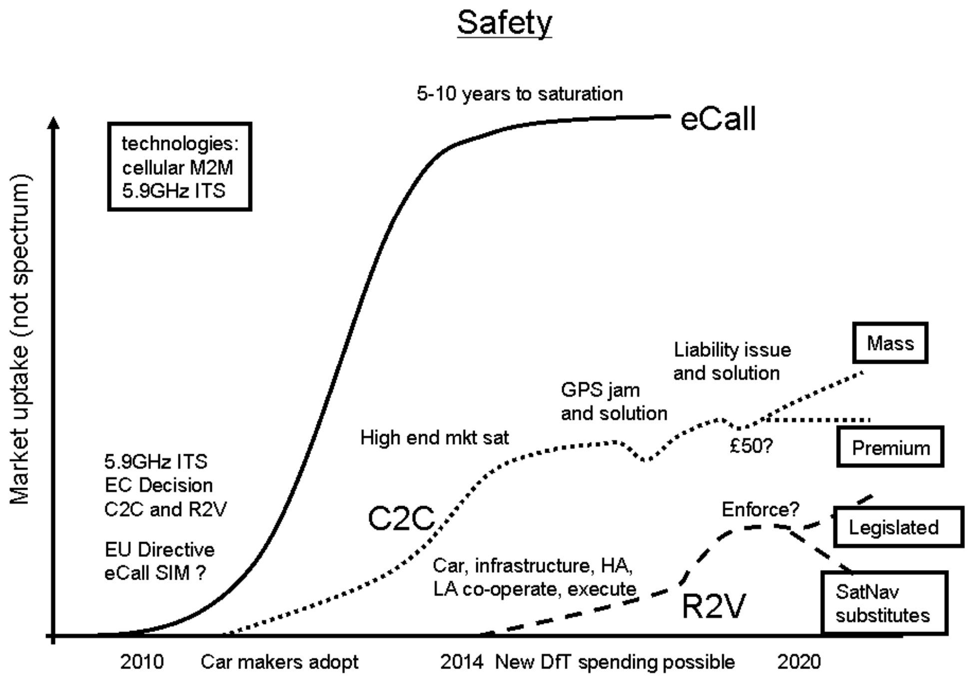
Figure 6: Artist's impression of vehicle safety communications using short-range wireless[7]



The justification for effort in this area is increased safety, leading to clear social benefits, but also to public spending benefits (at hospitals etc.). Our predicted roadmap for road safety is shown in Figure 7.

[7] Source: BMW presentation

Figure 7: The roadmap for our future story for the use of wireless for safety in road transport



The story begins by assuming that the EU introduces legislation as a result of its eSafety initiative. Amongst other things, eSafety includes eCall, which is our main interest here. After a crash eCall is designed to call the relevant authorities, so that help may be sent to the occupants with the minimum of delay. Via the subscriber identity module (SIM) card installed in the vehicle at manufacture, eCall generates a machine to machine (M2M) message such that the authorities are made aware of the crash, the state of the vehicle as far as it is known (it may be upside down, for example) and the precise location of the vehicle when last determined, via its positioning system, such as GPS. eCall is expected to reduce response time by 10 minutes on average. This is expected to reduce fatalities by the order of 10%.

Turning now to the use of 5.9GHz intelligent transport system (ITS) spectrum for safety services, it seems most likely that car-to-car services will appear before roadside-to-vehicle services. This is for at least two main reasons. Firstly the applications enabled by car-to-car are attractive to all parties concerned. Taking the example of Electronic Brake Lights (EBL)[8], the driver clearly benefits from improved safety, the car manufacturer benefits from being able to advertise improved safety for their vehicle and the authorities benefit from reduced accidents and thus reduced costs. Secondly, the process of introducing such a product to the market is simpler than for roadside-to-vehicle applications, due to the smaller number of stakeholders involved. For car-to-car applications, consortia consisting of only car manufacturers will be needed to agree on standards. However, in the case of roadside-to-vehicle communications, the infrastructure manufacturers will also need to be involved, along with the Highways Agency and the Local Highways Authorities.

The main indicators to look for in the future will be:

- the EU directive making eCall mandatory in all new type approved vehicles;

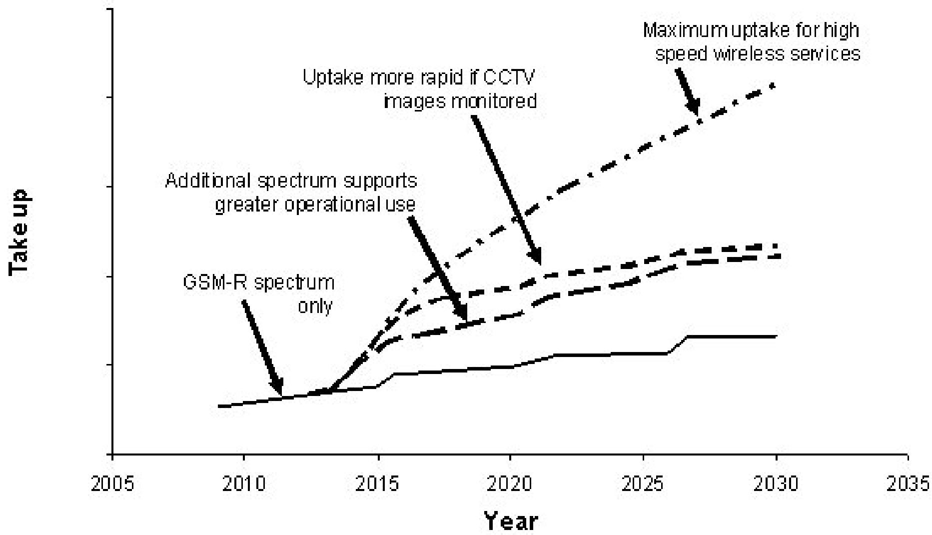
[8] With EBL a warning message is passed from the braking vehicle to the following vehicle, assuming both are EBL equipped.

- GPS jamming solutions;
- liability issue test cases;
- EU ITS spectrum moving to a decision from its present draft status;
- cost of car-to-car units being an acceptably small compared to the cost of a new car; and
- entertainment applications that are intended for roadside-to-vehicle delivery in preference to cellular delivery.

Wireless Corridor for Rail

To support future railway operational requirements, it is clear that further wireless capacity below 1GHz will have to be provided along the track, beyond that provided by GSM-R. Furthermore, other applications would also benefit from a wireless corridor. Our predicted roadmap for the rail wireless corridor is shown in Figure 8.

Figure 8: Wireless corridor roadmap for operational and commercial services



Our future story would begin with Network Rail acquiring additional spectrum below 1GHz, for example through auction or by using a third party operator. This will satisfy many of the railway's operational requirements and possibly allow limited monitoring of CCTV images, i.e. selectively in the case of an incident.

At the moment, Network Rail have permitted planning rights to use trackside masts for operational use only and they will need to obtain government agreement to use this infrastructure for commercial purposes, for example to offer Internet access to passengers. We assume this will be achieved with Department for Transport (DfT) support. Other legal agreements will also need to be put in place before Network Rail will be able to proceed with commercial services.

The business case will also need to be made. High bandwidth commercial services will need to use spectrum well above 1GHz. For contiguous coverage, additional base stations will be needed between the existing GSM-R masts. In some areas this may be provided using railway stations; for example some lines in the southeast are already covered by WiMAX services based on station deployment alone. In other areas it may be economic to construct additional trackside base stations, for example on busy commuter routes into major cities. In other cases, a hybrid solution may see available bit rates varying along the track, perhaps disguised from the end user to some extent by smart boxes on the train used to buffer incoming and outgoing data, for applications which can tolerate this such as email.

It is likely that Network Rail would implement a commercial service in partnership with third parties, for example those currently providing Internet services on trains.

The key indicators are:

- Network Rail seeking DfT support for, and acquiring, additional spectrum below 1GHz;

- Network Rail successfully negotiating planning and other rights so that they can offer commercial wireless services from trackside masts; and

- Network Rail acquiring high frequency spectrum or entering into agreement with third parties who will provide infrastructure and spectrum.

Broadband Connectivity for Passenger Aircraft

Onboard telephony and Internet access services have been offered to airline passengers for some years but have not to date achieved noticeable commercial success. Nevertheless, there is an increasing belief that this is about to change, driven by three factors:

- people are increasingly used to having wireless connectivity wherever and whenever they wish, for both business and private use;

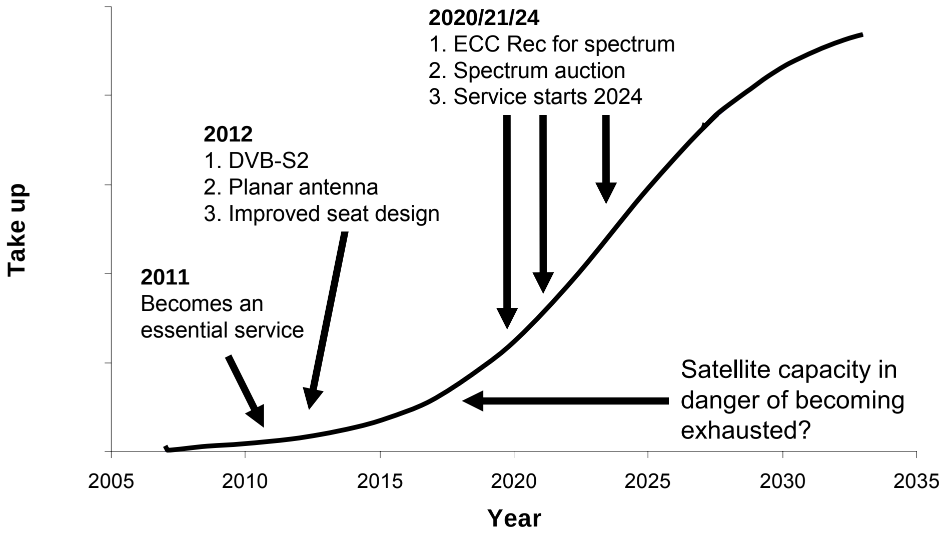
- the new aircraft systems allow passengers to use their own devices, mobile phone or computer, which is seen as attractive and convenient by users; and

- lower costs are achieved with more modern equipment.

The current service offerings are in the main limited to mobile phones (and to a small number of simultaneous calls per aircraft) or to messaging only, and there is considerable debate as to how the use of communications devices onboard aircraft will develop. However, the consensus from our stakeholder meeting was that passengers will increasingly demand onboard facilities similar to those they have on land.

Given the higher costs of in-flight connectivity (phone calls will be charged at rates similar to those for international roaming calls), and the limited privacy and space on aircraft, we expect that it will be a few years before these services become a must-have for all airlines and that take up will be somewhat slower than that seen in the move from dial up to broadband internet access. Thus, as illustrated in Figure 9, in-flight connectivity becomes a must-have around 2011 and the major growth occurs between 2015 and 2025.

Figure 9: The Roadmap for the take up of in-flight broadband connectivity



Existing satellite operators currently provide in-flight connectivity within their spectrum assignments in the L and K bands. Improvements in the technology (for example, the new DVB-S2 standard[9]) and the launch of additional satellite capacity are expected to support the growth in traffic for several years to come. However, if in-flight usage reflects terrestrial use, very large traffic levels (by satellite standards) will occur, eventually leading to the possible need for additional capacity. In this case, the lower capital costs, faster deployment times, and scalability of terrestrially-based systems compared to satellite, would be attractive provided suitable spectrum was available. We speculate that, over the time scales considered here, suitable spectrum could be released by the military within Europe to provide this additional capacity (and potentially new service providers) by around 2024.

The market for in-flight connectivity is in its very early phases today, thus key indicators will be developments over the next couple of years. Particularly relevant will be the experience of the early adopters in terms of the take up by passengers and what onboard usage patterns and etiquettes develop. Subsequent key indicators for the development of this scenario will be:

- passengers' flight selection being influenced by the availability of the service and the airlines coming to regard it as a must-have offering;
- the deployment of technology upgrades to increase satellite capacity, and the services which take up the capacity of new satellite launches; and
- lobbying activity for additional spectrum within Europe.

<u>Broadband Connectivity at Sea</u>

This is very similar to broadband connectivity for aircraft, leading to similar satellite spectrum requirements.

Spectrum

We have found that increased spectrum usage within transport is most likely to occur in the following four general areas:

[9] The second generation of the Digital Video Broadcasting (satellite) standard

- more use of existing short range applications, such as RFID;
- more use of other existing licence exempt applications, such as WiFi and Real Time Location Systems (RTLS);
- more use of cellular spectrum, specifically for machine to machine (M2M) applications; and
- new and expanded applications requiring new, exclusive or protected spectrum, such as for ITS.

Our predictions cover the next 10 to 20 years. We have found that the introduction of communications technology into transport can be very slow in some cases, which can be independent of the technology itself. It was clearly fed back to us in our stakeholder meetings that the slower cases often relate to those arising from public initiatives, whilst a commercial driver often results in a relatively faster introduction.

Increased use of existing spectrum

Looking at the list above, the first two cases may generate a requirement for a relatively modest increase in the total amount of spectrum set aside for licence exempt devices. In the third case, we expect that the spectrum requirement for transport M2M, which is low duty and low data rate, is not likely to strongly impact the cellular operators and, in any case, is certain to be dwarfed by future requirements for multimedia traffic over cellular. The fourth case is the most interesting from a spectrum point of view, since new spectrum is required for some modes of transport.

In the area of short range applications, we see Near Field Communications (NFC) being used for electronic payments for relatively low cost services such as car parks, travel ticketing and tolling. NFC is based on RFID at the physical level. We also foresee increases in the use of RFID for e-tags, especially on baggage, where future bags may be fitted with an e-tag at the time of manufacture, and for tagging freight at the item level. The International Air Transport Association (IATA) foresees major savings for the airline industry through the introduction of RFID-based baggage handling systems, although it will be several years before the majority of major airports will have deployed them.

From a spectrum point of view, both NFC and RFID are similar, narrow band applications. They are also short range, in fact very short range in the case of NFC. This reduces concern over their usage from a spectrum point of view. However, sheer volume of use may create a problem for the relatively longer range of RFID, if this also causes a very high density of devices in a given area. There will come a point where the RFID readers cannot cope with the density of tags. Some in the wider RFID industry think this point is approaching and have begun to campaign for more spectrum, taking into account projected RFID growth over the next 15 years. Such spectrum is proposed to be in the ultra high frequency (UHF) band, potentially using 2×6MHz of Global System for Mobile communication (GSM) spectrum, which presently lies dormant.

In the area of spectrum for other licence exempt devices, firstly we see more use being made of WiFi and similar future services to disseminate traveller information. Such operation is initially most likely in the 2.4GHz band, to match the converged phones and devices coming onto the market. As users employ services that are more demanding of the network, we expect that complaints of ‘congestion’ may arise within the 2.4GHz band. Users of these applications may see a need to move to WiFi in the 5GHz licence exempt bands in the future. Indeed, we understand that Heathrow Terminal 5 is already provided with complete coverage in both the 2.4 and 5GHz bands. WiFi coverage and use in train stations will also increase significantly, leading once again to potential questions over congestion.

Secondly with respect to licence exempt devices, we see a growth in RTLS. Typically these devices use the RFID bands, such as 433MHz, 868/915MHz[10] as well as 2.4GHz. Although these devices are RFID-like, they have a major difference that makes them more interesting from a spectrum usage point of view. Such devices belong to the second generation of RFID, often called Active RFID. Unlike today's typical RFID, they are always-on devices, have longer range and are full transceivers rather than readers or tags. One implication of this is that, unlike RFID, no advantage can be taken of a low duty cycle, whereby devices may effectively co-exist in the same spectrum in the same physical area. In fact, conventional RTLS devices have much more in common with communications devices than with RFID devices. But whilst many communications devices, such as WiFi, have built in spectral resource sharing mechanisms, RTLS devices presently appear not to have a sharing function, although power management does attempt to reduce duty cycles, albeit in a non-cooperative fashion. RTLS is thus likely to require more spectrum and to be a cause of interference to other band users.

In the area of machine to machine applications over cellular, we see demand being generated from traveller information systems, road network management systems and safety. However in almost all cases, M2M communications are expected to consist of relatively low data rate and low duty cycle, irregular communications. To take an example, M2M over cellular could be used in conjunction with a vehicle's satellite navigation device, so that up to date information can be found for the car driver. The M2M link allows much more personalisation of the travel information, since the satellite navigation position can be reported via the M2M link. The bandwidth consumed however will likely be smaller than a voice call and much less than a multimedia connection. Where large downloads may be required, such as complete map revisions, these are typically downloaded at home, via WiFi network.

Finally, for M2M over cellular, we see a particular aspect of the eSafety initiative coming to fruition. This is eCall, whose function is post crash safety. In a car equipped with eCall, the emergency services could be called automatically, and the condition and location of the car given automatically. eCall will stipulate the fitment of a SIM in every new type-approved car in Europe. The European Commission expects eCall to be deployed by 2011. However there does seem to be an open issue regarding the business case for the involvement of cellular operators, who are clearly essential to the operation of eCall. This issue is that, whilst emergency traffic would hopefully be small, the number of eCall units that would need to register with a network would be very large. Operators would need compensation for both the static registrations and the emergency calls on their networks. It is not clear that a suitable business case has yet been found which is acceptable to all parties.

Cellular M2M applies beyond private vehicles. Traditionally, buses and other public transport modes have relied on private mobile radio but systems being delivered today are designed increasingly to use GPRS over public cellular networks. The advantage of cellular is fairly ubiquitous coverage, even in rural areas. Private mobile radio (PMR) is able to offer guaranteed levels of service but this distinction may fade with the introduction of 3G networks offering defined levels of service. Much greater use on buses may arise in the next 20 years for improved fleet control and position reporting. One trend is the use of navigation systems to derive virtual SVD (selective vehicle detection) points, reducing the need for road-side infrastructure and providing greater flexibility[11].

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[10] 868MHz in UK, 915MHz in US, usually jointly referred to as the UHF RFID band.

[11] Selective vehicle detection is used for traffic light and barrier control within bus priority schemes.

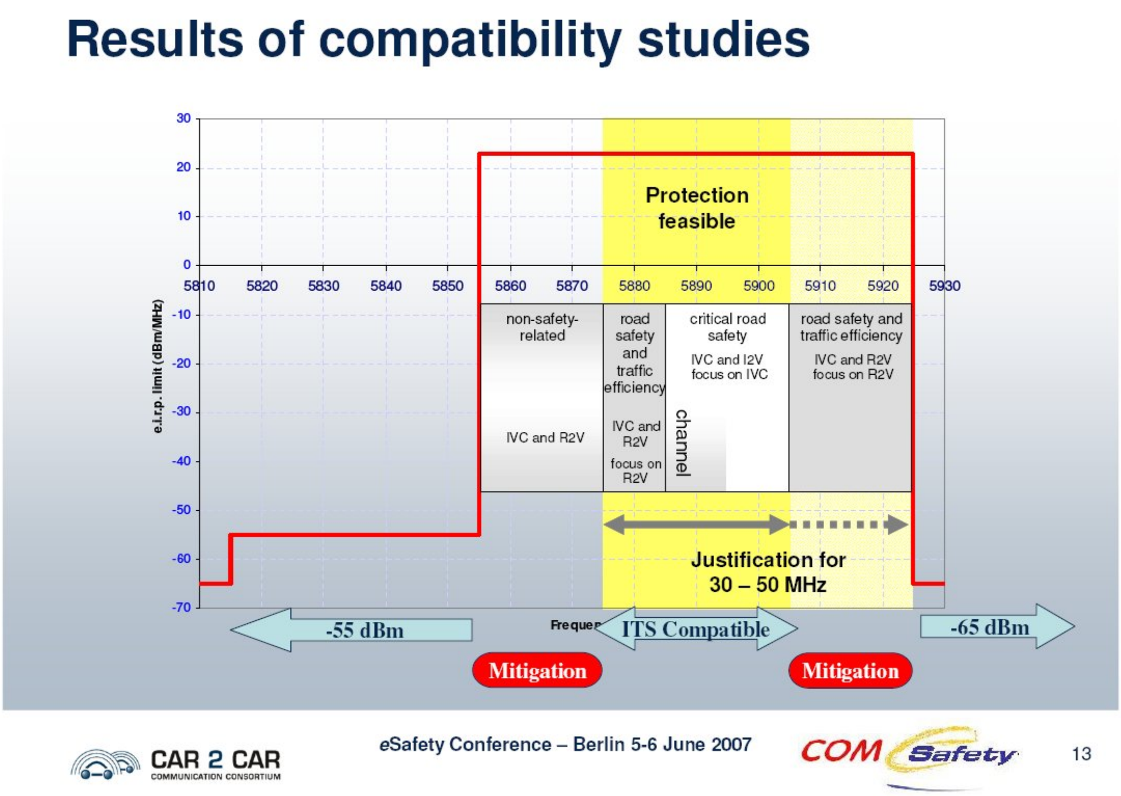
The load on cellular networks for these applications is not high but may become more appreciable once other applications are considered, including on-bus security, ticketing, and passenger information, and where high bus traffic densities are involved.

The need for new and expanded applications

In the area of new spectrum, there are several requirements from each of the transport modes.

Roads. Spectrum to satisfy the needs of an Intelligent Transport System (ITS) for the roads is needed. In fact provision of such spectrum is already well advanced within the European Commission, who in turn are following the US and Japanese allocations of spectrum for ITS. The European proposal is for 50MHz of spectrum at 5.9GHz, of which 20MHz will be for the most latency critical safety related applications, probably involving mostly direct car to car communications. The remaining 30MHz is for relatively less latency critical communications and may contain a higher amount of car to infrastructure communications. There are at least two interesting aspects to this spectrum. Firstly, whether the 50MHz total is appropriate for the applications and secondly whether non-exclusive use of the spectrum is suitable for safety related applications.

Figure 10: ITS proposed allocations at 5.9GHz



Apart from the 50MHz for safety, Figure 10 also shows 30MHz for non-safety related transport applications. This spectrum is to be discussed separately. It is also worth noting that an allocation has existed for some time at 63GHz for ITS, but this is not intended for safety applications either.

The amount of spectrum under discussion has been driven by two considerations. Firstly the critical safety spectrum is closely harmonised with the rest of the world, which mainly means the US and Japan at this point in time. Secondly the total amount of spectrum, up to 50MHz, has been calculated by a rather empirical approach, by considering a particularly busy and complex road junction on the Paris Périphérique. The uncertainty of this approach is part of the reason why the spectrum will be released in stages, as demand is found to exist. The first stage is the 20MHz of critical spectrum plus the lower 10MHz of the safety and efficiency spectrum, together shaded solid yellow in the figure. This may be followed by a decision on the upper 20MHz safety and efficiency band. In summary a total of 30MHz is expected to be released first, with 20MHz more potentially to follow.

Rail. Spectrum is needed to provide additional data and voice capacity along railway lines, creating a wireless corridor. In fact the wireless corridor covers two different needs. The first of these is to support operational requirements and the second is to provide a range of commercial services including passenger Internet access and voice services. Network Rail has identified both of these as a priority, although commercial services have a lower priority and are dependent on the strength of the business case. The spectrum requirements for operational use and for commercial services are also quite different.

GSM-R is being introduced over the next few years (to be completed by 2012) and has two main purposes. The first of these is as a replacement for the cab secure radio and trackside voice communications. The second is as the bearer for the new signalling and traffic management system, ERTMS (European Railway Traffic Management System). Unfortunately GSM-R does not have sufficient capacity to support other operational requirements. Other operational requirements include train condition monitoring, wireless transactions (e.g. credit card verification) on-train and at stations, on-train stock control, ordering and passenger data.

This means that more spectrum is needed and it is important that it should be around or below 1GHz, which of course is prime *sweet spot* spectrum. This choice of frequency is to enable contiguous coverage from current GSM-R masts. The cost of deploying higher frequencies (requiring additional masts) would prove prohibitive when applied to the whole rail network. This spectrum will probably need to be won at auction or could possibly be licensed from third party providers. It is possible that additional spectrum may be allocated for GSM-R use at a European level.

There is also interest in providing higher data rates that could be used to support commercial services (for example passenger Internet access, business email, cellular telephony via in-vehicle pico-base stations) and high bandwidth operational applications such as on-train CCTV.

In this case, higher radio frequencies will be essential to support the data rates involved and use of GSM-R masts alone will not provide adequate coverage. In parts of the network, contiguous coverage using WiMAX, for example, may be feasible using GSM-R masts and stations together – or it may be economic to deploy some additional base stations along the line. In other areas, a hybrid approach may be favoured based on variable data rate (depending on distance from the base station) plus smart caching of uplink and downlink data on-board.

When considering spectrum, clearly there will be a trade off between radio frequency, coverage and cost and the capacity that can be provided. Spectrum might be acquired by Network Rail, or in partnership with third parties such as those currently providing Internet services.

Air transport. The two key current drivers for additional, exclusive or protected spectrum in the air transport sector come from air traffic management, which is faced with continuing growth in the numbers of passenger aircraft flying within Europe, and from the increasing demand from passengers for in-flight connectivity. Recent changes to the aeronautical allocations, agreed at World Radiocommunication Conference (WRC) 2007, and the migration to narrower channelling in the VHF communications band are expected to accommodate the air traffic management requirements at least until around 2020.

Although there is considerable debate as to how the use of personal communication devices onboard aircraft will develop, our view and that of our stakeholder meeting is that these facilities will quite quickly become an essential service for all airlines and that the corresponding growth in traffic will be large. With improvements in technology and the launch of new satellite capacity, the growth in traffic is likely to be accommodated within the current satellite allocations for several years to come. In the longer term, however, satellite capacity may need to be augmented leading to the possible demand for additional, exclusive spectrum. Air to ground systems could be an attractive option and a possible source of spectrum could be released military spectrum around 9 to 10GHz.

Additional spectrum requirements in the longer term could arise from two wireless applications. Firstly, the use of unmanned aerial vehicles may develop to the extent that they need to be integrated into the air traffic management system. Secondly, wireless sensors are under consideration for future aircraft systems. It is possible that the latter could make use of application specific licence exempt spectrum but, given the potential safety implications, detailed studies will be required first. Whether or not licence exempt spectrum turns out to be suitable, the telemetry characteristics of the application suggest that the amount of spectrum required will be relatively small.

Maritime transport. Within the maritime sector there is a major move to the use of electronic navigation aids and towards greater integration between shipboard computer systems and their shore based counterparts. These changes, however, are generating little demand for new spectrum. Electronic navigation aids are largely broadcast systems (e.g. GPS and the long range navigation system, or LORAN) and greater use does not require additional spectrum. Electronic chart updating and the expanding use of ICT are leading to increasing levels of traffic. However, the resulting levels are small compared to that expected from broadband connectivity (discussed below) and can make use of the same communication channels.

The VHF communication band is reported to be congested in places but proposals to move to narrower channel spacing are likely to obviate this issue within a few years. The Automatic Identification System (AIS), if widely adopted by leisure sailors, could exhaust the capacity of its existing allocation. However, 50kHz of spectrum would double the capacity and could be obtained from the process of migrating to narrower VHF channels.

The key driver for additional spectrum is therefore expected to arise from the demand for broadband connectivity for both passengers and crew. Part of this demand may be met by public terrestrial mobile networks, where coverage is extended out to sea. However, this will only be practical on short routes and the major part of the demand will be satisfied through satellite links, which will often be shared with aircraft. As in the case of in-flight connectivity, satellite capacity is expected to be adequate for several years but could become a limitation in the longer term. In this case the continuing expansion of maritime use will rely on capacity released through the move of aviation traffic to new spectrum.

Section 3

Research into technologies

3.1 Dynamic Spectrum Access

How does it help?

What if it were possible to pick up a phone and use any network available, based on information about the price or quality of service that network offers in that location or at that instant in time? What if the cheapest selection could be made by a user’s phone automatically, for whatever service was required at that time and place, be it texting, multimedia messaging, video calling or browsing the web? What if this was possible without the user knowing if the person they were connecting with was on the same network, another network, or even in another country?

At the moment, such a dynamic pricing and quality of service selection scheme is not available to the end user. They typically subscribe to a single network and use only that network for months or years. Furthermore, as the range of services that mobile devices are able to offer increases, it makes comparisons and choice complex and time-consuming.

This research investigates the infrastructure and regulatory regime required to address the questions posed above, looking to a future where open competition is available for services in a simple and useable manner. This might result in the best provision of services to the end user as well as utilising market forces dynamically to gain highly efficient utilisation of the radio spectrum.

In last year’s Technology Research Report we discussed the design of a candidate architecture for the introduction of Dynamic Spectrum Access (DSA). This year we investigated three key issues for DSA: network signalling delays, dynamic pricing and mobility. In each case, a network simulation was developed in order to better understand the issues and behaviour of the DSA network. These aspects are reported here.

Explanation of the technology

In this research, we envisage a situation where connection to one of many networks is possible at any point in time from a mobile device. Price and quality of service information would be provided to the mobile device in order that it may choose the best network routing option available for its owner.

The choice would depend on which networks were available at the user’s location. If the user wished to connect with another party, for example to make a call, it would also depend on which networks were available to the receiving party. It would further depend on the service, for example, texting, sending a multimedia message, making a video call, or downloading information via the Web. In short, access to the spectrum from a device would be dynamic, connecting to the best radio network available given the task in hand.

We have investigated a concept where owners of spectrum transmit “pricing” information and some basic parameters of the system, such as maximum bandwidth and delay. Devices such as a mobile telephone would then read a number of quotes for a wireless service and decide on the best operator or service provider to use for transmission of their information.

Quotes for provision of spectrum related services are likely to be rapidly varying, depending for example on the level of congestion of a particular network, or the cost to that network of satisfying this particular user's requirements. In principle, this dynamic approach to spectrum allocation could lead to high utilisation of the radio spectrum through a close linkage of supply of spectrum with demand for services.

Current state of the art and our research

This research is being undertaken in a landscape where convergence is already beginning to have considerable effect on networks and communication devices. Currently an individual or household is likely to have multiple phones in operation; already we see in many homes a fixed line phone, connected for example with BT, operating in addition to one or more mobile phones. In many homes, this might also be supplemented by a WiFi phone for VoIP calls, from services such as *Skype*. Whilst each of these dedicated services have their own fortes, duplication is clear. Examples such as BT's *Fusion* initiative and the emergence of WiFi capable mobile phones show the shift in direction to address this. This research looks further to the future; beyond simply the capability of devices to connect to multiple networks, it addresses the complexity of providing centralised pricing and quality of service information across multiple networks, effectively dynamically allocating spectrum resources based on the demands of the user.

We reported on the first phase of this work in the last Research report[12]. Since then we have:

- undertaken simulations to investigate the practical operation of DSA, particularly signalling delays, the stability of pricing mechanisms and mobility aspects; and
- developed a roadmap outlining the steps necessary for the successful introduction of DSA in the UK.

Candidate architecture

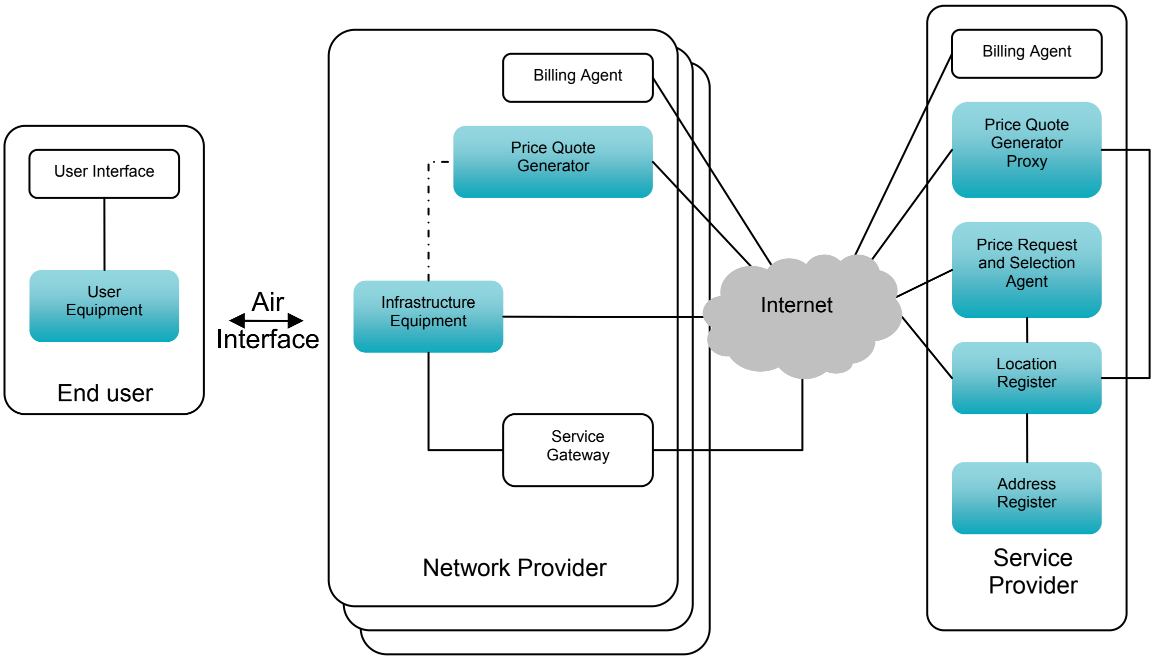
The candidate architecture for DSA has been further refined during the second project phase and is shown in Figure 11.

DSA is best described as a 'network of networks', since a number of participating access networks operated by network providers are affiliated to an overlay network operated by a DSA service provider. The DSA concept is technology agnostic so that the network access technologies can range from, say, cellular through WiFi to Private Mobile Radio (PMR) systems. Networks operate infrastructure equipment that can be simply modified to support DSA. The Internet provides the interconnection between network and service providers, as well as access to services for end users.

We summarise key elements of the architecture in the following sub-sections.

[12] http://www.ofcom.org.uk/research/technology/overview/techrandd0506/report0506.pdf

Figure 11: DSA candidate architecture



User Equipment. DSA-enabled user equipment is capable of operating across multiple physical layers. The user equipment must be registered (via a service contract) to a service provider and notifies a location register of its current location. The DSA architecture is designed to minimise the complexity in the user equipment, instead concentrating additional functionality within the service provider.

Network Provider. A network provider operates an access network that has an affiliation to one or more service providers. It allows user equipment to roam onto its network, through association with its infrastructure equipment, which essentially consists of basestations or access points. The network provider also features a price quote generator, which is one of the most important aspects of the architecture as it provides pricing information to drive both spectral and economic efficiency. A billing agent within the network provider provides billing information to service providers.

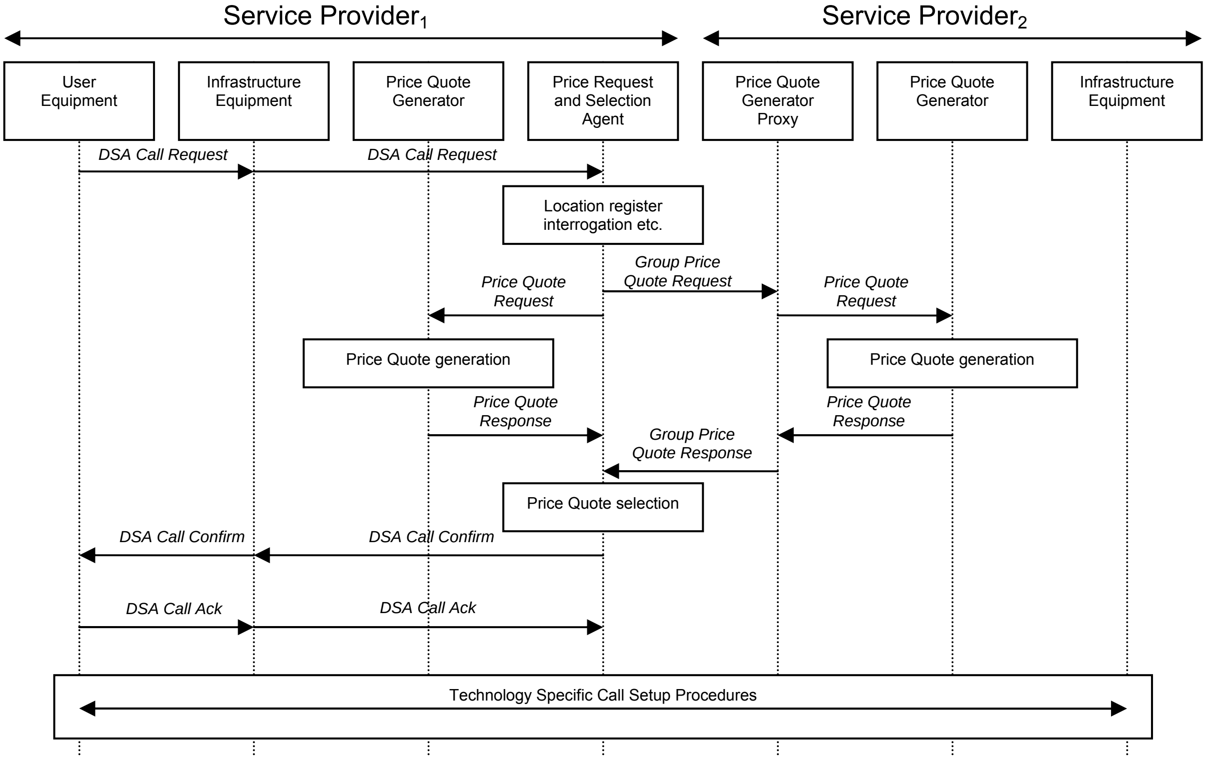
User equipment is capable of attaching to more than one access network. In order to keep track of the user equipment, the network to which it is currently connected is designated the paging network.

Service Provider. The service provider is at the heart of the DSA architecture as it manages all call requests and facilitates the exchange of pricing messages. A service provider also maintains a list of all registered user equipment in the location register and the address register contains information on all subscribed network infrastructure equipment. Within the service provider, a price request and selection agent selects the infrastructure equipment that will be used for each call based on pricing information received from the network providers. Finally, a billing agent exchanges billing information with the network providers.

Signalling procedures

This section illustrates the sequence of steps taken in setting up a call within the DSA architecture. The research covered signalling both at the initiating and terminating end of the call; for brevity, we only cover the former here.

Figure 12: Message sequence for the initiating-end portion of a DSA call setup



In the example shown in Figure 12, user equipment is associated with a service provider (here designated Service Provider$_1$). During the course of the call setup, Service Provider$_1$ will liaise with Service Provider$_2$, to determine pricing information. The steps in establishing an initiating-end call are described as follows:

i) Call Initiation – When the user equipment initiates a call, it sends a *DSA Call Request* message via the infrastructure equipment to its associated price request and selection agent. This message includes the destination number;

ii) Price Quote Request – The price request and selection agent obtains a list of all available infrastructure equipment from the location register. This list will consist of both infrastructure equipment affiliated to the same, and alternative, service providers. The process for obtaining price quotes is slightly different in each case:

- For infrastructure equipment that is affiliated to the same service provider (i.e. Service Provider$_1$), the price request and selection agent can address the infrastructure equipment directly. It does this by sending a *Price Quote Request* message to each of these to the associated price quote generator.

- For infrastructure equipment that is affiliated to a different service provider (i.e. Service Provider$_2$), the price request and selection agent cannot address the infrastructure equipment directly[13]. Therefore, a *Group Price Quote Request* message is sent to the price quote

[13] Service providers are assumed not to have addressing information for infrastructure equipment affiliated to other service providers.

generator proxy in Service Provider$_2$, which then obtains the price quotes on the behalf of the price request and selection agent.

iii) Price Quote Generation and Reply – The price quote generator associated with the infrastructure equipment responds by sending a *Price Quote Response* message back to the originating price request and selection agent, via the proxy if necessary;

iv) Price Quote Selection – Once the price request and selection agent has received all of the price quotes it can select the 'best' infrastructure equipment to provide the initiating-end radio tail for the user equipment;

v) Call Confirmation – The price request and selection agent sends a *DSA Call Confirm* message to the originating user equipment to notify it of the selected infrastructure equipment and this is acknowledged with a *DSA Call Ack*;

vi) Technology Specific Call Setup – The call is established via the normal procedure for that particular air interface;

vii) Billing – On termination of the call, the relevant billing agents trigger the exchange of billing information with the various parties so that the charges can be settled between the network and service providers involved in the call.

Simulation work

Simulations were performed to investigate three key issues for DSA:

- signalling delays associated with location updates and call setup;
- dynamic pricing, and;
- mobility.

Signalling delays. In order to determine the delays associated with DSA procedures for call setup and location updates, a DSA protocol simulation model has been developed. This models the main functional elements of the candidate DSA network architecture, as well as the associated procedures and protocols.

The main conclusion from this work is that the average call setup delay across all test scenarios is less than 1s. Furthermore, in the worst case, the call setup delay is 1.1s for a reduced feature DSA, supporting only outgoing calls, and 1.3s for full feature DSA, supporting both outgoing and incoming calls. To put these numbers into context, typical Session Initiation Protocol (SIP) based voice over IP call setup times in Universal Mobile Telecommunications System (UMTS) networks are almost 8s. For a streaming session, the call setup delay for High Speed Downlink Packet Access (HSDPA) networks is about 10s. This suggests that the extra delay introduced by DSA call setup procedures will constitute around 10% of the total delay. Thus, it is reasonable to say that the introduction of DSA will not introduce excessive call setup delays. In other words, if the underlying network providers are capable of supporting certain quality of service (QoS) guarantees with respect to call setup delay, DSA will not impair their ability to do so.

Dynamic pricing. In the context of DSA, dynamic pricing is the varying of the price offered for carrying a call in response to network conditions and/or end user demand. A simulation was developed in order to demonstrate the stability of potential pricing algorithms. One use of dynamic pricing is to perform congestion-based pricing. Here the algorithm works to increase the price of calls as network loading increases. During periods of overload this results in less blocking because it has the effect of deterring some end users who effectively 'self-block' by declining the price quote. From an economic perspective this is an efficient process as it means that those end users who place most 'value' on making a call at that time can do so whilst those who value it less (or cannot afford to pay the price) choose not to place a call.

In all of the scenarios investigated, it proved possible to implement stable algorithms. In effect this is because of the negative feedback in the price quote generator algorithms, which means that prices go up in response to higher levels of congestion.

Mobility. User equipment mobility is extremely problematic for DSA. Link characteristics, available services and QoS will fluctuate depending on the extent of mobility. The simulation tool used for investigating mobility employed a discrete time method to model a WiFi-based network. This allowed mobility to be modelled more simply at the expense of increased computation time and some time granularity. The performance of two affiliation algorithms (i.e. the basis on which the connection between the user and infrastructure equipment is selected) was investigated. These were a 'non-DSA' algorithm based on maximum signal strength and a 'DSA' algorithm based on minimum price. The following three mobility experiments were performed:

- experiment 1 investigated the effect that a single mobile user equipment may have on a DSA network with many stationary user terminals;
- experiment 2 evaluated the performance of a fully mobile DSA network, that is where all user terminals were mobile; and
- experiment 3 compared the performance of a non-DSA system and a DSA system.

The simulations demonstrated that a marginal capacity benefit of around 3% could be achieved for an 'ideal' DSA WiFi-based network, i.e. one with zero handover execution delays. In practice, this gain is more than offset by the requirement to introduce a higher handover margin to counter the longer connection setup times in DSA. Without the handover margin, the number of dropped calls increases. In effect, there is a trade-off between efficiency and QoS.

The mobility simulations have shown that DSA can accommodate user mobility with a fairly simplistic price function, albeit with reduced spectral efficiency gains compared to non-DSA systems.

Conclusions

The first phase of this project concerned the design of a candidate architecture for the introduction of Dynamic Spectrum Access (DSA). The design took account of the need to be technology agnostic and adopted the principle of minimising the modifications required to legacy networks and infrastructure to enable them to participate in DSA. The second phase of the project investigated three key issues for DSA: network signalling delays, dynamic pricing and mobility. In each case, a network simulation was developed in order to better understand the issues and behaviour of the DSA network. As a result of this work, we find there are no major technical barriers to the introduction of DSA.

However, there are some technical choices for prospective service providers, such as deciding whether to offer both incoming and outgoing calls and the level of mobility support to provide. We also conclude that there is minimal spectral efficiency gain over comparable non-DSA systems.

The project's second phase also included market and business analysis of the DSA concept. The main message is that there is large scope for market-driven innovation and specialisation that should ultimately benefit the end user. Indeed DSA is really all about facilitating market-driven competition in the provision of wireless service access. DSA can also be seen as part of a wider trend that offers 'convergence' across different access networks and services with the end user able to gain access to different services and in different locations using a single wireless terminal.

In summary, we are confidant that the implementation of DSA is technically feasible and that the prospects for its introduction rest mainly on the business case.

3.2 Wireless sensor networks

How does it help?

The healthcare and transport sectoral studies described elsewhere in this report make frequent mention of *sensors*. These typically monitor particular aspects of the environment, an object or an individual. For example, the healthcare study discusses medical sensors, which monitor heart rate or blood sugar levels. Communicating the measured data is also important, suggesting networks of interconnected sensors.

As a research area, wireless sensor networks have been investigated for number of years, primarily for military purposes. However, there is increasing interest in developing such technology for civilian and commercial applications. There are many barriers to the widespread deployment of sensor networks, including:

- sensor devices are currently too expensive for many applications;
- there is a need for power supplies that can last for many months or years; and
- difficulties in building a reliable wireless network, perhaps based on a meshed topology, to transport the data from the sensors.

These difficulties aside, there is sufficient momentum in the research and development community to suggest that sensor networks are likely to become commonplace in the future. Given the use of wireless technologies to network these devices, we commissioned this study to answer the following questions:

- what are the key barriers preventing the widespread deployment of sensor networks today?
- are these barriers likely to be overcome? If so, how and in what timescales?
- what are the resulting implications for sensor deployments? When and how densely can we expect to see sensor networks deployed and in which situations?
- which wireless technologies are likely to be used for which network deployments?
- what will the spectrum implications of such deployments be?

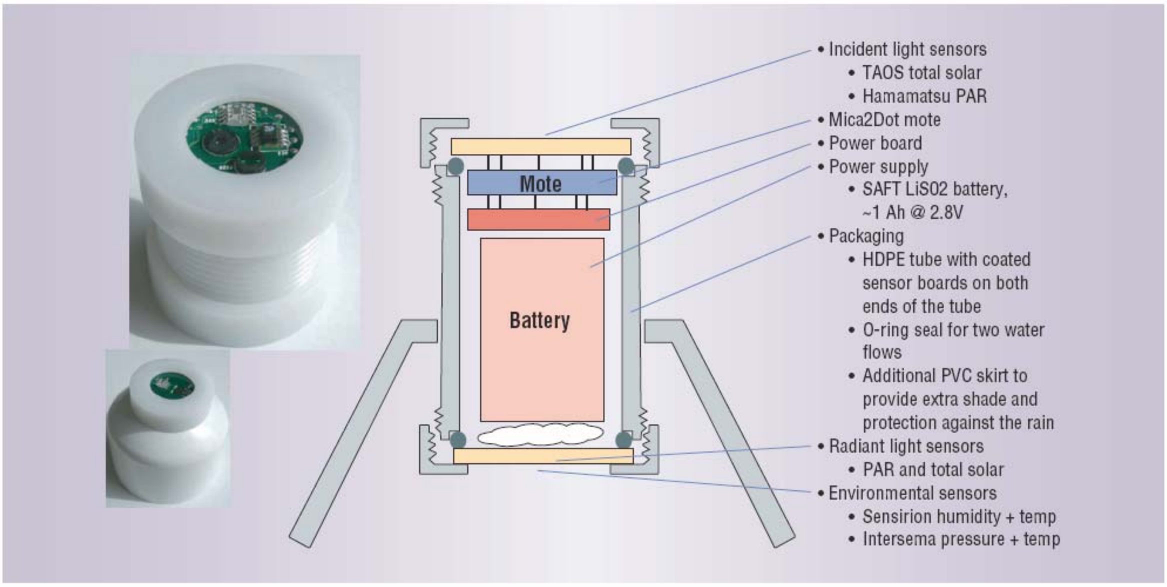
Explanation of the technology

A practical wireless sensor node must consist of the following:

- a sensor (e.g. an accelerometer, or a light sensor);
- a signal converter (usually an analogue to digital converter);
- a processor and memory (minimum capability for minimum power drain);
- a network interface (wireless; either radio or optical);
- a suitable packaging solution (a reliability and cost driver); and
- a power supply (or a method of harvesting power in situ, e.g. from vibration or light etc.).

A diagram of what a sensor can look like is shown in Figure 13. These sensors, when used as a network, form a mini weather station. They use commercially available hardware and software.

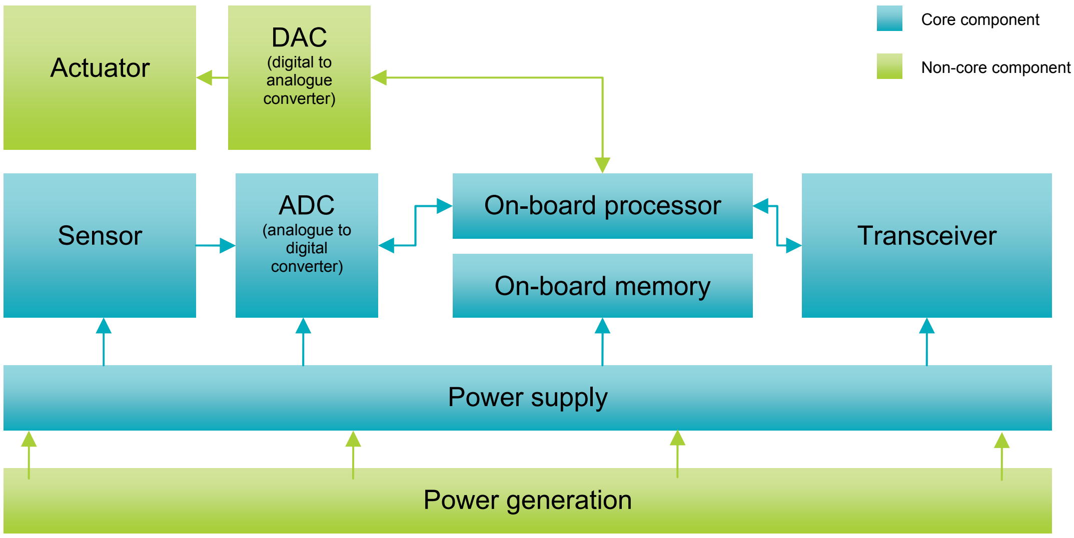
Figure 13: A wireless sensor node (or *mote*)



Often sensors are limited in terms of their resources and abilities; they might, for example, monitor a single aspect of the environment and only in their immediate vicinity. In order to get a more complete picture, multiple sensors need to be networked together. Processing of the information would typically occur at a dedicated *base unit*. Communication to this unit may also bring a challenge. The attraction of a sensor network comes from the fact that even though the nodes are quite limited, the whole array becomes very powerful when networked. Thus sensor networks are likely be large in scale, in the sense that they have many nodes and they are likely to be self configuring, to bring reliability. Also the nodes themselves are likely to be cheap, such that many nodes may be economically deployed.

Progress in sensor technologies and the emergence of new wireless communication networking techniques are increasing the deployment potential of wireless sensor networks (WSNs). A typical WSN node will always include parts of Figure 14 that are shaded blue, but a node or mote may also contain an additional actuator and/or a local power generating device, shown in green in the figure. These non-core components could extend the role of motes in many future applications for WSNs. We adopt use this wider view of what a mote may contain.

Figure 14: Block diagram of a basic WSN node



The development of standard protocols, such as used in Bluetooth, ZigBee and WLAN systems, offers key benefits which include interoperability and economies of scale for manufacture. But there are applications where the absolute lowest power consumption is required. Here, proprietary solutions can still prove more suitable than the standards.

Current state of the art and our research

Wireless sensor networks are often discussed and compared with similar technologies, such as mesh networking nodes and radio frequency identification (RFID) devices. It is worth clarifying some fundamental differences between these technologies outlined in Table 3.

Table 3: Comparison of wireless sensor nodes with similar technologies

	Wireless Sensor Node	RFID (passive type)	Mesh Network Node
Cost	Low	Insignificant price for simplest device	Expensive
Power	Restricted energy resource	No power source necessary	Good, rechargeable battery
Functionality	Single function	Not a network – needs a reader	Multi-functional
Complexity	Can run only basic processes	No or limited processing	Can run ‘complex’ protocols like TCP/IP
Range	Radio range is small	Very short range	Radio range can be large
Size	Tiny	Embeddable	Handheld or larger

Mobility	None or nomadic	None or nomadic	Full mobility

Examples of each type of network are as follows:

- **Sensor Networks.** Environmental monitoring and smart buildings are the most commonly cited applications for WSNs for now and into the future. The big differentiators of WSN from mesh are the limited data capability and the associated power savings. WSNs may require only a few bit/s per day, on average. WSNs do not carry real time streaming services, nor are they used where latency is critical. In other words, WSNs are not video or even voice capable, although people have tried VoIP over the IEEE 802.15.4 standard with limited success. WSNs' biggest source of power saving is their low duty cycle, less than 1%.

- **RFID.** RFID is used for asset tracking and car immobilisers or remote keyless entry. RFID is intended for the lowest cost, even literally throwaway applications and is not operated as a network. There are four possible classes of RFID, with the lower classes being overwhelmingly more common today, and so forming the basis of comparison in the table:

    - Passive RFID. This type has no built-in power source and must be read by a scanner. This is the cheapest tag, used for item identification and theft prevention;

    - Semi-passive RFID. This type has a built-in power source for use in processing and by other peripherals, perhaps sensors, but the power source is not used for the transceiver and so does not boost range. This type of tag is used in road tolling schemes;

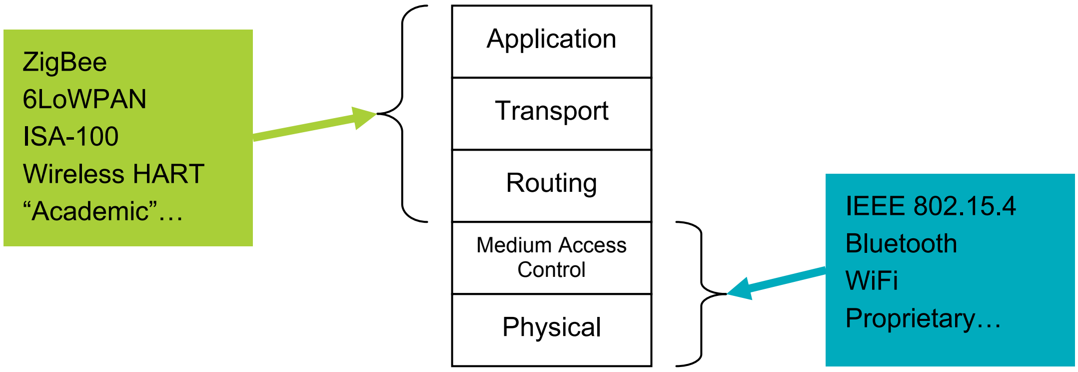
    - Semi-active RFID. This type has a power source, which is available to the transceiver. However the node is expected to have a low duty cycle. The tag is capable of initiating communication, making it quite different to the passive tags; and

    - Active RFID. This type is powered and the transceiver is always on. This can make it somewhat similar to a WSN. Active RFID can be very capable and could become indistinguishable from a WSN in an application. We thus expect Active RFID and WSN devices to converge.

- **Mesh Networks.** Example applications today include municipal wireless rollouts and, in the near future, we expect Vehicle Ad Hoc Networks (VANETs) to be a large application. VANETs are driven by the need for car-to-car and car-to-infrastructure communication in order to build Intelligent Transport Systems (ITS). Such concepts are discussed within the transportation sectoral study elsewhere in this report.

There are a great many terms for ad hoc and de facto standards in use in the field of wireless sensor networks. At the top level, we can clarify the situation somewhat by reference to Figure 15, which splits the standards into those that apply to the physical layer/MAC and those which apply to the networking/application layers. This is particularly useful in showing the difference between ZigBee and IEEE802.15.4. These two terms are often used almost interchangeably, yet they refer to quite different functionality, although they are indeed often used together in an application. The term "academic" refers to university research activity, which often uses IEEE802.15.4 as a base for their investigations at higher levels of the system.

Figure 15: WSN standards and their positions in the communications system



By 2011, around 90% of WSN implementations are expected to use IEEE 802.15.4 for the radio functionality. Very many of these are expected to run ZigBee on top of 802.15.4, whilst others will run application specific networking, including the two industrial sensor standards Wireless HART and ISA-100. The minority not based on 802.15.4 will use a variety of proprietary radio protocols. The 802.15.4 standard is targeted at very low power and very long battery life applications. It is specifically targeted at sensor networks, interactive toys, smart badges, remote controls and home automation, operating in international license exempt device bands.

The aim of ZigBee is to identify the common applications and to make them particularly easy to implement and to ensure interoperability between compliant devices. ZigBee provides various profiles in the following groups:

- a general group including simple on/off functionality and applications to measure received signal strength;
- an HVAC group (heating, ventilation and air conditioning);
- a lighting group;
- a security group; and
- a measurement and sensors group.

Historically, the Internet Protocol (IP) suite was thought to be too heavyweight for low power radios like 802.15.4 due to the amount of management traffic and typical payload sizes. However, the 6lowPAN standard is attempting to address this and is intended for facilitate deployment of IP on low power devices, including sensor nodes. 6lowPAN comes later to the market, but competes directly with the ZigBee approach by offering a more open standard and direct access to nodes via IP, rather than through a protocol translation gateway. In other words, a user anywhere on the Internet may address any 6lowPAN sensor node as freely as any other Internet device. Of course, not all applications require this, but where they do it is an appealing prospect for the end user.

For balance, it should be pointed out that for really low resource sensors, 6lowPAN still remains too heavyweight in memory footprint and computational power (e.g. for header compression). For larger wireless sensors, however, it may be a good match, to allow existing applications or control protocols for other devices (alarms, lighting control) to be ported to WSNs.

All the published work we have seen to date has used the industrial, scientific and medical (ISM) bands at 433MHz, 868/915MHz (UK/US) and 2.4GHz. All of the above except 433MHz is specified by the 802.15.4 standard and it follows that the many things based upon it (ZigBee, 6LowPAN and more loosely ISA-SP100, wireless HART etc.) use the same spectrum. The 433MHz band is used by WSNs with proprietary radio solutions.

We have seen no work that suggests operation at higher frequencies, such as 60GHz, in the future. Possibly this is because there is an intrinsic trade-off between antenna efficiency (related to the space available to form the antenna) versus power consumption, as frequency increases. This makes 2.4GHz looks attractive, and where the relatively lesser amount of spectrum is sufficient, it makes 433/868 and 915MHz attractive too. The amount of spectrum used by WSNs is small due to their small data rates and duty cycle and presently the ISM bands appear adequate.

Two major factors that will affect future take up of WSN technology are cost and reliability. Absolute cost of WSN nodes are steadily falling, and will need to continue to do so as this will be important to reduce price differentials against wired sensors. Basic node cost is a dominating factor in many applications, given the number of sensor nodes employed, and will be the major cost driver for large scale applications. However, the whole life-cycle cost must also be considered. Feedback from our research suggests experience of detailed cost analysis for WSNs is still somewhat limited.

Our research confirms that power consumption, energy scavenging and batteries continue to be seen as a key issue to be improved for WSN systems, and much research and development work is focused on this area. Energy scavenging technologies have the potential to make wireless sensors much more competitive against wired sensor approaches in terms of operational and running costs.

It is predicted that costs for WSN nodes will fall during the next 3 to 4 years. We expect that a $10 node is likely to be achievable in the 2010 to 2015 timeframe. It is clear that the radio cost is not the overriding factor, given highly integrated radio and protocol chips are available as part of solutions from a number of vendors.

Another major factor to affect WSN take up is reliability. Issues include:

- wireless link reliability;
- robustness of nodes in the application environment;
- power/battery life performance (including operation near the end of battery life); and
- network topology to deal with link and node failures (mesh, retry protocols, redundancy).

The first of these is seen as the most important. Our research confirms that system and data reliability is seen as a key requirement by 90% of users. However, extended experience of permanent medium- and large-scale WSNs in real-world environments is still limited, and the general characteristics of node availability, data integrity and 'drop-outs' are still being understood. A particular aspect of this is the effect of a crowded RF environment on battery life; depending on the exact protocols and system operation adopted, battery life can be impacted if the nodes attempt to retry sending data, or send via alternate nodes or paths (mesh approaches). This can lead to reduced performance and apparently unreliable WSN systems, where in fact the key factor is crowding with other users rather than inherent system or link unreliability.

We can categorise the findings of our market research as *enablers* or *barriers*. These are summarised in Table 4.

Table 4: Summary of enablers and barriers to wider WSN deployment

Enablers	Barriers
Clear evidence of a sustained, growing market	Suitable batteries and power scavenging techniques are still being developed
Core technologies are well developed	A lack of major systems providers or integrators
Communications standards are emerging	Limited end user experience over the entire product life cycle
A wide range of trials in progress	Immature application level software
Increasing focus on sensor applications, rather than just on technology	Possible negative public perceptions of the use of sensors for evasive monitoring

Conclusions

After considering both the technical and commercial perspectives of wireless sensor networks, the key conclusions from the work of this study may be summarised as follows, firstly from a technical viewpoint:

- IEEE 802.15.4 radios are the basis for the majority of industrial activity;
- unstructured networks, where all nodes are equal, are the subject of much academic research and military interest, but they have not seen the level of industry interest consistently focussed on structured networks such as 802.15.4;
- the presence or absence of network structure and/or node equality are key determinants of network suitability for a given application; and
- 802.15.4 is designed to be polite and to check for clear channels before transmitting. The resultant potential latency hit is usually tolerated, but this could become a problem when bands get crowded and 802.15.4 suffers due to its politeness, in the face of increasing WiFi usage, particularly for streaming applications, for example. This may lead to the appearance that WSNs are unreliable. This is an especially important issue as the perception of unreliability is one of the key barriers for WSN adoption.

Secondly, from a commercial viewpoint, we have noted that:

- wireless sensors constitute a growing market with many active academic and industry players; and

- the technical standards being adopted are great enablers.

Bringing the technical and commercial aspects together, we see that there is really no ‘killer’ application currently in evidence. In particular we have seen no big consumer pull, rather a range of industrial/commercial applications. The applications perspective is further complicated by a clear overlap between WSNs and RFID. This overlap is growing and we see convergence likely in many cases, such as location systems for example.

The lack of a killer application may be due to such limiting factors: as cost and a limited understanding/experience by users, especially regarding ‘real-world’ reliability. This in turn leads to a lack of clarity for the cost-benefit balance in a given application. One likely signpost of a movement towards a killer application would be the involvement of major systems integrators. Such players will come on board when there is a need to take a professional approach to defining, installing and maintaining large wireless sensor networks. We do not see this happening just yet, but as experience is gained with WSN deployments over the next 3 to 5 years, the major sensor system suppliers and sector-specific integrators can be expected to increasingly build their WSN expertise.

In terms of the frequencies to be used in the future, we expect they will all continue to fall into existing licence-exempt bands as follows:

- 13.56MHz – for existing passive RFID, and the next generation Active RFID, using existing standards;

- 433, 868, 915 MHz – for outdoor RTLS & sensing using standards and proprietary approaches; and

- 2.4GHz – indoor RTLS and sensing - IEEE802.15.4, ZigBee, WiFi.

It should be noted that some in the RFID industry have begun to campaign for more spectrum, taking into account projected RFID growth over the next 15 years. Such spectrum is proposed to be in the UHF band, potentially using 2×6MHz of GSM spectrum, which presently lies dormant. This is not spectrum driven by WSN requirements, but nonetheless WSNs might be able to take advantage of it, depending on how the technical campaign details evolve.

In summary, from our market evaluation conducted as part of this study and our view of the commercial potential and predicted growth of WSN usage, it is not evident that, even with much greater deployment of WSNs and sensing nodes (to the level of millions of nodes nationally), there will necessarily be major demands on spectrum. This is given the low-power, low-duty cycle, non-real-time nature of most WSN requirements. The low-power and low duty-cycle characteristics in particular permit significant geographic frequency re-use.

However we do conclude that the main issue for WSNs will be being crowded-out of the bands, especially 2.4GHz, particularly by the increasing use of WiFi for streaming services, which are inherently impolite during the real-time streaming itself. This is likely to be evidenced as variable performance of WSN networks, with perceived (and actual) reduced reliability/availability by users.

3.3 An assessment of the theoretical limits of copper cabling in the last mile

How does it help?

With the rapid adoption of residential broadband access, deployment of broadband modems over the UK copper-based telephone network has grown very rapidly in the past few years.

The vast majority of such modems use Asymmetric Digital Subscriber Line (ADSL) or ADSL II+ modems installed in local exchanges.

Current Digital Subscriber Line (DSL) technologies achieve remarkable performance relative to the state of the art available just ten years ago in voiceband modems. This has been achieved through significant advances in modulation techniques and in cost-effective digital signal processing. It may be expected that performance could be improved by further such advances in the future. However, the transmission over the copper access network is subject to absolute physical limits of bandwidth, attenuation, noise and interference in the form of crosstalk.

We commissioned a project that would take a step back from the complexities of the copper network as it is currently deployed and managed and, with the benefit of this idealised and abstract view, estimate the theoretical capacity limits for the underlying network. While the simplification of the problem may not reflect the current realities of network deployment, the estimates will set an upper bound for the expectation of what future modulation technologies may have to offer.

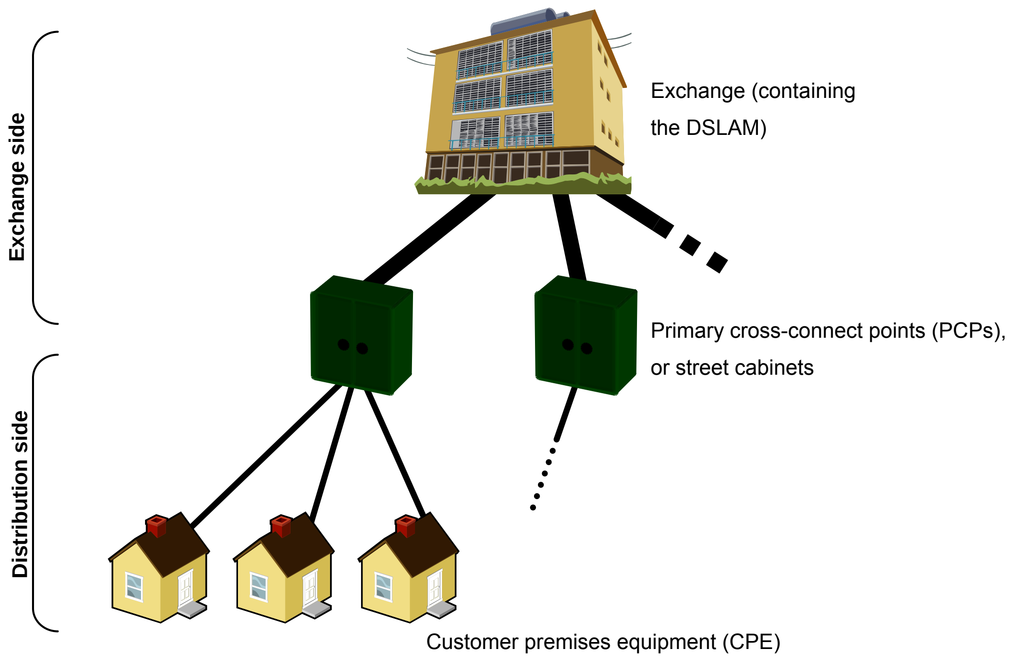
Explanation of the technology

In the UK, BT operates the largest copper-based network, capable of supporting voice and data services. An example of the latter is ADSL, which is the dominant technology, in terms of subscribers, for home broadband services in the country. The network has a *dentritic*[14] structure; at the top there is an exchange that hosts one or more Digital Subscriber Line Access Multiplexers (DSLAM). The exchange is connected by large multi-pair cables to a number of street cabinets known as primary cross-connect points (PCPs). From these street cabinets, smaller multi-pair cables progress to the customer premises equipment (CPE).

Our investigations have shown that, on average, there are 14 street cabinets per exchange with each exchange side cable carrying approximately 350 pairs. It is important to note that the cables from the exchange to a particular street cabinet are all the same length. Therefore, signals carried along these cables will experience identical attenuation over this distance. From the street cabinet, a number of cables radiate out into the distribution side of the network. These multi-pair cables are therefore isolated from one another. A simplified illustration of the structure of a typical copper-based network is shown in Figure 16.

[14] Branched or tree-like.

Figure 16: Typical copper-based network structure (simplified)



In practice, the capacity of the network is set by three factors:

i) the physical and electrical topology of the network and the noise environment in which it operates;

ii) the transmission techniques and equipment used at the exchange (DSLAM) and the customer premises; and

iii) the access network frequency plan (ANFP), which specifies the power spectral density (PSD) upstream and downstream in different circumstances.

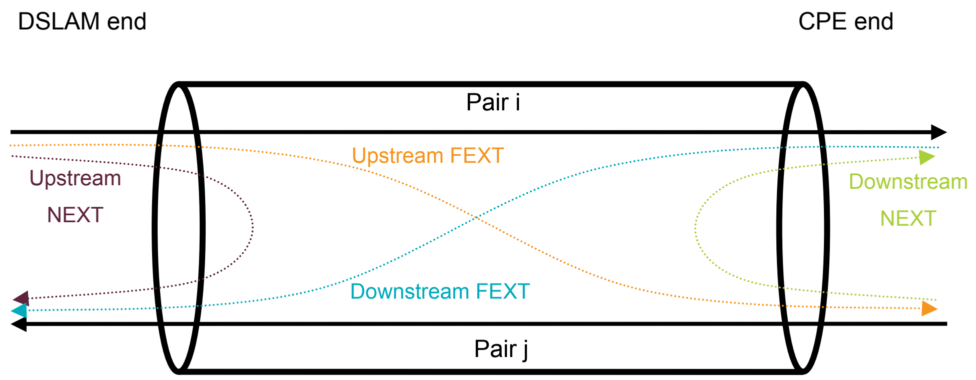
In looking at maximum capacity, the first of these factors is considered a 'given' and cannot be changed. The other two factors are open to change and improvement.

The second factor comprises the transmission techniques (such as modulation) and equipment. To calculate the maximum capacity, it is necessary to take a view on the limits to improvement in techniques and in equipment. Pointers to these improvements are given by the research being undertaken in universities and the developments being announced by vendors. They principally concern the use of techniques to reduce the SNR required.

The third factor is also open to change. The ANFP is a standard that allows different operators, services and types of equipment to coexist by managing crosstalk interference in multi-operator environments. Crosstalk refers to the signals from one pair coupling into another pair. The ANFP manages crosstalk by partitioning spectrum between different uses and by limiting the PSD at each frequency.

Crosstalk can limit the capacity of a channel. There are two types of crosstalk, near end and far end, referred to as NEXT and FEXT respectively. These are further split into upstream and downstream variants, as illustrated in Figure 17.

Figure 17: Illustration of NEXT and FEXT



NEXT is the leakage of signals from transmitters on other pairs in the same cable back to the input of a receiver at the same end. It is not an issue so long as the frequency plan does not allow overlapping (this is normal practice).

FEXT is the leakage of signals from transmitters on other pairs in the same cable to the input of the receiver at the other end. It causes the "near far" effect, where weaker, attenuated signals are drowned out by stronger crosstalk.

FEXT can theoretically be eliminated by dynamic spectrum management (DSM) level 3 - a process known as vectoring. This method of crosstalk cancellation uses techniques very similar to those of an echo canceller. If the other modems using that group of cables, or binder, are co-located then their signals are known. It is, therefore, possible to predict the induced crosstalk on all the other lines. This predicted value can then be subtracted from the actual received signal to reduce the amount of crosstalk.

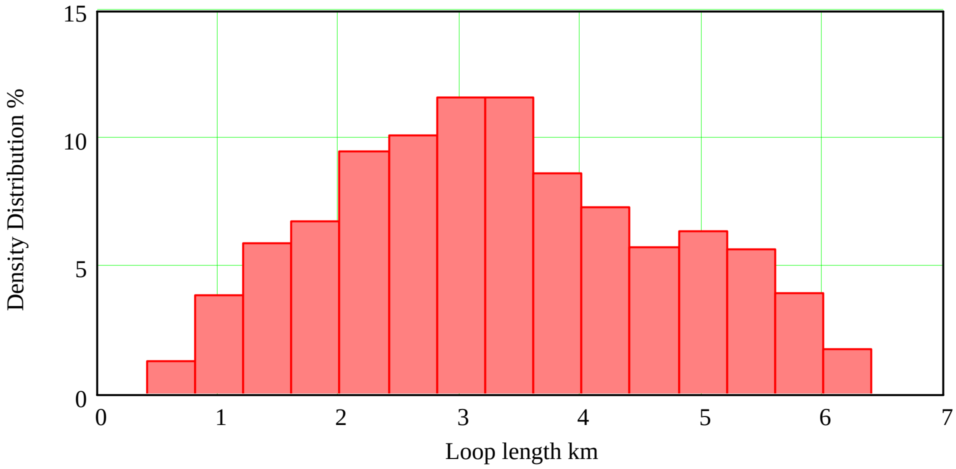
Current state of the art and our research

The data rate performance of ADSL varies with distance from the exchange and, therefore, cable length. To capture this effect, we simulated three scenarios:

- all modems are hosted in the exchange (case 1);
- all modems are hosted in street cabinets (case 2); and
- a mixed distribution, with modems hosted in both the exchange and street cabinets (case 3).

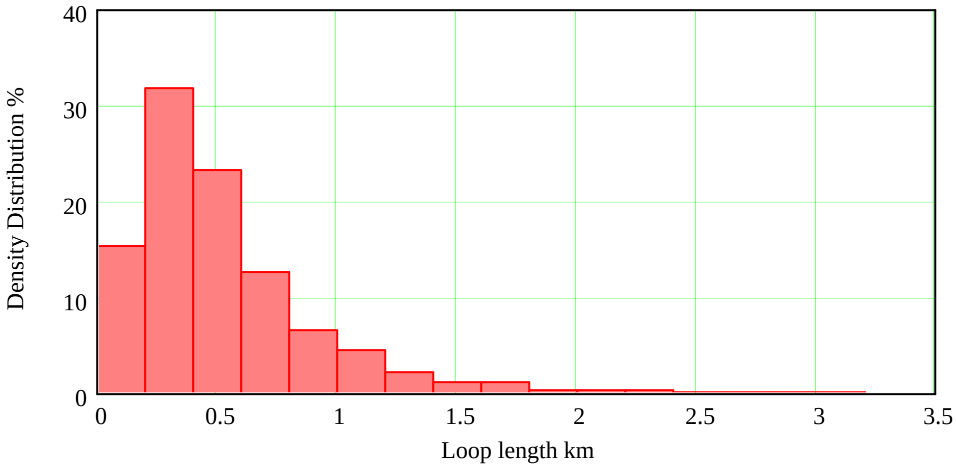
Underpinning all of the scenarios is data on actual cable lengths deployed in a UK network. First we consider case 1, which covers the entire loop length, from the exchange to the customer premises equipment (i.e. covering both the exchange and distribution sides). Figure 18 presents the data of loop lengths as a simple distribution, showing a broad peak around 3km.

Figure 18: Distribution of loop lengths, including both exchange and distribution sides (case 1)



Secondly, we present case 2, which covers the length of the loop between the street cabinet and the customer premises equipment (i.e. covering just the distribution side). Figure 19 presents the data as a simple distribution, showing a pronounced peak at approximately 350m.

Figure 19: Distribution of street cabinet (distribution side) loop lengths (case 2)

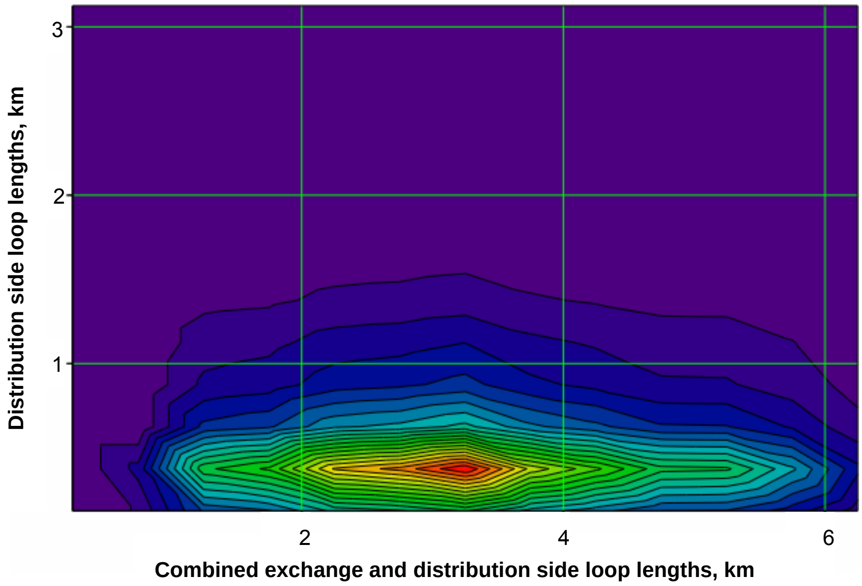


Case 3 is more complex to model. It is necessary to posit the relationship between the two 'pure' distributions of cases 1 and 2, as we need to be able to remove some proportion of exchange lines (including both exchange and distribution sides) and replace them with a known distribution of street cabinet lines (comprising just the distribution side). To do this, we would ideally know, for each exchange line, the length of the exchange side and the length of the distribution side. Unfortunately, we do not have this data, so we have estimated the data by making two assumptions:

- that the two sets of data are approximately independent of each other; and
- that the sum of the exchange and distribution lengths is always greater than the distribution length.

With these two assumptions we have constructed a two dimensional probability density function of combined distribution and exchange side loop lengths against distribution side loop lengths. The result is shown in Figure 20, showing a strong peak around about 3km and 400m.

Figure 20: 2-dimensional probability distribution of copper loop lengths (case 3)



Theoretical results

This section discusses the simulation results obtained for the three cases. To recap:

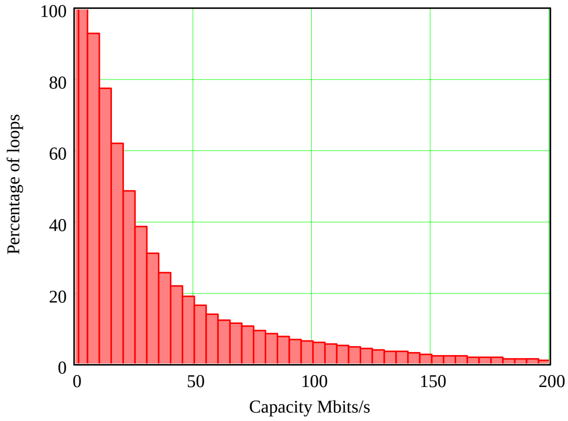
- in case 1 all modems are hosted in the exchange;
- in case 2 all modems are hosted in street cabinets; and
- in case 3 we consider a mixed distribution, with modems hosted in both the exchange and street cabinets.

In all cases we assume that the loops are driven by the highest power possible given current technology, i.e. 25dBm.

Results for case 1 are shown below. Figure 21a shows a cumulative distribution of the achievable bit-rate capacity. This shows that 50% of the loops described by this case should get a theoretical data rate greater than 22Mbit/s. Figure 21b illustrates how the data rate varies with loop length.

Figure 21: Results for case 1

a) Theoretical cumulative distribution of capacity from the exchange



b) Loop bit rate capacity varying with length

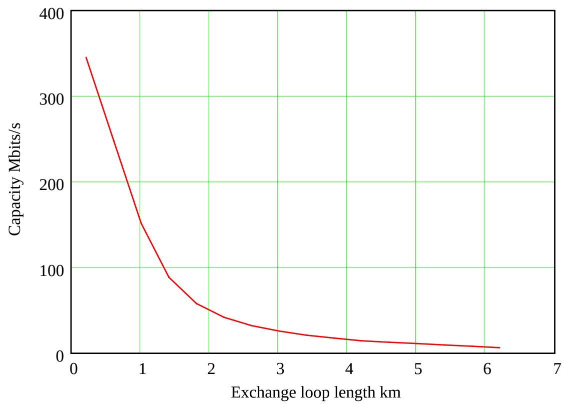
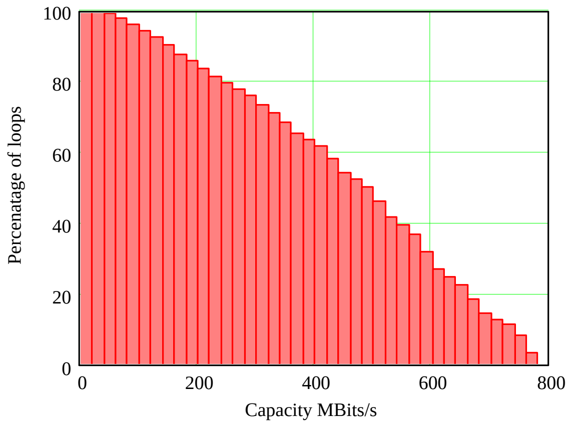


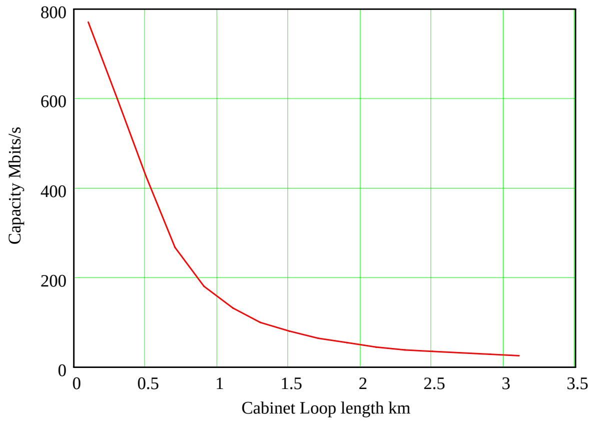
Figure 22 shows the results for case 2. The cumulative distribution of theoretical capacity possible from a street cabinet is shown in Figure 22a; we can see that, in our idealised environment, 50% of customers could theoretically receive 500Mbit/s. Figure 22b shows how the bit rate capacity varies with loop length.

Figure 22: Results for case 2

a) Theoretical cumulative distribution of capacity from the street cabinet

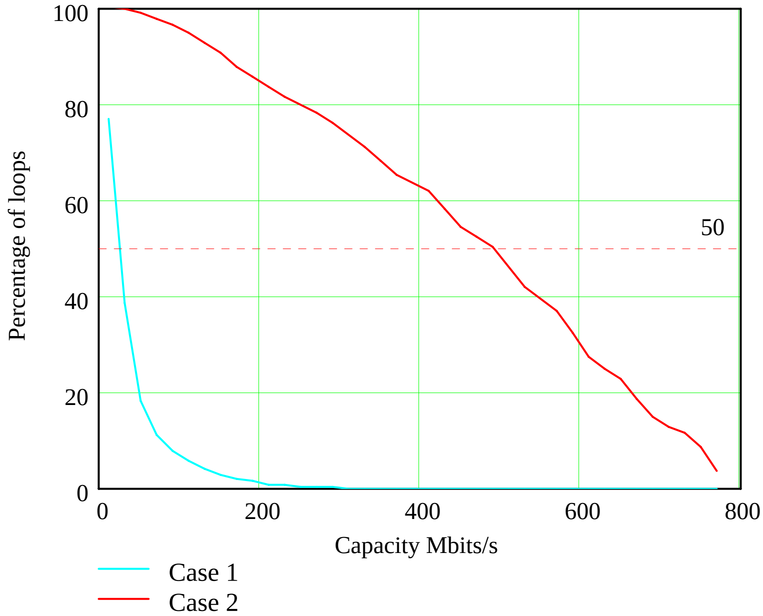


b) Loop bit rate capacity varying with length



The capacities achieved for the two pure cases are summarised in Figure 23. The space between the two curves represents the potential options for case 3.

Figure 23: Theoretical capacity profiles for cases 1 and 2

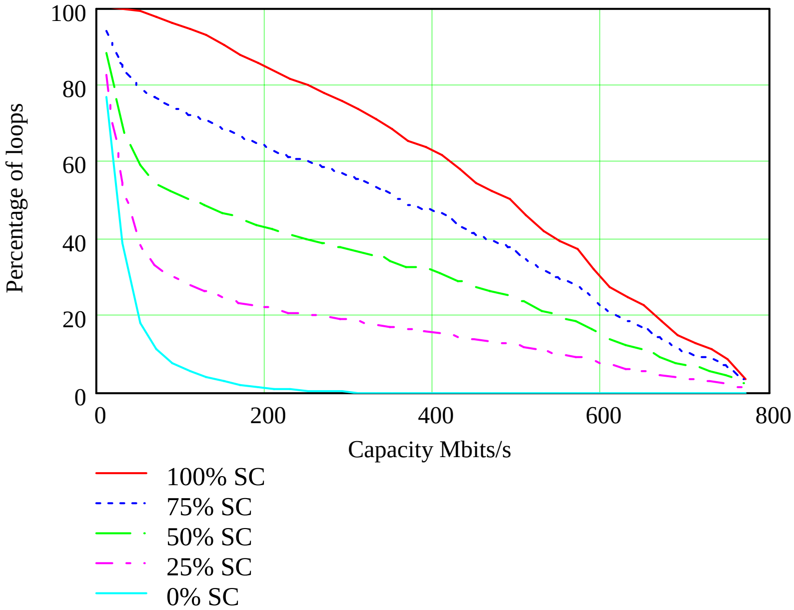


There are a number of ways in which the mixed deployment of modem equipment described by case 3 can be implemented. We consider the most likely approach is that requests to be upgraded to the faster service (i.e. modems deployed in the street cabinet) will drive deployment. Such customers will be scattered all over loop lengths so that street cabinets will be installed across the network as required and each one will host a mixture of traffic from the exchange and street cabinet. We term this *loop length independent deployment*.

One of the ways to realise loop length independent deployment is called binder switchover. It is assumed that each multi-pair cable radiating from the street cabinet will split off individual pairs at the same point. In other words, the loss and crosstalk environment for all pairs in one of these cables will be the same. It is thus possible to consider the possibility of switching over all the pairs in such a binder and preventing any crosstalk.

Since crosstalk happens within all pairs of a binder, if the whole binder radiating from a street cabinet is switched over together, then there can be no crosstalk. The results from this deployment scenario are the best that can be obtained since they are identical to those using a FEXT cancellation technology. Figure 24 shows the effects on the cumulative capacity as such binders get converted across the network, from a 0% street cabinet (SC) deployment, up to 100%. Assuming a 50% distribution of modems split between the exchange and street cabinet, we can see that 50% of the loops should support a theoretical capacity of approximately 100Mbit/s.

Figure 24: Cumulative capacity results for the binder switcher method for realising a mixed deployment (case 3)



Conclusions

Table 5 summarises the headline results of our modelling of the theoretical maximum capacities. Case 3 is for 25% street cabinet deployment. The indicated capacity is the total for both upstream and downstream combined.

Table 5: Headline theoretical capacity limits for cases 1, 2 and 3

	Percentage of households achieving above 50Mbit/s	Percentage of households achieving above 100Mbit/s	Median data rate, Mbit/s
Case 1: Modems in exchanges	17.7%	6.1%	22
Case 2: Modems in street cabinets	99.1%	95.5%	492
Case 3: Binder switchover @ 25%	38.4%	28.8%	35

The results for case 1 show that even removing crosstalk cannot compensate for the signal of the longest loops being ultimately limited by the noise. The power spectral density could be increased for these loops; however there is a limit to the total power that can be transmitted and impossible levels would be required (tens of watts) to have any worthwhile effect. As it stands, the theoretical achievable data rate is not substantially higher than those currently commercially available.

However, data rates could be significantly higher if the modem is moved closer to the customer premises equipment. The results for case 2 show that broadband capable of delivering almost 100Mbit/s becomes possible for the majority of loops, with only 4.5% of loops unable to support this speed. In the mixed deployment of case 3, data rates are still higher than those currently available, with almost 30% of loops able to support speeds of in excess of 100Mbit/s. We should emphasise again, however, that the underlying network deployment and management regimes needed to achieve these data rates do not reflect the current situation, rather an idealised situation to support our theoretical study.

The overall implication of this work is that the capacities currently achieved are lower than theoretically possible. How far technology can be improved to approach these ideals was not considered in detail within this project. Technologies already exist which eliminate crosstalk at the street cabinet. In the exchange, far end crosstalk elimination has not yet been demonstrated, although it is considered feasible.

3.4 Technology watch

Introduction

As well as selecting topics for research that appear to us to be of particular importance, we also maintain a "technology watch" where we ask consultants to examine technologies that we might not be aware of but that might have longer term implications for communications. Over the past twelve months, a number of important emerging technologies have been identified and investigated. Knowledge of such technologies and trends enables us to better anticipate how to execute our regulatory duties in the future.

Research trends in radio frequency mixers and oscillators

Mixers are required to convert between a radio frequency (RF) and an intermediate frequency (IF), or sometimes straight to or from the baseband frequency. The target frequency is dependent on the local oscillator (LO), which feeds into the mixer, along with the information stream.

Figure 25: The number of publications on mixers and oscillators over period 1995 to 2005

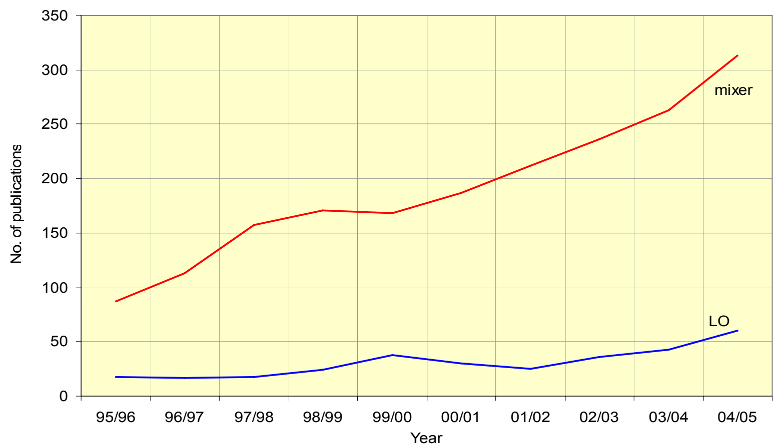
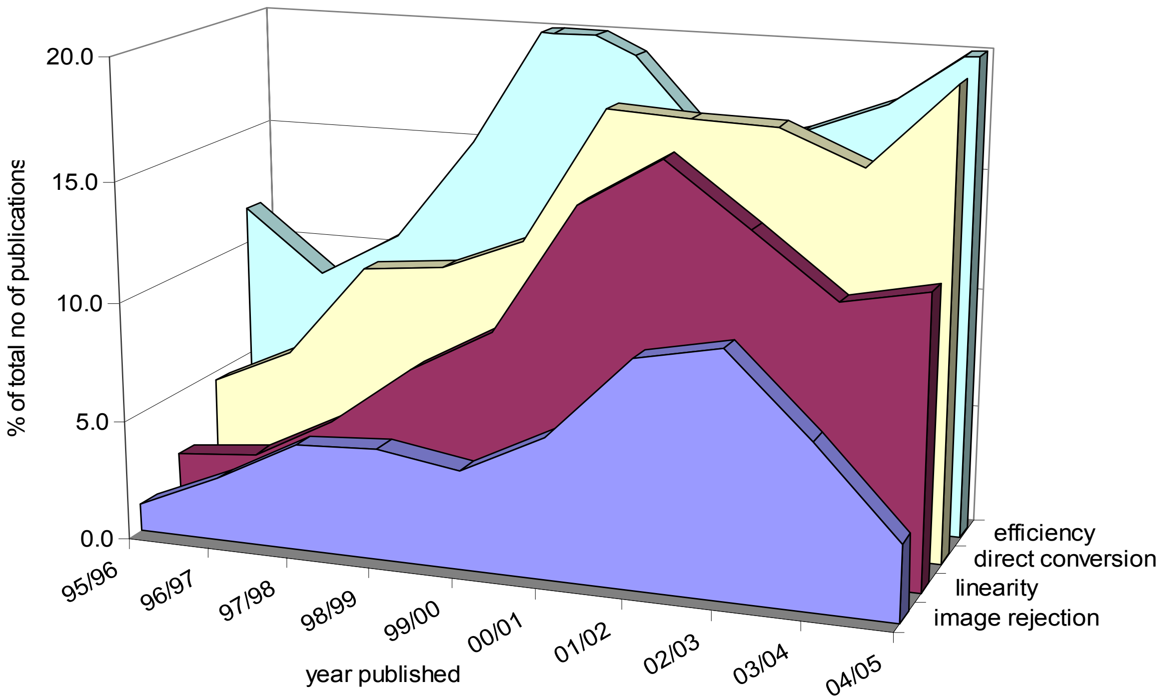


Figure 25 shows that the number of publications on mixer technologies is healthy, but there is very little evidence of research into LO technologies over the last 10 years and little sign of this increasing. Important characteristics for mixers are the insertion loss (or conversion loss), drive level, image rejection, linearity and power efficiency. The latter two characteristics tend to be more popular for research, since insertion loss and LO drive level can be overcome by mid-stage RF amplification, and image rejection through good filtering. Important LO characteristics are power efficiency and frequency stability (or phase noise performance).

An alternative approach is direct conversion (zero intermediate frequency conversion). This is a system design technique, not a mixer characteristic, that eliminates the need for an IF stage by converting straight from RF to baseband. Publications indicate a gradual trend towards more linear mixers, and more systems employing direct conversion. There is also a growing trend in the power efficiency of mixers. Image rejection, however, does not appear to be a research priority. The most likely impact of mixers and/or LOs on communications will not be the devices themselves, but the migration from a superheterodyne receiver design to a direct conversion design. Benefits include cheaper, lighter and lower power radio systems, but there are issues with frequency stability, selectivity and tuneability. Any significant steps in direct conversion would be an indicator of change to come.

Figure 26: With the exception of image rejection (which appears in decline), research into mixing appears fairly evenly split



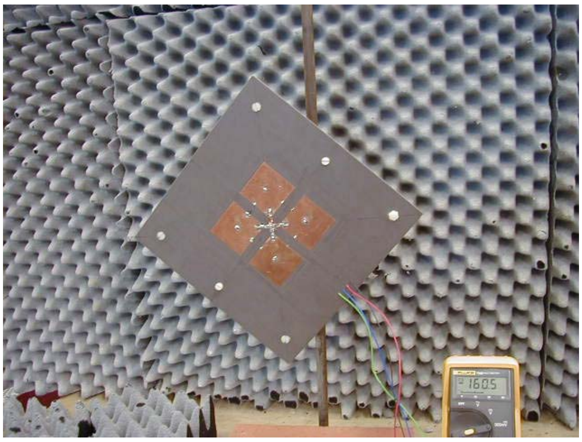
Rectennas and their Application to Recycling Ambient RF Energy

There is a general technology trend towards the miniaturisation (size, weight) of complex digital systems. This trend gives rise to new application possibilities such as wearable devices and wireless sensor networks. The current solution to powering these applications may be to use conventional batteries. This, however, possesses several disadvantages such as the need to replace or recharge them periodically and their large size and weight in comparison to the device. One possibility to overcome these is to extract or harvest ambient energy from the environment to either recharge a battery, or to directly power the electronic device.

Energy can be harvested from a range of potential sources; kinetic, thermal and electromagnetic (i.e. solar energy or radio-frequency). Here we report on work on the rectification of low power ambient microwave radio signals using a rectenna to augment the direct current (DC) power supplies.

The term rectenna refers to a **rec**tifying an**tenna**. A rectenna converts directed or ambient electromagnetic energy into a DC voltage or current. In microwave power transmission, the antennas have well-defined polarization and high rectification efficiency enabled by single-frequency, high microwave power densities incident on an array of antennas and rectifying circuits. High-power rectennas have been operated over incident power intensities of 10^{-2} to 10^{2}mW/cm^{2} with RF to DC efficiencies between 40 to 80%. Low power rectenna technology is seeing a resurgence due to the potential of rectifying low-power densities on the order should be 10^{-3} to 10^{-5}mW/cm^{2} for battery-free transponders.

Figure 27: A 4-element wideband rectenna array



The frequency of 2.4GHz has emerged as the transmitting frequency of choice due to the efficiency of silicon technology, placement in the industrial, scientific and medical (ISM) spectrum and low propagation losses through the atmosphere and water vapour. However, with the reduced cost of microwave sources and the increased use of 3G devices, rectennas are now being seen in the 5 to 6GHz frequency range. If the technological challenges of impedance matching can be overcome then power harvesting for long deployment-duration sensor networks could become a reality.

Antennas for vehicular applications

As we have already discussed previously in this report, wireless systems within vehicles are increasingly being used for entertainment, car safety and navigation. There are significant challenges, however, for the antenna engineer when designing antennas for these markets, and these must be overcome if wireless systems are to meet their potential for vehicular applications.

The traditional roof-mounted monopole antenna remains a favourite at the budget end of the market due to its low cost and good all round performance. However many manufacturers now insist on hidden antennas to meet aesthetic and design criteria. This presents mounting, shadowing and reflection problems when compared to a roof mounted option. Often cost rules out numerous innovative designs in the automotive industry.

In the near future new applications will be introduced into vehicles, for example:

- 2.4GHz and 5.3GHz for home linked wireless networks;

- 5.9GHz and 63GHz for automotive ad-hoc networks[15];
- at 77 to 81GHz we find radar systems for anti-collision and automatic cruise control systems; and
- Ultra Wide Band (UWB) systems, which will also be used for general short range communication in the home and office, may also be used in the car.

These new spectrum bands present challenges due to the reflection of signals in these environments and particularly in the confined space of a metal box such as a car.

In addition to the use of new spectrum bands, vehicle construction is also changing and we are seeing composite panels for parts of the roof, boot and side panels to reduce weight. Glass windows are becoming metallised to improve energy efficiency. These construction changes are also potentially removing areas of a vehicle commonly used for mounting antennas. Simulation of antennas on vehicles presents significant challenges and this is an area of significant research and development effort for manufacturers. New techniques are therefore needed to meet the increasingly complex challenge.

In 1999 a new type of electromagnetic structure was developed that was characterised as having a High Impedance Surface (HIS). Although made of metal surfaces, within a forbidden band it did not conduct an alternating current (AC) and its image currents were not reversed. The meta-material also stopped the propagation of surface waves. The composition of the structure was essentially that of a Frequency Selective Surface (FSS) over a ground plane.

This new meta-material structure had the potential to be used to create thin, compact antennas that would normally require to be spaced by a quarter wavelength above a ground plane. The construction of a HIS consists of placing a layer of periodic elements between the ground plane and antenna. The overall thickness of the complete antenna is typically less than 0.05 wavelengths. Another key requirement is that HIS must be sufficiently small to enable compact antennas to be produced. To achieve this, key research is being conducted to reduce the size of each cell that makes up the periodic structure in the HIS. The development of single frequency band antennas is feasible but multiband antennas remain challenging. The research is currently embryonic and various dual band designs are under investigation, but such technology for vehicles is probably 10 years away.

Wireless communications within robotic swarms

Autonomous miniature robots, the size of a few millimetres, behaving as ecological systems such as a swarm of bees or ants, are seen to have significant commercial and military applications for surveillance, microassembly, biological, medical, or any tasks where a collective action can provide a greater benefit than a single unit or small groups of robots.

Although the technological challenges are similar to traditional wireless sensor networks, swarm robots are an order of magnitude smaller and consequently will challenge the technologists even further. One critical aspect is the short range (centimetre) communication link required between the robots to enable them to perform their actions collectively.

A traditional approach to the communications problem would be the use of RF technologies or optical communications. The hundreds of robots required in a swarm, however, will challenge the spectrum efficiency requirements when using RF and the loss of line of sight, which could cause reliability issues when using optical communication. A promising solution

[15] See the earlier discussion of the transport sector

being investigated uses inductive communications, which uses modulated magnetic fields as opposed to RF modulation. The inductive technique has the advantage that the magnetic field falls off at a rate of $1/r^6$ as opposed to $1/r^2$ for RF. This could result in an extremely high re-use factor for a communication link requiring modest (440bit/s) data rates and guaranteeing the short range links.

If swarm robotic systems are deployed in their thousands, inductive communication solutions could mean that there is no significant demand for communications spectrum.

Overcoming scintillation in FSO communications links to increase range

Free space optical (FSO) communication systems use a laser transmitter and a receiver with telescope optics to focus the beam onto a photodiode detector. By modulating the laser beam data-rates between 100Mbit/s and 1.25Gbit/s can be achieved over relatively modest ranges, typically less than 1km. To increase the communications range in clear air conditions when FSO should operate, the effects of atmospheric turbulence, which causes rapid signal fluctuations (scintillation) must be overcome. Using higher power sources is one technique, but the scintillation fade depths may make this prohibitively expensive.

A technique commonly used by the astronomy community to overcome scintillation is Adaptive Optics (AO). This is used by several astronomical sites routinely to actively compensate for the image degradation caused by the inhomogeneous nature of the atmosphere. A significant cost, however, of these AO systems is the wavefront sensor. If a cheap wavefront sensor could be developed then their application to widespread FSO links could enable them to be used over ranges greater than 1km. We identified a novel wavefront sensor that makes use of an image multiplex grating. This grating, along with the remaining AO system, has been used with a laser beacon to demonstrate its potential. The results obtained showed a significant improvement in received signal power and a significant (25dB) improvement in reducing the scintillation fade depth over a 4km propagation path.

If cost effective AO can be integrated into FSO communications systems, then their operating ranges may be increased to greater than 1km in clear air. The high capacity (Gbit/s) data-rates potentially available from FSO systems could be used for “burst” type communications links where terabits of time insensitive data could be transferred wirelessly. These systems could then compete with RF systems where temporal spectrum usage could be high due to the lower-data (Mbit/s) rates achievable and the longer on-air time required to transfer terabits of data.

Active Retro-reflecting Optical Tags (AROTs)

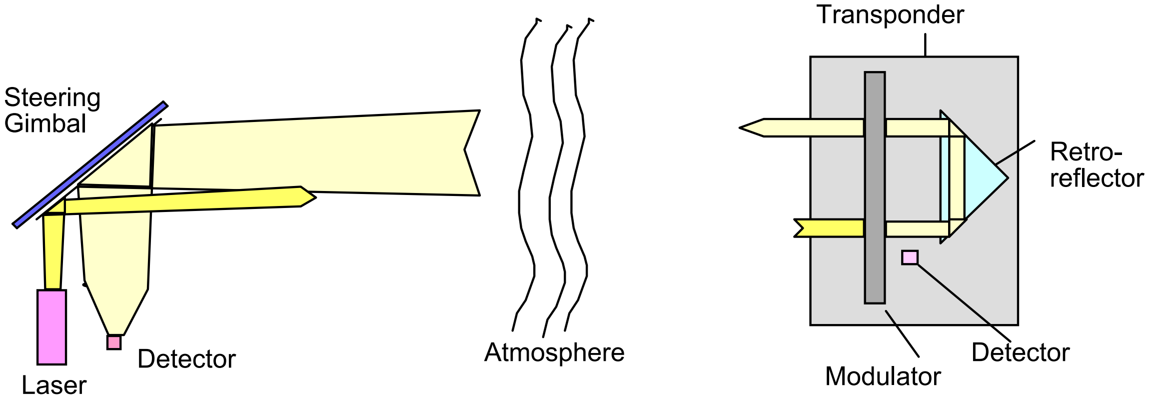
As previously mentioned, FSO is a method of laser communication that uses coherent light instead of radio waves to propagate information through the atmosphere and/or space. Fixed FSO links have been available for many years but the application to mobile scenarios is limited. This is because FSO systems are very difficult to use on mobile platforms for reasons such as accurate alignment of the highly directional laser beam, susceptibility to atmospheric conditions and safety concerns.

One approach to overcoming this is to use optical tags that function by producing modulated retro-reflection. The tags have to be interrogated and tracked by an interrogator, but they automatically send their message back to whatever interrogator is pointing at them, and they require only a little power to modulate their return signal. This removes the problem of pointing, tracking and laser light generation from one end of the communications link, and is particularly useful in asymmetric links when one ‘hub’ station is communicating with many ‘outposts’. Such tags are known as modulated retro-reflective (MRR) tags or active retro-reflecting optical tags (AROTs).

There are two types of MRR tags, the multiple quantum well (MQW) and the micro electromechanical system (MEMS). The MQW is expensive but can offer up to 1Gbit/s data rate. The MEMS is one significantly cheaper of MQW, but can only offer 300kbit/s at best.

All research and development into MRR tags seems to be funded by the military at the moment, with no apparent interest from commercial or civil sectors. This does not mean that future uses of optical tags will not transfer into the commercial market; some suitable applications have been identified and if FSO in general becomes more widely used then this could ease demand on the electromagnetic spectrum.

Figure 28: Free space communication using a modulated retro-reflecting transponder or tag



Towards a gigabit per second radio – 10 years on

In 1997, the defence and security technology company QinetiQ produced a report entitled “Towards a Gigabit/second Radio”. The aim of this *blue sky* research report was to identify enabling technologies and trends that could lead to the realisation of a future 1Gbit/s radio system for long range (greater than 50km) military systems.

In 2007, short range (less than 5km) gigabit radios are a reality, with wireless point-to-point links offering up to 1.25Gbit/s, with 10Gbit/s on the horizon. The millimetre-wave bands around 35, 60, 70 and 80GHz have sufficient spectrum available to support such links. Some important enabling technology advances have been in analogue to digital converters (ADCs), monolithic microwave integrated circuits (MMICs), new and improved semiconductor processes and advances in digital processing capabilities.

In 1997 it was envisaged that, given the continued trends at the time, 11 or 12 bit ADCs operating at 1GHz sampling frequency were predicted to be widely available in 2007. However, current ADCs operating at 1GHz or more are limited to 8 or 10 bits at the most – presumably because there is no market driver. This has not stopped the emergence of gigabit radios however, largely due to the limited dynamic range required for the current implementations.

In the last 10 years MMICs have continued to be developed, offering higher frequency operation, greater power output density, lower noise and improved efficiency for a lower cost. The development cycle is slow, with an indicated 10 year gap between state-of-the-art research (as defined in 1997) and production devices of today. Digital processing of multi-Gbit/s data is now possible due to advances in microprocessors, digital signal processors (DSPs) and field programmable gate arrays (FPGAs).

In 1997 aspects such as Ultra Wide Band (UWB), power consumption and systems on a chip were not even considered as part of the report; all of these are mainstream in 2007. The 1997 report foresaw that the millimetre wave band would be required, but did not anticipate that rapid exploitation of frequencies above 60GHz.

Challenges still remain to achieve the scenarios analysed, such as Gbit/s data links to mobile platforms and long-range (much greater than 1km) concepts. It will be interesting to see in the next 10 years how much further these are progressed, taking into account new system concepts such as systems on chip (SoC), power consumption minimisation and whether high ADC bit resolution is actually required.

The review of this 1997 report demonstrated that, for some technologies, it may take around 10 years to move from state-of the art research to mainstream.

Hollow waveguide integrated optics: the optical printed circuit board (PCB)

If the worldwide aspirations for significantly increased broadband access are to be realised the cost of fibre optic networks must be reduced. We have highlighted the potential that a novel hollow waveguide based hybrid integration technology has to offer in enabling the low cost, mass manufacture of hybrid optical modules for fibre optic networks.

The hollow waveguides take the form of microscopic trenches etched in the surface of silicon substrates. These provide a means of guiding light from one discrete component to another, in what is effectively the optical equivalent of the electronic printed circuit board. In a physical sense, hollow waveguide technology is the exact opposite of the traditional approach to integrated optics where light is guided in solid core rib waveguides. Hollow waveguide hybrid integration technology has the potential to provide significant cost reductions in a wide range of hybrid optical modules, including splitters, diplexers and triplexers for passive optical networks and transceivers. Lower priced fibre optic modules could dramatically reduce the per-kilometre rollout costs for broadband services and reduce the pressure on certain parts of the electromagnetic spectrum.

Section 4

Better managing the spectrum

One of Ofcom's major responsibilities is the management of the radio spectrum. Better spectrum management leads to more efficient utilisation and an increase in value for all stakeholders. The Spectrum Framework Review[16] recommended a new approach to spectrum assignment, a *liberalised* arrangement, in which spectrum is assigned without restrictions on technologies or applications. In such an approach there are incentives on licence holders to invest in appropriate research and hence less of a role for Ofcom. However, there remain a number of areas where it is appropriate for Ofcom to conduct research, such as in those areas of the spectrum in which we have chosen not to adopt a liberalised regime. In these cases there may not be sufficient incentives for users to upgrade their systems to more efficient technology and, in other cases, it may be that proof of concept work is required before users will invest in further understanding new technology.

This year our work has divided into three areas – enhancing our understanding or propagation, examining whether certain applications can be moved to higher frequency bands and providing better information about spectrum usage. Concerning propagation there is an on-going need to extend our expertise, for example, to assist our new licensing approach of Spectrum Usage Rights (SURs) which relies on accurate underlying models for verification and to understand better the effect of new network topographies such as mesh systems for which little propagation data exists. The propagation projects we report on here are:

- propagation involving the indoor/outdoor interface;
- understanding the effects of wind farms on communications systems;
- the Generic Radio Modelling Tool (GRMT); and
- propagation between terminals at low height.

There is more spectrum available at higher frequency bands. Market mechanisms tend to move many applications ever higher in frequencies but may not always be effective in demonstrating what is possible. As a result, we conduct work on selected applications to understand the potential for their using higher frequencies. Two such projects are reported here:

- the use of millimetre wave and free space optical fixed link services in rural environments; and
- examining the potential to use super high frequency and extremely high frequency spectrum to support wireless camera applications.

Finally, in the same manner that it is difficult to manage a company without management information, it is difficult to manage the spectrum well without information on its usage and quality. In this section we also report on a project that is providing us with a better understanding of how spectrum is used: The Autonomous Interference Monitoring System (AIMS).

[16] http://www.ofcom.org.uk/consult/condocs/sfr/sfr2/sfr.pdf

4.1 Propagation projects

Propagation involving the indoor-outdoor interface

Despite the increasing use of wireless systems in and around buildings, there is no widely accepted model for radio propagation involving the passing into or out of buildings. In view of this, we commissioned some work to study the subject and produce a model suitable for regulatory purposes. This model must be statistical in nature, able to work from general classifications of urban areas, and not require detailed information on individual buildings.

Instead of a measurement program, a ray-tracing model was used. This allowed the generation of many more results than would have been practicable had physical measurements been used. Computer aided design files of actual buildings were converted into 3-dimensional models for use in the ray-tracing tool. The buildings relate to urban classifications as follows:

- dense urban areas typical of city centres were represented by a form of construction often used for high-rise commercial buildings. This consists of a reinforced central core surrounded by open-plan floors with lightweight external cladding;
- urban areas were represented by two constructional types typical of medium-rise commercial building:

  i) non-open-plan office with masonry external walls; and

  ii) concrete-slab open-plan floors supported by concrete columns.
- suburbia was represented by a substantial Victorian style dwelling, selected as intermediate between modern affordable housing and buildings typical of small-town high streets.

In addition, a building typical of many public indoor spaces was modelled having a metal roof, high-ceiling atriums, and a mezzanine floor covering part of the ground-floor area. This was used to study general principles.

Statistical analysis of the ray-tracing results produced a wealth of information concerning indoor/outdoor propagation generally. These are summarised as follows:

Additive losses. An important question to be answered by the project was whether indoor/outdoor propagation can be characterised by losses expressed in decibels, which can simply be added onto general path losses. An illustration of this issue is whether losses vary with linear or logarithmic indoor distance. The only internationally accepted method, recommendation ITU-R P.1238, uses logarithmic distance, but this is restricted to indoor-only propagation, not paths involving the indoor/outdoor interface. A special set of ray-tracing calculations were used to study this question, producing a definite result in favour of additive losses based on linear indoor distance. This is an important result with a major advantage. It means that additional losses due to signals passing in and out of buildings can be combined with other propagation models. Thus account can be taken of building losses on long terrestrial and earth space paths with the same facility as short urban paths, such as inter- or intra-building.

Signal reinforcement. It is well known that propagation within a room or corridor can be reinforced due to multiple paths caused by reflections. In effect, the building structure acts as a waveguide. Although this produces a pattern of reinforcement and cancellations, which radio systems must either combat or exploit, according to their design, the overall effect when averaged over space or frequency is an increase in the received power. As a result, signals can sometimes be received, on average, more strongly indoors than at the same distance out of doors. This effect was observed in the ray tracing results. However, statistical analysis showed that the resulting signal enhancement affects paths much longer than those within one room or even the same building. It was found necessary to take account of this "room gain" as an intrinsic part of the model.

Inter-floor propagation. Attempts to determine whether inter-floor losses can be modelled as a simple loss per floor, or whether a non-linear element needs to be introduced, have generally proved inconclusive. The COST 231 report indicated a small improvement for non-linear losses, but based on a limited set of measurements. Analysis of ray-tracing results in this project found that there is a small preference for the non-linear approach. This has been tested up to five floors; it is possible that a greater improvement would be found for a larger numbers of floors.

Urban shadowing. It was found that the simple statistical model developed by the project was not suitable for the shadowing effect of a complete building when neither terminal is inside it. This is because the model is intended for propagation into or out of a building, or between buildings. More detailed calculations showed that losses for signals passing through a building were of comparable strength with signals diffracted or reflected around it. Thus a separate statistical model was developed to represent shadowing. In comparable circumstances this gives similar results to other models predicting what is sometimes referred to as "clutter loss", but with somewhat higher losses reflecting the addition loss of building entry.

High-angle paths. Earth-space paths were modelled with an elevation angle of 40°. This showed that building penetration has generally higher losses than for terrestrial paths. For high-rise buildings entry losses tended to increase for lower floors, even in the absence of shadowing by other buildings.

Interpretation of indoor distance. The model is able to predict average signal level as a function of position across the floor of a building. Individual cases would in practice vary according to the details of building construction, but clear statistical trends were evident.

Use of the model for coverage and interference. Because the model is statistical, and does not use detailed building information, there will be a significant spread of prediction error in any comparison with real radio signals. The distribution of errors is itself predicted by the model, and thus estimates are available for the percentage of results expected to have more or less than a given signal level can be derived.

Understanding the effect of wind farms

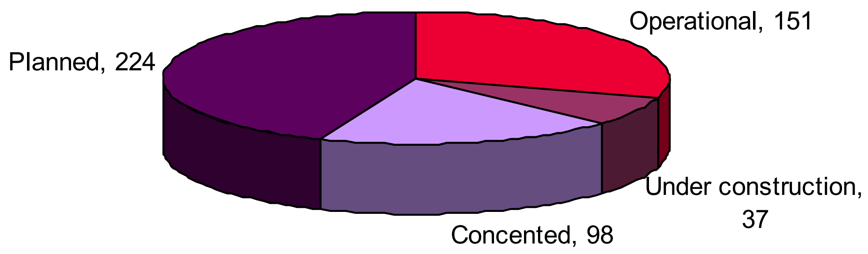
<u>How does it help?</u>

Renewable energy is an integral part of the Government's longer term aim of reducing CO_2 emissions by 60% by the year 2050, as set out in the Energy White Paper of May 2007[17]. The Government has set a target of 10% of electricity supply from renewable energy by 2010, and the development of wind technology is a core part of achieving this aim. Figure 29

[17] Meeting the Energy Challenge: A White Paper on Energy, Department of Trade & Industry, May 2007

shows the number of wind farm projects in the UK registered with the British Wind Energy Association[18] (BWEA), including both onshore and offshore projects.

Figure 29: Status of wind farm projects (on- and off-shore) in the UK, registered with the BWEA as of September 2007



As both offshore and onshore wind farms continue to proliferate, concerns have been raised over their impact on radiocommunications systems. The effects of wind farms on radar and broadcasting services have been studied extensively, but the effect of onshore wind farms on fixed links and scanning telemetry is less well understood.

Ofcom has previously commissioned a study[19] in an attempt to propose a practical method for establishing an exclusion zone around the path of a fixed radio link within which it would be inadvisable to install a wind turbine. The study identifies three principle degradation mechanisms to the communications link and presents a formula based on Fresnel zones by which these mechanisms may be analysed. The model predicts relatively small minimum clearance zones for fixed links but notes a number of uncertainties, including:

- the potential for more complex multipath effects to occur in multiple turbine wind farms; and

- lack of measured data on the Radar Cross Section (RCS) of a wind turbine, resulting in conservative coordination distances.

Scanning telemetry systems transmit over wide geographic areas in the ultra high frequency (UHF) band and are therefore vulnerable to multipath effects from wind turbines. Consequently the requested clearance zones may be large in comparison with fixed links, and Ofcom currently recommends that consultation be undertaken for any wind project within 1km of a scanning telemetry link.

In order to ease the coordination burden Ofcom commissioned a measurement study to better understand the effects of wind farms on fixed link and scanning telemetry systems. At this point we are reporting on the theoretical analysis conducted. A series of field trials will be undertaken in the second quarter of 2008 and the data used to verify and refine the theoretical model. This will be reported on in next year’s report.

Explanation of the technology

It is widely agreed that radio signals can be affected by wind turbines. The main issue is the multipath effect where the received signal experiences interference due to reflection from the tower or turbine blade. Vulnerability to multipath effects is a function of the frequency and

[18] British Wind Energy Association: www.bwea.co.uk

[19] A proposed method for establishing an exclusion zone around a terrestrial fixed radio link outside of which a wind turbine will cause negligible degradation of the radio link performance, Dr D. Bacon, October 2002

length of the link; the lower the frequency and the longer the link, the more risk there is of multipath interference. Previous work[20] has shown that the tower can cause 3dB of attenuation at 100MHz, increasing to 8.5dB at 1GHz. However, the tower has a negligible effect compared to the blades.

A modern wind turbine blade is commonly made from glass-reinforced plastic (GRP) with an epoxy or polyester resin. The blade surface has to remain smooth to reduce turbulence and the possibility of the blade stalling, while within the blade there may be metal supports and balancing weights. Carbon fibre reinforcement is a common feature on larger blades, adding strength while reducing weight. Most turbines typically have three blades, although two blade designs have been marketed in the past. Higher power rated wind turbines will tend to have a larger blade size and slower rotational speed, although trade-offs can be made between size and speed depending on design specifics. Typical characteristics are shown in the table below.

Table 6: Typical wind turbine characteristics

Rating	850 kW	1.5 MW	3 MW
Diameter (m)	52	76	90
Blade length (m)	26	38	45
Hub height (m)	40-86	60-110	80-105
Swept area (m^2)	2,124	4,536	6,362
Number of blades	3	3	3
Rotation Rate (rpm)	26	17	16.1

The size and rotation of the turbine blades can have a significant impact on radiocommunications systems. The main interference mechanisms are:

- near-field effects, whereby a transmitting or receiving antenna has a near-field zone in which local inductive fields are significant. Within this zone it is not simple to predict the effect of other objects;
- diffraction, whereby an object detrimentally modifies an advancing wave front when it obstructs the wave's path of travel; and
- reflection or scattering, whereby the physical structure of the turbines reflects interfering signals into the receiving antenna of a fixed link.

The criterion for avoiding diffraction effects from wind farms is based on calculating an exclusion zone equal to the 2nd Fresnel zone.

The extent to which an object will reflect or scatter radio waves is usually quantified by its RCS. Any interference effect from the wind turbine can be calculated by its RCS in terms of carrier-to-interference (C/I) protection ratio. A fixed radio link is normally designed with a large C/I, which should be exceeded for all but 20% of time, and a somewhat lower value, which must be exceeded for all but a much smaller percentage of time, typically in the range

[20] TV interference from wind turbines, C. Salena, University of Coimbra, 2001

0.1% to 0.001%. The choice of C/I protection ratios will depend on the modulation and coding schemes of the link and the required performance. To ensure that a wind turbine has negligible effect on performance it has been suggested that the calculation of reflection or scattering should be based on a C/I protection ratio somewhat higher than the 20% value.

Current state of the art and our research

The majority of practical trials previously undertaken to investigate the impact of wind turbines on radio systems have made use of existing radio link equipment. Examples include the BBC measurements of Danish TV signals in the presence of turbines[21] and the investigation of interference to a scanning telemetry system by a wind farm in Northern Ireland[22] performed by the Joint Radio Company (JRC).

Such an approach is conceptually simple, and may be able to provide data of relevance to a specific operator, but also has several disadvantages. Firstly, the method is rather inflexible, as it will generally be difficult to investigate the range of geometries and frequencies required for a complete characterisation of the problem. This is a particularly acute problem in the case of fixed links, where the bore-sight of an existing transmitter is unlikely to be changeable. A second problem is that the results of such measurements are likely to be system-specific, and hard to generalise.

The proposed approach is to make use of a pair of transportable terminals, mounted on Land Rover measurement vehicles, to explore a wide range of configurations. The measurements will not attempt to replicate the characteristics of a particular radio system, but will characterise the impairments to the propagation path in a more fundamental and general way.

2nd Fresnel Zone Interference Measurements

Measurements will be carried out to assess the effects of potential wind farm interference where the radio path relative to the turbine is adjusted from a position falling well beyond the exclusion distance defined by the 2nd Fresnel zone, to a bore-sight alignment with the turbine. The absolute median path loss will be determined for each location, together with the statistics of fading due to the moving turbine. Such measurements will be made with the turbine(s) at a variety of distances from the terminals, depending on local access and surrounding terrain.

Measurements will be made for a range of relative turbine azimuths, as allowed by wind direction, local road layout and operational requirements. The captured data will be presented as probability of signal fluctuation (%) versus signal fluctuation from the median level (dB) in terms of a cumulative distribution function.

Reflection / Scattering Interference Measurements

Measurements will be carried out to assess the effects of potential wind farm interference where the location of the turbine(s) is defined by a C/I protection ratio for a given distance D_s.

The measurements will be performed using a wideband sounding transmitter/receiver system that allows the channel impulse response to be measured in the time or frequency

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[21] Effects of wind turbines on UHF television reception. Field tests in Denmark. D.T. Wright, BBC Research, November 1991

[22] Tappaghan Wind Farm County Fermanagh, Northern Ireland: Analysis of the interaction between Wind Turbines and Radio Telemetry Systems, March 2006

domain. The delay of the signal reflected/scattered from the wind turbine(s) will be measured relative to the direct wanted signal and difference in amplitude between the two signals can be correlated to the C/I protection ratio. Such measurements will also allow an estimate of the RCS of the turbine to be made.

Conclusions

The interference effects of wind farms on radar and broadcast services have been studied extensively, but the effect of onshore wind farms on fixed links and scanning telemetry is less well understood. As the number of wind farm planning applications continues to grow in order to meet Government renewable energy targets, there will be continued requirement for coordination with the telecommunications industry.

The main interference mechanism is the multipath effect, where the received signal experiences interference due to reflection from the tower or turbine blade. Vulnerability to multipath effects is a function of the frequency and length of the link; the lower the frequency and the longer the link, the more risk there is of multipath interference.

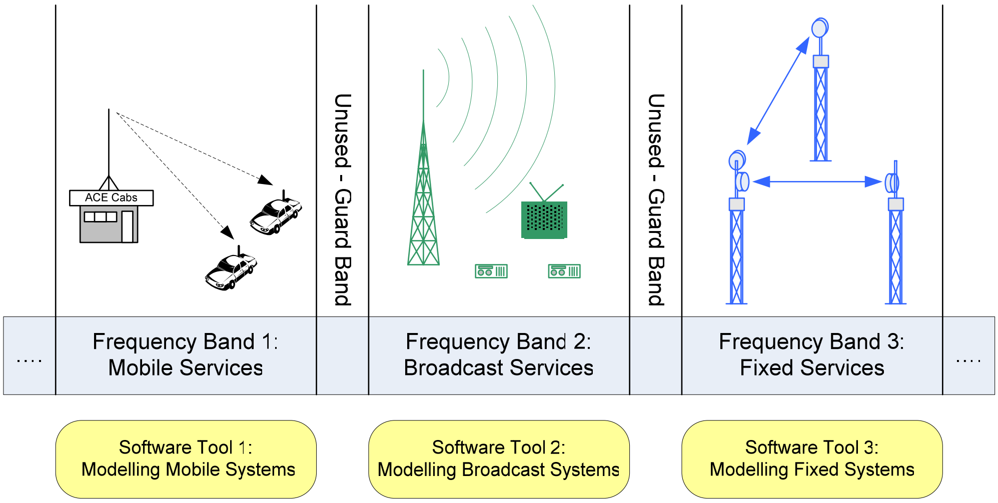
This current study aims to refine existing theoretical models through measurement of some of the key parameters, in particular the C/I protection ratio that is required to determine the RCS of the turbine.

Generic Radio Modelling Tool (GRMT)

Objectives

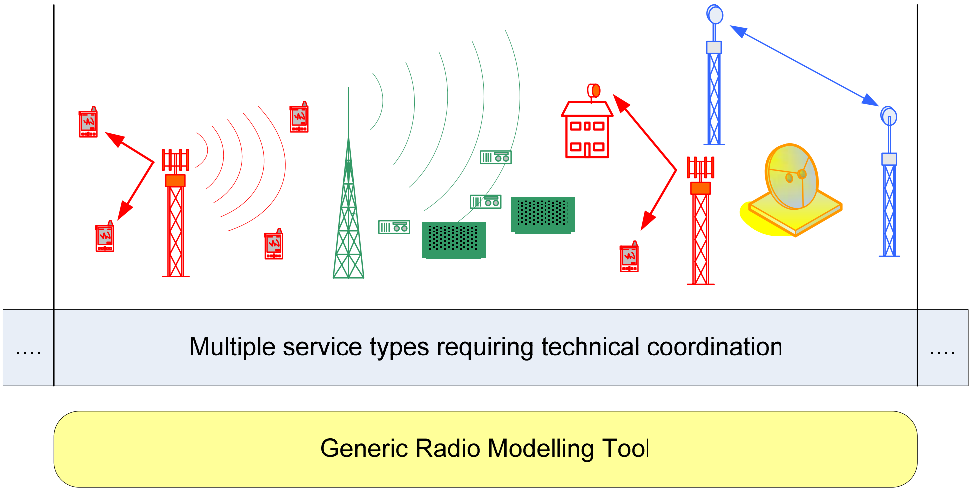
In a traditional “Command and Control” regime, the radio spectrum is divided into bands that are allocated to services. Each band would be managed using a software tool developed specifically for that service, as in Figure 30. The tools would undertake tasks such as service planning and assessing the potential for interference.

Figure 30: Software tools for traditional spectrum management



With liberalisation there could be a mixture of services within a band or in adjacent bands. The objective of the Generic Radio Modelling Tool (GRMT) is to provide us with an analysis and licensing tool that can undertake a technical assessment of the potential for interference between any of the main service types. The GRMT approach is summarised in Figure 31.

Figure 31: Software tools for a liberalised spectrum environment



In particular, three scenarios for the use of GRMT were identified:

- scenario 1: *What-if* studies;
- scenario 2: Assessment of change of use request against current assignments; and
- scenario 3: Management of a liberalised band

GRMT software

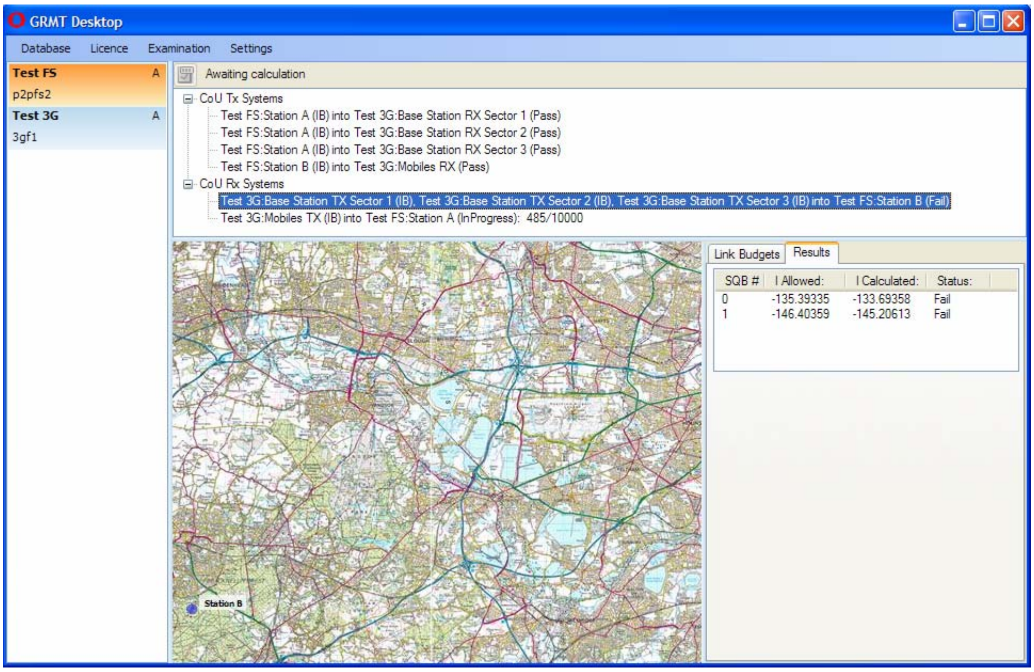
GRMT comprises the following key components:

i) *GRMT Online.* This is shown in a standard web browser. When used in conjunction with client management software on the GRMT Application server it can be used to create new or change-of-use licences, submit for examination, view status and results of examinations, and perform licence management tasks.

ii) *GRMT Desktop.* This is a standard Windows desktop application that interfaces to the GRMT Application server. It uses a local database of licences in GRMT's Spectrum Usage Right (SUR) format to allow complex "what-if" calculations. It can import licences from the central database or they can be created locally. An example screenshot is shown in Figure 32.

iii) *GRMT Application Server*. This is the core of GRMT. It undertakes queries of databases, performs the necessary computations for the technical examination of licences, and supports multiple user interactions.

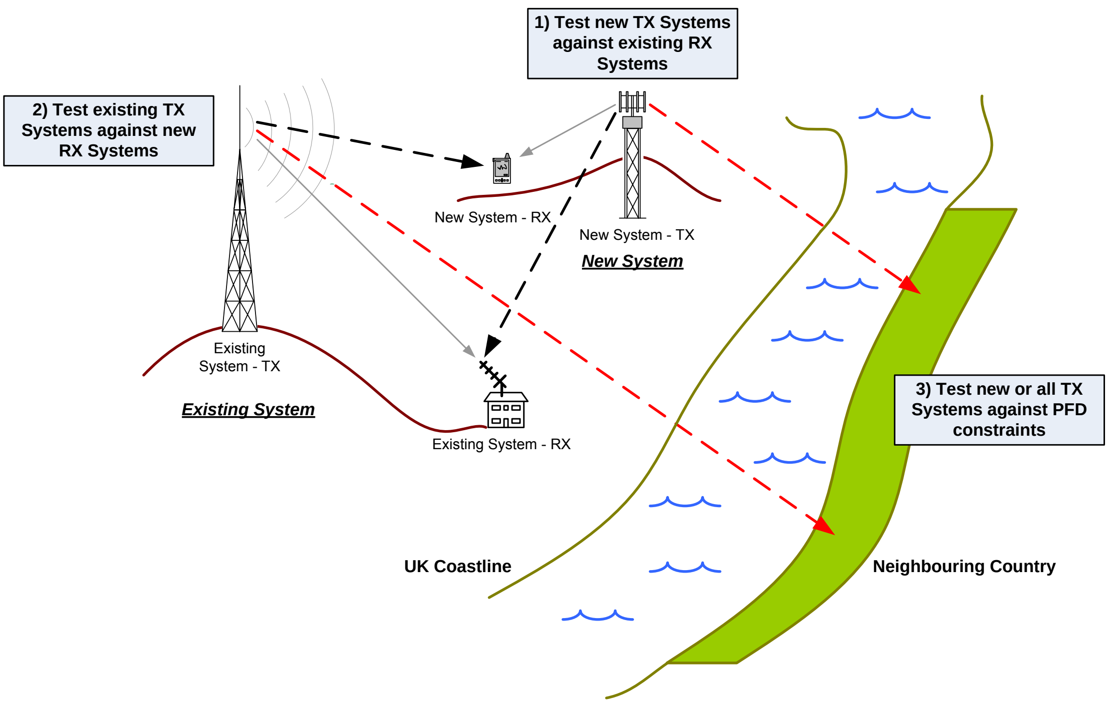
Figure 32: Screenshot of the GRMT desktop application interface



Examination process

At the heart of the GRMT is its ability to undertake a technical examination of whether a new or changed licence application should be approved or rejected. An examination is based upon a series of tests, with the three main ones shown in Figure 33 below.

Figure 33: Examination tests required on a new or changed Licence



In all cases two tests are required:

i) test whether the new licence would cause harmful interference into existing licences; and

ii) test whether the new licence would suffer harmful interference from existing licences.

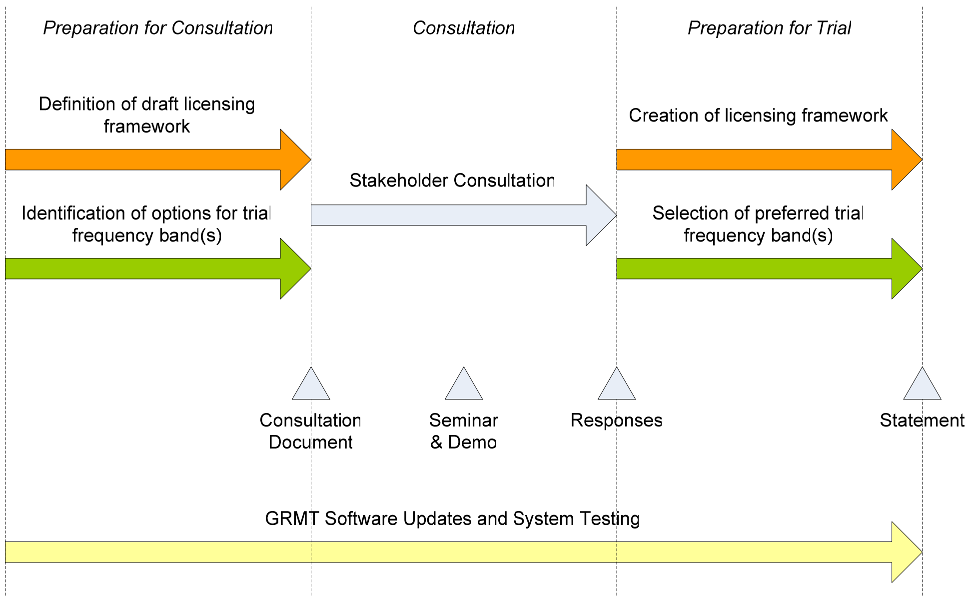
In some bands there will be additional constraints that should be included in the examination, such as a test as to whether the new licence would result in power flux density (PFD) or field strengths on or beyond a boundary that are above levels defined for that band.

The assessment of the impact of one licence on another is based upon the relevant emission rights and Spectrum Quality Benchmarks (SQBs). In the GRMT these technical parameters comprise the SURs of the licence, and are mapped onto transmit systems and receive systems respectively. Definition of the SURs is facilitated by the use of the spectrum templates, and hence the GRMT approach allows automatic interference analysis between different types of licence.

Way forward

The GRMT project gives Ofcom the potential to introduce liberalisation into bands it manages while ensuring licensees have protection from harmful interference. A possible approach could be to identify a trial band for which GRMT could be applied, with a road-map as shown in Figure 34.

Figure 34: Elements of an implementation plan for a GRMT trial



Propagation between terminals of low height

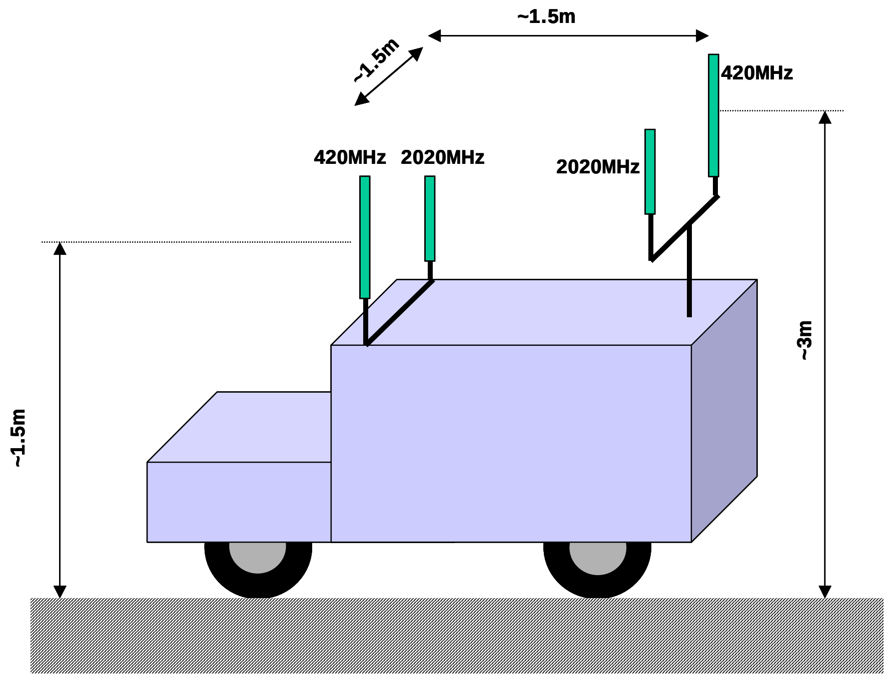
How does it help?

The increasing use of "micro-cells" in mobile radio systems and the possible future use of mesh networks highlight a need for a general-purpose propagation model appropriate for making coverage and interference predictions where both terminals in a link are of low height. Existing methods of predicting signal strength for a range of services generally assume that at least one terminal's antenna is clearly above the surrounding building clutter. In our previous research report, we introduced the first steps in a project that aims to understand better this propagation environment. The project has since completed and we can now report on its conclusions.

Current state of the art and our research

The aim of this project was to produce a modelling tool, the use of which will provide a better understanding of the propagation characteristics of communication paths between terminals at low height. The model is based on real-world values obtained from a measurement campaign. The campaign was designed in such a way as to test a diversity of parameters (frequency, terminal height, distance from transmitter etc.) and environmental categories (dense urban, urban, suburban and rural). Measurements were made at 420MHz and 2020MHz and at antenna heights of 1.5m and 3m above ground level. Figure 35 shows a schematic of a typical receiving station, with antennas mounted on a car.

Figure 35: Illustration of the receiver antennas on the vehicle



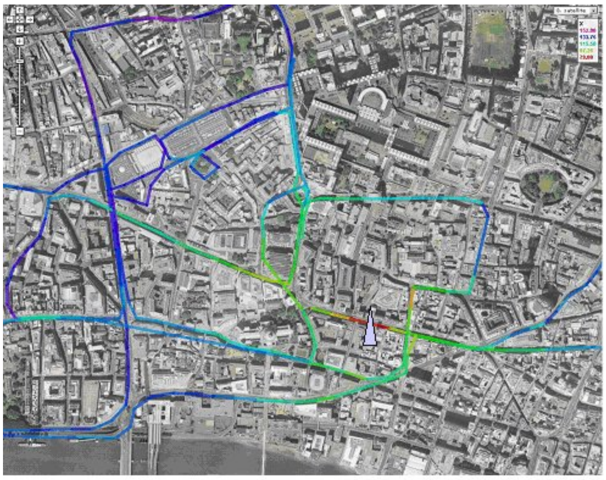
Typical urban locations were selected for the surveys in order to provide a wide range of building height and separation, street width and vegetation type parameters. The selection process was based on the following two steps:

i) first, survey locations were selected according to the height distribution of the surrounding buildings; and

ii) second, survey locations were selected according to the build density/vegetation density/road width but in areas where the building height remained on average the same.

London and Reading were selected to represent built-up areas, while Horsham was used to represent the rural environment. Figure 36 shows a typical survey route overlaid onto an aerial photo in central London. The position of the TX site is shown by the small triangular symbol at the bottom of the figure.

Figure 36: A typical survey route in Central London



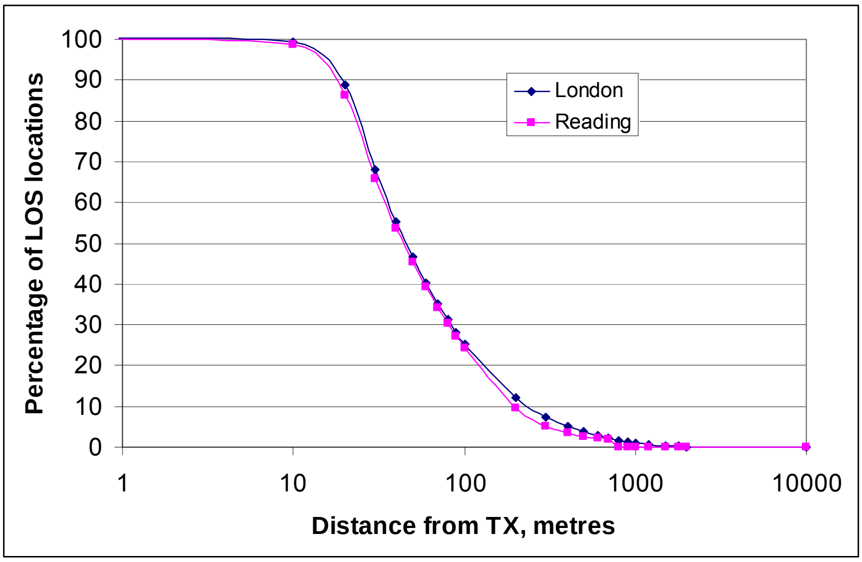
The survey data was put through a series of processing stages before it was used in the modelling. These stages included:

- distance averaging to remove the fast fading components from the data;
- basic pathloss extraction using the transmitter and receiver characteristics;
- alignment onto the road, primarily in dense urban areas;
- filtering (receiver linearity/saturation); and
- checking interference occurrences.

Each of these stages was carried out separately using the original data. Data was then combined into a single data set before it was further processed.

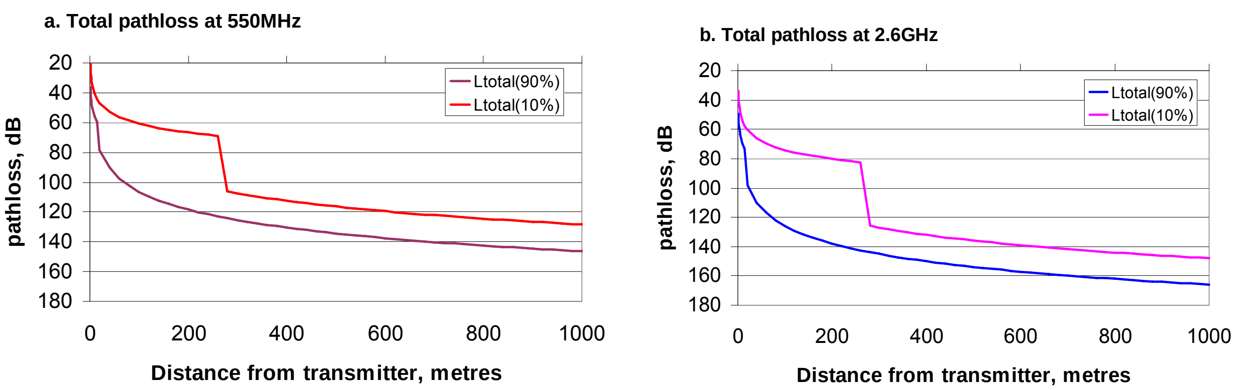
The experimental campaign revealed that the received signal strength reduced sharply as the receiver moved out of direct line-of-sight from the viewpoint of the transmitter. Some results are illustrated in Figure 37. For example, for a particular environment, it was found that at a distance of 44m 50% of points would enjoy line-of-sight to the transmitter but, at a distance of 906m, only 1% of points would enjoy line-of-sight. The combined model for 50% of locations consists of a line-of-sight model, a non line-of-sight model and a distance at which the transition should occur (note that there will be a discontinuity at this distance). The model also shows how all three of these elements can be modified in order to consider the location percentage that is required for a particular application.

Figure 37: Percentage of line of sight (LOS) locations as a function of distance from transmitter (TX) location in London and Reading



The model was used to derive the pathloss curves for the 10% and the 90% location availability. A building separation value of 46m was used for the model and represents the average value derived over the London data set.

Figure 38: Predicted total pathloss at 550MHz (left) and 2.6GHz (right) for 10% and 90% of locations



This suggests that the maximum coverage radii predicted by the new model are 200m and 650m at 2.6GHz and 550MHz respectively. The interference zone on the other hand is predicted to extend out up to 560m and 1840m at the two frequencies. Table 7 shows how this new model compares with existing International Telecommunications Union (ITU) models most relevant to this application.

Table 7: Coverage and interference radii predicted by the new model at 550MHz and 2.6GHz

	New Model		ITU-R P.1411	
	550MHz	2.6GHz	550MHz	2.6GHz
Coverage radius	650m	200m	310m	255m
Radius of interference region	1,840m	560m	515m	430m

At 2.6GHz, the ITU-R P.1411 model and the new model yield very similar results for the extent of both coverage and interference regions. At the lower frequency though, the difference is quite large, with P.1411 predicting almost half the size of coverage radius than the new model for the same percentage locations, and almost one third of the interference region.

These results underline the limitation of models that were originally developed for purposes other than those intended in this study and show that large discrepancies can result from that.

4.2 Millimetre Wave & Free Space Optical fixed link services in rural environments

How does it help?

The demand for spectrum in the highly congested lower frequency bands of the spectrum is leading to the need to consider higher frequency communication systems. If greater use of the bands above 60GHz could be made then this would provide a useful increase in the spectrum available for new services and could also release spectrum at lower frequencies for other purposes.

Millimetre wave communications systems at frequencies above 60GHz have the potential for very high capacities. More than 10GHz of bandwidth is available in the current frequency allocations offering the potential for provision of high data rates for future applications such as medium and short range fixed links, broadband last mile applications, and indoor wireless LAN. Another attraction of exploiting these high frequencies is that devices naturally reduce in size with increasing frequency, leading to more flexible equipment. However, one potential disadvantage of operating at these frequencies is a greater susceptibility to meteorological conditions.

We reported in our last technology research report on investigations combining Free Space Optics (FSO) and millimetre wave wireless links for provision of a short-range communications. A system combining links operating at 54.5GHz, 94.63GHz and 850nm were deployed in a rural location and initial results suggested that overall performance was acceptable given the meteorological conditions. We report on subsequent measurements, analysis and conclusions since then in this report.

By undertaking this work, we hope to establish the feasibility of applications such as fixed links operating at these high frequency bands, and to encourage and facilitate services to be deployed in this lightly used area of the spectrum.

Explanation of the technology

Frequency bands above 60GHz suffer severely from rain, resulting in low availabilities of a link using these bands. FSO systems are similarly affected by the presence of fog and mist and suffer even lower availabilities. Neither of these systems on their own is suitably robust to the propagation conditions to be able to provide a continuous communications link. However, FSO systems are little affected by rain; therefore there is potentially a significant increase in availability possible by combining the microwave and FSO systems into a dual frequency configuration.

Current state of the art and our research

A key aspect of the research is to investigate performance of a number of dual frequency fixed links along a 5km path and establish the impact of various environmental factors, such as heavy rain and fog. Particular conditions, such as a mix of small and large drops during heavy rain, are thought to cause high levels of attenuation in both the FSO link and the millimetre links, and thus cause outages.

Figure 39: Link transmitters (left) and line of sight path to the receivers (right)

The location of the 5 km path was carefully selected to enable a range of environmental factors to be captured and correlated with the availability data:

- the complete communications path can be scanned with a 3GHz meteorological radar. Data from the radar enables the distribution of rainfall along the path to be established;
- a Meteorological Particle Sensor (MPS) enables measurement of the instantaneous distribution of drop sizes; and
- a third sensor records the presence of fog in the vicinity of the link.

Three combined millimetre wave/FSO links were installed and used as the basis for the experimentation work. Link availability was recorded by measuring signal levels at 1s intervals. Availability for the millimetre wave link was above 80% for the last 5 months of the project. However, the FSO system experienced significant periods of unavailability, mainly because the transmitter became misaligned with the receiver, possibly as a result of wind buffeting or ground subsidence. This was a particular problem during the summer months. The most successful months, in terms of link availability, were May and September, during which all of the links were up for more than 92% of the time.

Another noticeable characteristic of the performance of the FSO system was a definite daily variation of received signal strength of up to 10dB. Peak received signal levels would normally occur around midday and the minimums occurring around midnight. The cause of this variation is possibly due to thermal gradient changes along the propagation path, which result in changes to the refractive index.

Scintillation was observed on all of the links at all times during the project, but only significantly affected the FSO link (levels of up to ±3dB). Scintillation was highly variable and most noticeable during daylight hours. The effect of aerosol[23] was also assessed. On a particular summer day, the loss over the 5km path due to aerosol alone was estimated to be just over 2dB. This value could rise to approximately 5dB on a heavily polluted day.

Measurements of the hydrometeor drop size distributions were made throughout the project by a Meteorological Particle Sensor (MPS). Foggy days were characterised by large numbers of very small drops (diameter < 50μm) and very few rain drops (diameter > 1mm). Under these conditions the FSO link suffered high attenuation and the millimetre wave links exhibited low levels of loss. During heavy rain (most drops with diameter > 1mm), the millimetre wave systems suffered higher attenuation than the FSO systems. Only on days when heavy rain was accompanied by drizzle did attenuation significantly affect both systems. Luckily, based on our observations during the project, the occasions when both links suffered significant levels of attenuation were rare.

Table 8 shows availability statistics for the three link types during two months of the trial. These two months form the basis of the analysis as, during this time, the FSO link suffered less from the aforementioned transmitter misalignment problem.

Table 8: Link availability statistics for May and September 2006

Link type, frequency/wavelength	May 2006	September 2006
Millimetre wave, 54 GHz	99.75%	99.5%
Millimetre wave, 94 GHz	98.8%	99.94%
FSO, 850nm	85%	82%

Given the complementary performance characteristics of millimetre wave and FSO links, there would appear to be benefit in operating a hybrid system that would utilise the link least affected by the prevailing environmental conditions. Based on analysis of data for which all links recorded availability information concurrently, three scenarios for a high-availability hybrid link were identified (Table 9).

[23] A suspension of fine solid particles or liquid droplets in a gas.

Table 9: Hybrid link scenarios and availabilities

	Primary link	Backup link	Availability, only primary link	Availability, with backup link
Scenario 1	FSO	54GHz	93.5%	99.91%
Scenario 2	FSO	94GHz	93.5%	99.7%
Scenario 3	94GHz	54GHz	99.25%	99.88%

There is a clear advantage in operating a dual frequency hybrid link. An FSO/54GHz offers slightly greater availability than the FSO/94GHz link; however, the latter link also offers the potential of higher data rates.

Conclusions

The use of longer range FSO fixed links in rural environments has been shown to be viable if availabilities of approximately 80% are acceptable. By adding a second wavelength in the millimetre wave region (possibly at 94GHz), it has been shown that availabilities greater than 99.5% can be expected. While some problems with aligning the FSO beam were occasionally reported, we conclude that this could be avoided by the addition of an active beam tracking capability. This may make the initial outlay more expensive, but the gains in reduced maintenance and improved performance are likely to be considerable.

4.3 Examining the potential to use SHF and EHF spectrum to support wireless camera applications

How does it help?

Wireless television (TV) cameras are already used extensively for electronic news gathering (ENG) and outside broadcast (OB) purposes and the usage is growing. Such cameras have allowed the programme producer to obtain video from locations where it is physically not possible to cable, for example due to health and safety concerns or difficulty of access. The use of wireless cameras has also improved the coverage of live sporting or news events, when the rapid deployment of mobile video capture equipment is vital to capturing the essence of the unfolding scene.

Given the suitability of wireless cameras for the capture of sporting events, it is anticipated that significant numbers will be deployed to cover the Olympic and Paralympic Games that will be hosted in London in 2012. However, due to ongoing technology standardisation in the mobile domain, there is likely to be a decreasing amount of spectrum available for the cameras to use. Additionally, more spectrum will be required to transmit high definition TV content. Therefore, it may be necessary to change the frequency at which wireless cameras operate.

Explanation of the technology

In this research, we investigated the feasibility of operating wireless cameras in the SHF (super high frequency) and EHF (extremely high frequency) bands. Wireless cameras typically consist of three component parts: the lens, the camera body and a wireless transmitter unit. In the UK, the transmitter units are made by a small number of specialist companies, such as Link Research and Gigawave. The specifications of two such transmitter units are shown in Table 10.

Table 10: Specification of two current HD wireless transmission units

	Link Research L1403 HD	Gigawave HD D-Cam
Frequency Range	1.95 – 2.7GHz 3.4 – 3.58GHz	1.3 – 7.5GHz
Channel	10MHz or 20MHz	10MHz
Video encoding	MPEG-2, 9 – 80Mbit/s	MPEG-2, 5 – 32Mbit/s
Modulation	DVB T-QPSK/16QAM/64QAM LMS-T (proprietary)	QPSK, 16QAM, 64QAM
Power Output	Up to 100mW	100mW
Power Consumption	24W	18W
Dimensions	61 × 206 × 121mm	160 × 130 × 54mm
Weight	0.995kg	0.95kg

The use of wireless cameras can be broadly categorised as either OB or ENG. OB cameras will typically be used in specific, predetermined locations with regular, predictable usage patterns. Cameras used for ENG, on the other hand, will be deployed in an ad hoc fashion with unpredictable peaks of usage. For example, OB cameras would cover major sporting events, while ENG cameras would cover breaking news stories.

Wireless cameras rarely, if ever, transmit directly to the studio. In general there are at least two hops involved, involving one or more intermediate points between the camera and the studio. However, this study only focused on the hop between the camera and an intermediate receiver. The length of links between the camera and the intermediate point can range from 250m for OB coverage of stadium-based events to 30km for ENG coverage of news events captured from a helicopter.

Current state of the art and our research

The current generation of wireless cameras makes use of the frequency band from 2.025 to 2.290GHz, known as the 2.3GHz band. During this study, this band was used as the baseline against which to judge performance.

The next substantial block of spectrum widely available for use by wireless cameras is in the 7.5GHz band (7.110 to 7.425GHz). A number of equipment suppliers either already have, or are working on, equipment for this band. One major advantage of operating in this band is that it exhibits similar propagation characteristics to the 2.3GHz band. This would mean that equipment designed to operate in one band could be used in a similar manner in the other band.

The final frequency band chosen for full analysis was the 60GHz band (approximately 57 to 64GHz). Technologies for this band are under development and, while they are unlikely to be sufficiently mature for integration into cameras for the 2012 Olympics, they might have potential for subsequent deployment. The range of 60GHz systems is typically short and the propagation characteristics imply line of sight operation. However, the bandwidth available makes such systems worthy of consideration.

Our study involved modelling the characteristics of wireless camera systems at the three frequency bands described above. A gross data rate of 90Mbit/s was assumed, based on discussions with experts on the requirements for high definition video capture. System bandwidth was set to 15MHz for the 2.3 and 7.5GHz bands, and 90MHz for the 60GHz band. The operational range for systems operating at these frequency bands and at three transmit powers were estimated and shown in Table 11. Note that the systems are assumed to benefit from multiple receive antenna diversity. The transmit powers were chosen based on current products (100mW), a reasonable maximum for amplifiers sited within the camera body itself (1W) and a reasonable maximum for amplifiers physically sited away from the camera (10W).

Table 11: Operational ranges for camera systems operating in different frequency bands and at different transmit powers, with diversity

Transmit power	Systems at 2.3GHz	Systems at 7.5GHz	Systems at 60GHz
100mW	2229m	684m	29m
1W	7049m	2162m	83m
10W	22291m	6836m	211m

Increasing the transmit power clearly increases range, albeit at the cost of increased power consumption and a corresponding higher drain on the battery powering the camera. The study involved a modelling exercise to predict the battery requirements for a given transmit power. It was found that the extra battery capacity required to increase the transmit power to 1W was feasible. However, increasing the transmit power to 10W will require six times the battery capacity, compared to existing products. Such a battery, with a form factor suitable for mobile applications, is currently impractical. The dissipation of the increased heat generated by inefficient power amplifiers is also likely to pose a problem. We concluded that raising the transmit power to 1W is largely feasible.

The modelling exercise enabled us to benchmark systems operating at 7.5 and 60GHz against state of the art systems operating at 2.3GHz. For systems at 7.5GHz, we state that:

- propagation characteristics and modulation schemes are similar to systems at 2.3GHz;
- for a given power level, the range of a system at 7.5GHz is roughly a third of a system at 2.3GHz. To compensate and achieve equivalent range, the 7.5GHz system would require a ten-fold increase in transmit power; and
- equipment is either currently, or imminently, available.

For systems at 60GHz, we state that:

- propagation is restricted to line of sight;
- range is restrictive and too short to be of use in most applications, and;
- wireless camera equipment operating at these frequencies is not currently available.

A number of ENG and OB application scenarios were compared against the performance characteristics of systems operating at 7.5 and 60GHz to determine their feasibility. Those applications for which higher frequency operation is feasible are outlined in Table 12.

Table 12: List of applications that could be feasibly deployed by systems operating at higher frequencies

Camera location	Intermediate receiver position	Maximum distance	Feasibility at 7.5GHz	Feasibility at 60GHz
Stadium	Base stations in stadium	500m	Yes, with sufficient receive antennas and/or increased transmit power	May be possible with sufficient receive antennas and/or increased transmit power
Inside a building	Static vehicle outside	200m	May be possible with increased transmit power	No, non line of sight
Open space	Static vehicle	Up to 1.5km	May be possible with sufficient receive antennas and/or increased transmit power	No, range too great
Motorcycle	Helicopter	1.5km	May be possible with sufficient receive antennas and increased transmit power	May be possible with sufficient receive antennas and increased transmit power
Helicopter	Static vehicle/fixed receive point	Up to 30km	May be possible with sufficient receive antennas and increased transmit power	A reduced range may be possible with sufficient receive antennas and increased transmit power

This analysis suggests that:

- frequencies around 2.3GHz will still be needed for situations where the power output is limited, where the propagation path is poor, and over long distances;

- frequencies up to 7.5GHz will be suitable in many situations, but will often require higher power transmitters and/or more receive antennas, and;
- at 60GHz, only line of sight applications will be feasible. These may not be naturally line of sight, because in a known environment such as a stadium it is possible to install several antennas in a diversity or cellular arrangement.

Conclusions

We have shown that there is scope in principle for migrating a proportion of existing usage at 2.3GHz to higher frequencies. While in some situations it may be possible to use higher frequencies, it is necessary to think of the practicalities. An OB or ENG unit will not generally go to a location armed with an array of different transmitters in order to select the highest frequency that will work. So in most situations they will want a transmitter that can be relied upon to perform well in different scenarios. Existing 2.3GHz equipment fulfils this need rather well.

In the case of ENG, the need to deploy equipment that will cope with unpredictable ad hoc situations will probably discourage migration to higher frequencies. Thus we judge that ENG will remain at 2.3GHz.

In OB applications, the line of sight limitations of frequencies above 7.5GHz mean that most migration will need to stay below 7.5GHz. Theory suggests that the performance of 7.5GHz equipment at 1W should not be dissimilar to the performance of 2.3GHz equipment at 100mW.

While there may also be scope for using other frequencies between 10 and 25GHz in some situations, the cost of purchasing equipment for relatively rare circumstances will discourage both broadcasters and suppliers from investing. Point-to-point links can use higher frequencies – as they sometimes do at present. This includes helicopter links, provided automatic antenna stabilisation is employed.

It is not possible to be prescriptive about the proportion of use that can be migrated but an approximate calculation is given below:

- no migration for ENG cameras (accounts for 50% of existing cameras), other than for line of site helicopter to static vehicle OB/ENG links;
- 100% migration to 7.5GHz or above for OB cameras used inside stadia or other venues (an estimated 25% of existing cameras); and
- 50% migration to 7.5GHz or above for OB cameras used in open air and for point to point applications (an estimated 25% of existing cameras).

Our analysis has shown that the majority of outside broadcast applications could be migrated to 7.5GHz, and that some line of sight outside broadcast applications could also be migrated to much higher frequencies. Increased transmitter power and the use of multiple receive antennas may make the use of 60GHz possible within stadia on the back of technology developments at this frequency. It may also be possible to deploy 60GHz line of sight links in mobile OB to helicopter applications and OB/ENG helicopter to static vehicle applications.

Overall, our analysis suggests that approximately one third of existing usage could be migrated to higher frequencies.

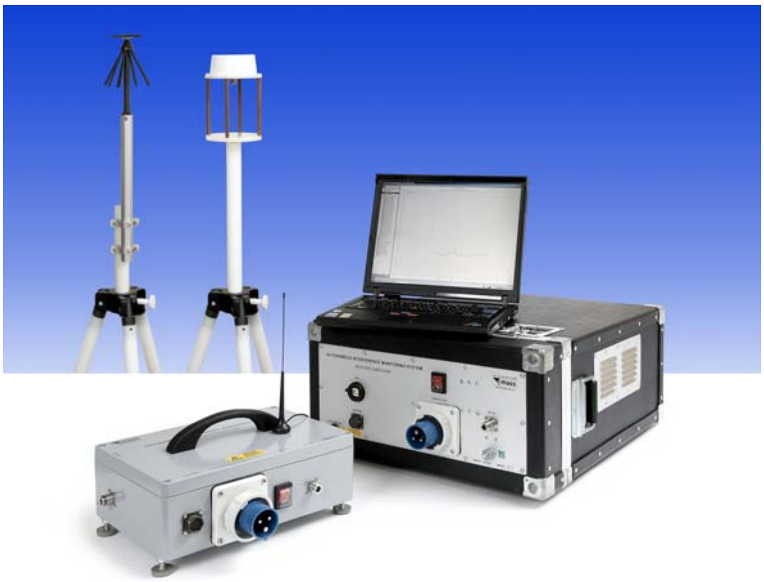
Though the activity at 60GHz will undoubtedly start to open up the use of higher frequencies, we do not think the existing applications are sufficiently close to those of wireless cameras to make the technologies relevant within the short term. We judge it unlikely that the use of 60GHz frequency bands will be feasible in time for the London 2012 Olympic Games and Paralympic Games, though developments in these technologies should continue to be monitored.

4.4 Autonomous Interference Monitoring System (AIMS) Phases 2 and 3

The first phase of the Autonomous Interference Monitoring System (AIMS) project has been reported in previous research reports. During the second and third phases of the project, AIMS has matured into a multi-function, accurate and highly efficient tool for assessing spectrum quality and usage, shown in Figure 40. New functionality includes:

- measurement of the interference levels in occupied regions of the spectrum, including Ambient Interference Level (AIL) measurement in the GSM bands;
- automatic measurement of spectrum utilisation;
- measurement of Man-Made Noise (MMN) in accordance with ITU-R guidance;
- automatic production of report documents;
- reporting of system health and test status via SMS text messages; and
- support for different antenna sets using a new antenna interface unit.

Figure 40: AIMS hardware

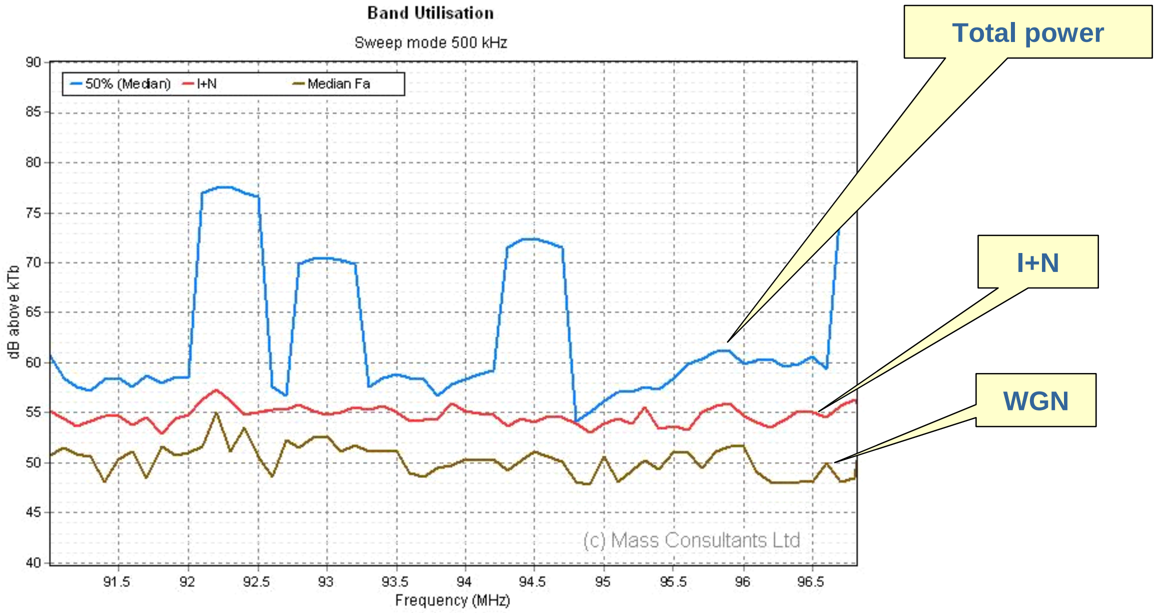


We have conducted an extensive UK field measurement campaign, monitoring interference, utilisation and MMN levels in a selection of licensed and licence exempt (LE) bands. In all, 39 sites have been surveyed. These surveys have shown that the equipment can be readily deployed by a single operator and left unattended for many days to collect valuable statistics about the usage and quality of the spectrum. The resulting statistics can be presented using an intuitive graphical software package, allowing trends and anomalies to be analysed.

Interference Measurements

As well as White Gaussian Noise (WGN), AIMS measures and records the Interference + Noise (I+N) power in a communications channel (Figure 41). This facility allows the analyst to accurately assess the interference that would be seen by a radio receiver in that band, even if that band is occupied at the time of the measurement. This provides us with a powerful tool to support a ranged of spectrum trading activities.

Figure 41: Example of interference measurement in the FM band

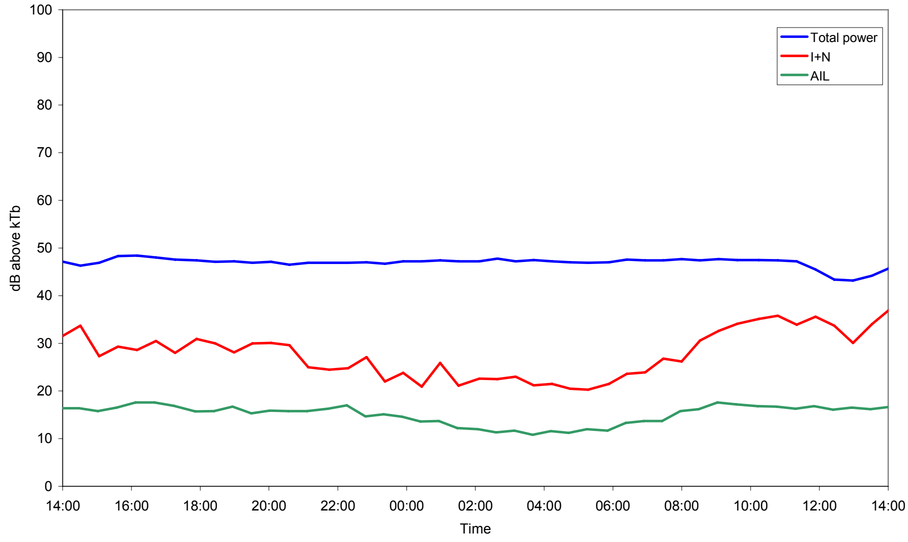


Field measurements of I+N have been carried out at 15 sites, covering:

- bands where there is expected to be the greatest economic activity (UHF TV broadcast and 2G/3G cellular);
- bands where UWB activity might occur in future (4.2 to 4.8GHz and 6 to 7GHz); and
- bands where noise is likely to be a problem (AM/FM broadcasting).

These measurements have shown that, not only is I+N measurement feasible and practical, but it can also reveal features of the spectrum that could probably not have been seen in any other way. During phase 3, an AIL estimator has been developed for use in the GSM bands. This measurement mode removes network self-interference (Figure 42) giving a better estimate of the underlying interference plus noise level.

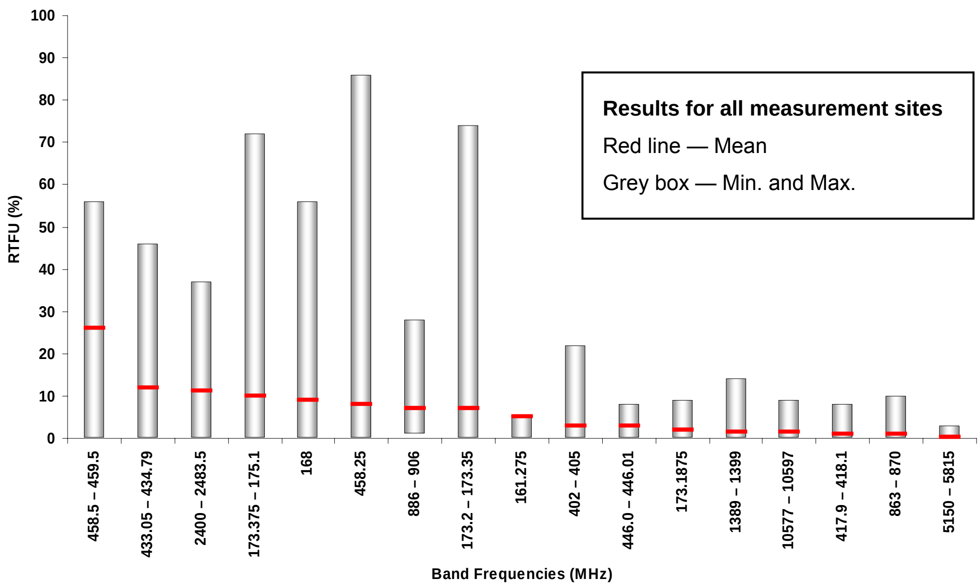
Figure 42: Example of AIL estimation in a GSM band



Licence Exempt (LE) Measurement

AIMS records the time-varying powers in a set of channels and automatically determines the spectrum utilisation. This capability has been exploited in a measurement campaign of 20 sites to assess usage of the LE bands. The results have been used as an input to the consultation document on LE band usage.

Figure 43: LE band relative time and frequency utilisation (RTFU), sorted by mean utilisation



The main finding was that, on average, the LE bands are not heavily used. The band displaying the highest usage was the 458.5 to 459.5MHz band, designated for use by telemetry systems. Use of RF heating equipment in the 886 to 906MHz band was also widespread but the low duty cycle meant that utilisation appeared low.

A surprising result was the relative lack of wireless LAN activity, especially in central London, probably attributable to signal propagation effects and the low power output of wireless LAN devices.

Comparisons were made with measurements of the 2.4GHz band carried out in 2003 at three sites. The average utilisation was 5.7% in 2003 rising to 14.3% in 2006; the increase in the level of activity was attributable to recent deployment of WLAN systems. Despite these increases, the 2.4GHz band is only heavily used at one of these sites.

Significant wideband interference effects were detected below 1GHz, mainly attributable to malfunctioning fluorescent lights.

Man Made Noise (MMN) Measurements

AIMS records both the WGN floor and the impulsive noise characteristics of manmade noise (MMN). The WGN algorithm developed for AIMS has been submitted to the ITU-R to be incorporated as an ITU standard method for calculating this parameter.

In December 2006, AIMS was successfully compared with the German Federal Network Agency's measurement system during a joint field trial. Measurements from both systems have been submitted to the ITU-R in April 2007 to update ITU-R Recommendation P.372 on radio noise. The measurement campaign visited 33 sites and concentrated on a part of the spectrum that is not well described by the existing ITU-R document. Our measurements were in line with the existing ITU-R recommendation and provide more detail to support the forthcoming update to that document.

Next Steps

We now see the AIMS systems as fully developed. We plan to make measurements with it every 1 to 2 years in order to understand the changing noise, interference and licence-exempt levels in the spectrum and to start to build trend information.

Section 5

Conclusions

5.1 Summary of research projects

Over the past 18 months we have undertaken a wide range of research projects, addressing three broad areas:

- sectoral studies;
- research into technologies; and
- better managing the spectrum.

Our summary findings from the research projects are set out below.

5.2 Sectoral studies

Health technology scenarios development

In the next twenty years, the healthcare sector is expected to benefit from the widespread deployment of information and communications technologies (ICTs). For example, a home hub could be used to analyse blood samples, dispense the correct dose of medication and link to the local GP to automatically book an appointment when needed. Body area networks could monitor vital signs and automatically change drug dosage. Many of the applications could be deployed over existing local area or cellular networks, requiring no further regulatory action from Ofcom. In such cases the challenge relates more to the fusion of healthcare information from disparate sources, rather than the physical means to create an underlying network. However, during our study we identified some applications that may require regulatory attention:

- Body area networks will be used to interconnect implanted medical devices. The safety critical nature of this application suggests a requirement for dedicated spectrum. Depending on the deployment of such networks, the existing allocation of spectrum at around 400MHz may need to be reviewed;
- Local area networks will be used to interconnect medical equipment or to bridge between diagnostic units and implanted body area networks. Conventional wireless local area network spectrum is available at 2.4 and 5GHz but safety critical data streams should be supported by dedicated spectrum. In the United States, a Wireless Medical Telemetry Service (WMTS) utilises the bands 608 to 614MHz, 1395 to 1400MHz and 1427 to 1432MHz. However, there is currently no allocation for such applications in the UK;
- Social and emergency alarms already use dedicated spectrum near 170 and 870MHz. Given the emergency nature of these devices and their controlled power level and duty cycle, the likelihood of congestion is low. However, increased deployment in the future may lead to congestion in these bands.

For the sector to realise the benefits of ICTs, the health sector (public and private providers and patient-representation) and the technology and telecommunications industry must work closely together. There may be a case for a task force to bring together the stakeholders, to monitor use of health ICTs and spread “best-practice” examples of its use, and to collaborate to overcome the barriers that may hold back the sector’s technology development.

We recommend that the Department of Health should take more active responsibility for the use and management of radio spectrum by the health sector (and particularly by the NHS). This could involve the establishment of an organisation within the Department of Health or the NHS to oversee and co-ordinate the use of spectrum, and more widely, all information and communications technologies. Such an organisation would represent the NHS’s (and ultimately of course, the patient’s) interests in order to bring about the optimal use of wireless technologies.

Socio-economic study of transport

These might include the provision of congestion and tolling information, automatic braking when the car in front stops unexpectedly or route planning across multiple types of public transport, including ticketing and real-time updates. The combination of these services will provide the consumer with the means to ensure their journey, however executed, meets their requirements in terms of cost, speed, safety and environmental impact. Again, there is a significant challenge in bringing together information from the various transport systems in order to provide the citizen with an integrated, intermodal journey. We also identified some applications that may require regulatory attention:

Spectrum is already allocated for very short-range communications systems such as radio frequency identification (RFID). The allocation is currently sufficient, but may need to be reviewed if deployment densities increase significantly. However, we expect any increase to be relatively modest.

A number of transport applications already use, or are expected to use, licence exempt spectrum, e.g. WiFi or Real Time Location Systems (RTLS). We expect to see an increase in the use of WiFi at 2.4GHz in the coming years. The increase in congestion in this band will stimulate a move to use the 5GHz licence exempt spectrum. Similarly, expected increases in deployment densities of RTLS devices will lead to congestion in current bands.

Intelligent road transport systems will require an allocation of dedicated spectrum, given their safety critical nature. There is already a European Union proposal for 50MHz of spectrum at 5.9GHz, in addition to an existing allocation at 63GHz. Spectrum for safety critical systems will require international harmonisation and utilisation of the spectrum will need to be monitored to see whether any additional allocations are required.

Spectrum is needed to provide data and voice capacity along railway lines, creating a wireless corridor. This could be used both to support operational requirements and to provide commercial services. Finally, the traveller will expect to be able to use broadband services whilst travelling by air and sea. This is likely to require additional capacity for satellite communications.

5.3 Research into technologies

Dynamic Spectrum Access (DSA)

The first phase of this project concerned the design of a candidate architecture for the introduction of Dynamic Spectrum Access (DSA). The design took account of the need to be technology agnostic and adopted the principle of minimising the modifications required to legacy networks and infrastructure to enable them to participate in DSA. The second phase of the project investigated three key issues for DSA: network signalling delays, dynamic pricing and mobility. In each case, a network simulation was developed in order to better understand the issues and behaviour of the DSA network. As a result of this work, we find there are no major technical barriers to the introduction of DSA.

However, there are some technical choices for prospective service providers, such as deciding whether to offer both incoming and outgoing calls and the level of mobility support to provide. We also conclude that there is minimal spectral efficiency gain over comparable non-DSA systems.

The project's second phase also included market and business analysis of the DSA concept. The main message is that there is large scope for market-driven innovation and specialisation that should ultimately benefit the end user. DSA can also be seen as part of a wider trend that offers 'convergence' across different access networks and services with the end user able to gain access to different services and in different locations using a single wireless terminal.

In summary, we are confidant that the implementation of DSA is technically feasible and that the prospects for its introduction rest mainly on the business case.

Wireless Sensor Networks (WSN)

We studied wireless sensor networks from both a technical and a commercial perspective. We concluded that currently there is no evident 'killer' application. In particular we have seen no consumer pull, rather a range of industrial/commercial applications. We also noted a clear overlap between WSNs and RFID; this overlap is growing and we see convergence likely in

We conclude that the commercial potential and predicted growth of WSN usage will not lead to major demands on spectrum. This is as a result of the low-power, low-duty cycle, non-real-time nature of most WSN requirements. The low-power and low duty-cycle characteristics in particular permit significant geographic frequency re-use.

However we do conclude that the main issue for WSNs will be being crowded-out of the bands, especially 2.4GHz, particularly by the increasing use of WiFi for streaming services, which are inherently impolite during the real-time streaming itself. This is likely to be evidenced as variable performance of WSN networks, with perceived (and actual) reduced reliability/availability by users.

An assessment of the theoretical limits of copper cabling in the last mile

In the UK, broadband penetration has increased dramatically over the last six years from 7% in 2002 to 57% in Q4 2007, driven in part by fierce competition amongst local loop unbundlers (LLUOs): almost 80% of these broadband connections are delivered across the copper local loop with the rest over cable. Consumers are benefiting from the choice that infrastructure competition is delivering and they appear relatively happy with the headline broadband speeds – if discontented when the reality does not meet the headline. Whilst there are no definitive indications of whether consumers will want significantly higher speeds, we are seeing evidence of increasing use of IPTV and other bandwidth hungry audio visual applications. This begs the question of when the current copper network would be unlikely to meet the expectations of the majority of UK consumers.

In practice, the answer to this question depends not only on the types of services consumers require but how technologies evolve: it is difficult to predict either accurately as there are many factors which effect both. To give some insight, we commissioned a study based on an idealised environment that does not reflect all the complexities of the current underlying network. This abstraction enabled us consider the theoretical capacity limits of copper networks and set an upper bound for broadband data rates that could be achievable across copper. Given the important relationship of distance to data rate, we based our model on information on cable lengths from a real network. We concluded that, in our idealised environment, capacities can further improve, compared to today's deployments. We found that if the upstream modem is hosted in the exchange, households within 2km of the exchange (approximately 18% of the total number of households) could, in theory, receive data rates above 50Mbit/s. If the upstream modem is moved closer to the customer premises and into the street cabinet, then almost 100% of households are within 2km of the street cabinet and could, theoretically, expect a data rate of 50Mbit/s.

These results are theoretical and do not reflect what could be achieved in practise. Data rates experienced by end users depend not only on the distance between the customer premises and the exchange but also on home wiring and interference at the exchange, cabinet and in the home. In the real world there are different providers with different equipment sharing the exchange, and perhaps the cabinet, and therefore impacting performance. Nevertheless the real value of this study is to suggest an upper limit, given all technical progress possible, of 50Mbit/s, with fibre to the cabinet.

Technology watch

Technology within the information and communication technologies sector continues to develop rapidly and continually open new opportunities. Breakthroughs leading to fundamental shifts in the underlying science are rare. Continuous development is more common and can be just as valuable in the evolution of services and applications.

It is vital for us to monitor advances in such technologies, as it enables us to better anticipate how to execute our regulatory duties in the future. During the year we surveyed a number of emerging technologies, including novel amplifier techniques, swarm communications and optical printed circuit boards. Our investigations revealed that innovation is strong in both industrial and academic research laboratories. However, we did not uncover any breakthrough technologies that are likely to lead to a substantive change in the telecommunications sector.

5.4 Better managing the spectrum

Propagation involving the indoor-outdoor interface

Despite the increasing use of wireless systems in and around buildings, there is no widely accepted model for radio propagation involving the passing into or out of buildings. We commissioned a study to produce a model suitable for regulatory purposes. Data generated by the model has produced a wealth of useful information.

Understanding the effect of wind farms

The interference effects of wind farms on radar and broadcast services have been studied extensively, but the effect of onshore wind farms on fixed links and scanning telemetry is less well understood. As the number of wind farm planning applications continues to grow in order to meet Government renewable energy targets, there will be continued requirement for coordination with the telecommunications industry.

The main interference mechanism is the multipath effect, where the received signal experiences interference due to reflection from the tower or turbine blade. Vulnerability to multipath effects is a function of the frequency and length of the link; the lower the frequency and the longer the link, the more risk there is of multipath interference.

This current study aims to refine existing theoretical models through measurement of some of the key parameters, in particular the C/I protection ratio that is required to determine the RCS of the turbine.

Generic Radio Modelling Tool (GRMT)

We have previously commissioned a Generic Radio Modelling Tool (GRMT), which can undertake assessment of the potential for interference in a liberalised spectrum environment. During this year the GRMT has been further developed, including the ability to undertake a technical examination of whether a new or changed licence application should be approved or rejected. A road-map for the further use of the GRMT has been proposed.

Propagation between terminals of low height

The increasing use of “micro-cells” in mobile radio systems and the possible extensive use of mesh networks highlight a need for a general-purpose propagation model appropriate for making coverage and interference predictions where both terminals in a link are of low height. We have previously commissioned a measurement campaign to enable us to better understand this propagation environment. The results obtained in this reporting period highlighted the limitations of existing, accepted models that have not explicitly been developed for such environments.

Millimetre wave and Free Space Optical fixed link services in rural environments

The use of longer range FSO fixed links in rural environments has been shown to be viable if availabilities of approximately 80% are acceptable. By adding a second wavelength in the millimetre wave region (possibly at 94GHz), it has been shown that availabilities greater than 99.5% can be expected. While some problems with aligning the FSO beam were occasionally reported, we conclude that this could be avoided by the addition of an active beam tracking capability. This may make the initial outlay more expensive, but the gains in reduced maintenance and improved performance are likely to be considerable.

Examining the potential to use SHF and EHF spectrum to support wireless camera applications

In the case of electronic news gathering (ENG) applications, the need to deploy equipment that will cope with unpredictable ad hoc situations will probably discourage migration to higher frequencies. In outside broadcasting (OB) applications, the line of sight limitations of frequencies above 7.5GHz mean that most migration will need to stay below 7.5GHz.

It is not possible to be prescriptive about the proportion of use that can be migrated but an approximate calculation is given below:

- No migration for ENG cameras (accounts for 50% of existing cameras), other than for line of site helicopter to static vehicle OB/ENG links;

- 100% migration to 7.5GHz or above for OB cameras used inside stadia or other venues (an estimated 25% of existing cameras); and

- 50% migration to 7.5GHz or above for OB cameras used in open air and for point to point applications (an estimated 25% of existing cameras).

Our analysis has shown that the majority of outside broadcast applications could be migrated to 7.5GHz, and that some line of sight outside broadcast applications could also be migrated to much higher frequencies. Increased transmitter power and the use of multiple receive antennas may make the use of 60GHz possible within stadia on the back of technology developments at this frequency. It may also be possible to deploy 60GHz line of sight links in mobile OB to helicopter and OB/ENG helicopter to static vehicle applications.

Overall, our analysis suggests that approximately one third of existing usage could be migrated to higher frequencies.

Autonomous Interference Monitoring System (AIMS) Phases 2 and 3

We have previously commissioned the development of the Autonomous Interference Monitoring System (AIMS), a multi-functional tool for monitoring the quality of spectrum. In the last year we have conducted an extensive field measurement campaign, including a study of licence exempt band utilisation and the measurement of the characteristics of man-made noise. The outcomes of the latter have been submitted to ITU-R. We plan to make further measurements every one to two years in order to understand the changing noise, interference and licence-exempt levels in the spectrum and to start to build trend information.

5.5 Overall key findings

Technology within the information and communication technologies sector continues to develop rapidly and continually open new opportunities. Breakthroughs leading to fundamental shifts in the underlying science are rare. Continuous development is more common and can be just as valuable in the evolution of services and applications.

Last year, we concluded that a breakthrough in communication technologies was unlikely within the next 10 years. Further horizon scanning, through our Technology Watch programme, leads us to make the same comment this year. This has great importance to a number of our policies, such as decisions as to whether to set spectrum aside for an "innovation reserve" – based on the conclusions here such an approach would be inappropriate. However, given a typical 10 year time lag from research to commercial deployment, continued monitoring of the technology horizon is prudent.

Breakthroughs aside, we note that the general pace of technology advancement, both within industry and academia, is very strong indeed. Wireless sensor networks are moving from the military to the civilian domain, attracting a significant amount of interest within the research community. However, their widespread deployment is still some way off and we conclude that no additional spectrum or regulation is necessary at this time. In the wired domain, the technologies underpinning copper telephone networks may progressively be enhanced to achieve higher data rates.

The sectoral studies into the health and transport sectors show that application of new and emerging technologies could have a major effect on the way we live our lives and the services that are delivered. Simply applying cellular communications, GPS positioning and short-range wireless to the car, for example, could revolutionise the way we conduct our journeys and safety levels on the roads. These studies make it clear that developing a new technology is generally simpler than introducing it into commercial use, especially where there are a number of inter-related parties or where Government plays a key role. Indeed, it is clear that delivering these services will require Government intervention and our studies have suggested that there may be a need within relevant Government departments for a team to identify and lead the delivery of these projects.

Overall, the research reported here suggests that no major changes to our regulatory policies are needed at this time. There may be a requirement to help identify incremental spectrum allocations, predominantly for licence-exempt usage, and copper networks may provide data rates that can compare with those currently being deployed in cabled systems. However, no dramatic changes requiring the review of regulation are presently foreseen.

5.6 Future research programme

Over the past six months, we have consulted widely, both within Ofcom and externally, on suitable topics for the 2008/09 research programme. At the time of writing, eight projects have been specified:

- **Estimating the value of spectrum.** An increasing amount of spectrum is allocated through market-driven approaches. However, this requires a good understanding of the real value of the offered spectrum. This project may assist trading markets by setting price expectations appropriately and help those who are interested in acquiring spectrum in understanding the likely amount that they might have to pay. We are proposing a study that will build a model that will enable us to estimate value across as much of the UK spectrum allocation as possible. The model will take a number of factors into account, such as the frequency and bandwidth, and will provide important information to drive the spectrum marketplace.

- **Capture of spectrum utilisation information using moving vehicles.** The use of spectrum in different parts of the country and across different frequency bands can vary quite dramatically. It is important that we are aware of such variations to enable us, for example, to determine whether additional licence exempt spectrum is needed or to build up a better picture of local interference. We propose to investigate a system comprising a number of vehicle-mounted nodes. Measurements would be taken as the vehicle moved, with the data stored locally until such time that it could conveniently be uploaded to a central database. Over a period of time the database will grow, building a detailed picture of spectrum use in key frequency bands across much of the country.

- **Socio-economic study of the entertainment sector.** Entertainment within and to the home is undoubtedly an enormous market. We anticipate that the manner in which video and audio is distributed, stored and subsequently consumed will have a major impact on the underlying communications infrastructure. We are proposing a study that will enable us to assess the changing entertainment sector in order to determine the impact on the regulatory environment. The study will develop scenarios describing a view of the future entertainment sector over periods of 10 and 20 years. These scenarios will then be examined to determine the technological developments required and the likely impact on spectrum and network demands.

- **Quality of service on the Internet and the implications for IPTV and other services.** The entertainment study discussed above will address an entire sector of society and will therefore be broad in scope. We are also proposing to conduct a narrower study that specifically investigates the technological and economic barriers to providing high quality television services over the Internet (known as Internet Protocol Television, or IPTV). One of the major reasons for poor quality of service over the Internet is congestion, i.e. too much data being carried at the same time, leading to some data being lost or severely delayed. In this study, we will seek to understand the various reasons why congestion occurs, the impact it has and whether we can take any regulatory measures to improve the situation.

- **Estimating the use of key licence-exempt spectrum.** Licence-exempt spectrum is important for delivering applications that generate significant consumer value, such as Bluetooth and WiFi. However, as the number of devices that support these technologies increases, so does the possibility of congestion, which can lead to degradation in quality or performance. Understanding the actual levels of congestion and the associated trends will assist us in making better-informed spectrum management decisions. Unfortunately, getting a good understanding of congestion is very difficult – congestion may only occur in a small area, such as in the centre of a shopping centre but not at the periphery, or it may only occur at certain peak periods of the day. We propose a study to seek out congested areas and measure levels of congestion.

- **Understanding the environmental impact of communications systems.** Communications systems in general might have two different environmental effects. On the one hand, transmitters and receivers consume energy and building mast sites can involve substantial activity and affect the landscape. On the other hand, effective communications, such as video conferencing, might save journeys and hence have a positive environmental impact. We propose to conduct a study to assess the relative energy consumption and environmental impact of a range of different networks as well as understanding how the benefits might vary according to network type.

- **Predicting areas of spectrum shortage.** There is a long-term view of spectrum use, in which networks are efficiently deployed in all places and at all times and there is sufficient spectrum available for a variety of demanding services. However, as we move towards that situation, the demand for spectrum may grow more quickly than the available supply. Hence, in the interim there may be areas of spectrum shortage, which may lead to poor coverage, dropped calls or low data rates. We propose a study that will enable us to model both spectrum demand and the ability of networks to respond to that demand. Potential areas of spectrum shortage can therefore be identified and, if necessary, regulatory action planned.

- **Wide-range propagation model.** Propagation tools are vital to understand the physical environment in which wireless and mobile systems operate. However, it is becoming apparent that existing propagation methods and tools will require updating, as use of the radio spectrum becomes more innovative and liberalised. We propose a study to develop a new model that will predict coverage and interference between radio networks operating in a liberalised spectrum environment.

Annex 1

R&D projects and project consortia

This report presents the findings of the consortia of industry, consultants and academic institutions that have undertaken the technical work on Ofcom's behalf. We gratefully acknowledge the work of the consortia on these projects and the help received from many of the consortia members in compiling this report.

Project title	**Consortium members**
Macro-economic scenarios to 2025	Indepen
Health technology scenarios development	Fathom Partners, Imperial College, Indepen, Aegis Systems Ltd
Socio-economic study of transport	Plextek, Quotient Associates
Wireless sensor networks	Plextek, University of St Andrews, TWI
Technology watch	Qinetiq
An assessment of the theoretical limits of copper cabling in the last mile	Sagentia, Birkbeck College
Understanding the effect of wind farms	ERA, Aegis Systems Ltd
Examining the potential to use SHF and EHF spectrum to support wireless camera applications	Sagentia
Autonomous Interference Monitoring System (AIMS)	MASS Consultants Ltd
Millimetre Wave & Free Space Optical fixed link services in rural environments	CCLRC-Rutherford Appleton Laboratory
Propagation between terminals of low height	RedM, dB Spectrum Ltd, CCLRC-Rutherford Appleton Laboratory, University of Surrey
Generic Radio Modelling Tool (GRMT)	Transfinite Systems Ltd, CCLRC-Rutherford Appleton Laboratory, University of Surrey
Propagation involving the indoor-outdoor interface	dB Spectrum Ltd, RedM, CCLRC-Rutherford Appleton Laboratory,

Annex 2

Glossary

ABS	Antilock Braking System
AC	Alternating Current
ADC	Analogue to Digital Converter
ADSL	Asymmetrical Digital Subscriber Line
AIMS	Autonomous Interference Monitoring System
AIS	Automatic Identification System
AM	Amplitude Modulation
ANFP	Access Network Frequency Plan
AO	Adaptive Optics
AROT	Active Retro-reflecting Optical Tag
AWGN	Additive White Gaussian Noise
BAN	Body Area Network
BWEA	British Wind Energy Association
C/I	Carrier to Interference
CCTV	Closed Circuit TeleVision
CEPT	European Conference of Postal and Telecommunications Administrations/ Conférence Européenne des administrations des Postes et des Télécommunications
COST	An organisation for European cooperation in the field of scientific and technical research
CPE	Customer Premises Equipment
DAC	Digital to Analogue Converter
DC	Direct Current
DCIE	DSA Capable Infrastructure Equipment, an element of the DSA candidate architecture
DCUE	DSA Capable User Equipment, an element of the DSA candidate architecture
DfT	Department for Transport

DNP	DSA Network Provider, an element of the DSA candidate architecture
DSA	Dynamic Spectrum Access
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DSM	Dynamic Spectrum Management
DSP	DSA Service Provider, an element of the DSA candidate architecture
DSP	Digital Signal Processor/Processing
DVB-S2	Second generation of the Digital Video Broadcast system for satellite
EBL	Electronic Brake Light
EHF	Extremely High Frequency
ENG	Electronic News Gathering
ERTMS	European Rail Traffic Management System
ETSI	European Telecommunications Standards Institute
EU	European Union
FCC	Federal Communications Commission
FEXT	Far End crosstalk
FM	Frequency Modulation
FPGA	Field Programmable Gate Array
FSS	Frequency Selective Surface
GDP	Gross Domestic Product
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GPS	Global Positioning System
GRMT	Generic Radio Modelling Tool
GRP	Glass Reinforced Plastic
GSM	Global System for Mobile communications
GSM-R	Global System for Mobile communications – Railway
HIS	High Impedance Surface

HVAC	Heating Ventilating and Air Conditioning
IATA	International Air Transport Association
ICT	Information and Communications Technology
IEEE	Institute of Electrical and Electronic Engineers
IF	Intermediate Frequency
IMO	International Maritime Organisation
ISM	Industrial, Scientific and Medical
ITS	Intelligent Transportation System
ITU	International Telecommunications Union
LAN	Local Area Network
LE	Licence Exempt
LO	Local Oscillator
LORAN	LOng RAnge Navigation
LOS	Line of sight
M2M	Machine to Machine
MEMS	Micro Electro Mechanical Systems
MMIC	Monolithic Microwave Integrated Circuit
MMN	Man Made Noise
MPS	Meteorological Particle Sensor
MQW	Multiple Quantum Well
MRR	Modulated Retro-Reflective
NEXT	Near End crosstalk
NHS	National Health Service
OB	Outside Broadcast
PCB	Printed Circuit Board
PCP	Primary Cross connect Points
PFD	Power Flux Density
PMR	Private Mobile Radio

PMSE	Programme Making and Special Events
PQG	Price Quote Generator, an element of the DSA candidate architecture
PRSA	Price Request and Selection Agent, an element of the DSA candidate architecture
PSD	Power Spectral Density
QoS	Quality of Service
R&D	Research and Development
RCS	Radar Cross Section
RF	Radio Frequency
RFID	Radio Frequency IDentification/IDentifier
RTLS	Real Time Location Service
SC	Street Cabinet
SHF	Super High Frequency
SMS	Short Message Service
SNR	Signal to Noise Ratio
SQB	Spectrum Quality Benchmark
SUR	Spectrum Usage Right
TETRA	Trans European Trunked RAdio/TErrestrial Trunked RAdio
TV	Television
UHF	Ultra High Frequency
UWB	Ultra Wide Band
VANET	Vehicle Area NETwork
VHF	Very High Frequency
VoIP	Voice over Internet Protocol
WAN	Wide Area Network
WGN	White Gaussian Noise
WLAN	Wireless Local Area Network
WMTS	Wireless Medical Telemetry Service

WRC	World Radiocommunications Conference
WSN	Wireless Sensor Network