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Executive Summary

Introduction
This report provides an overview of the technology research and development programme at Ofcom. It presents key findings and outlines the conclusions and implications that Ofcom has drawn from this work.

Ofcom intends to publish an overview of technology research and development on an annual basis to inform stakeholders of findings and to solicit feedback on both the results and the direction of the programme.

Context
Ofcom regulates a sector where technology developments are key to delivering new applications and services to the consumer. Technology development can be both facilitated and hampered by regulatory policy. Ofcom must therefore take a forward view to understand the benefits and impact that emerging technologies may bring and inform appropriate regulatory action. It is one of Ofcom’s statutory duties to encourage the most efficient use of the radio spectrum, so the research effort aims to investigate the technologies which can help to achieve this.

Most visions of the future foresee dramatic increases in the amount of information sent wirelessly. However, the areas of the radio spectrum that can be used for this kind of transmission expand slowly. Only by making better use of the radio spectrum can the visions be achieved. For example, broadcasting content to mobiles may require greater spectrum efficiency; in the future this could be provided by Mesh networks or using adaptive antenna technology. By understanding potential future developments, Ofcom can determine how technologies and services might develop and shape regulation policy accordingly. Hence the technology R&D programme is focused around understanding and furthering the fundamental building blocks for a whole raft of new technologies and services.

Ofcom’s technical research programme is divided into three strands:

- **Understanding and furthering emerging technologies**, such as Software Defined Radio and Smart Antennas. This will allow Ofcom to develop an appropriate regulatory environment to enable future developments.

- **Understanding the state and use of the spectrum**, by monitoring its quality and usage. This will allow Ofcom to look at ways of enhancing efficiency and ensure that spectrum is not becoming progressively polluted by interference.

- **Enhancing spectrum efficiency**, for example looking at options for improving the use of spectrum by existing radar systems. This will help to ensure there is sufficient spectrum to allow for the envisaged growth in usage.

While Ofcom is the regulator for the UK communications industries, with responsibilities across television, radio, telecommunications and wireless communications services, this research programme is deliberately biased towards radio spectrum. This is because spectrum underpins the operation of broadcasting, fixed and wireless telecommunications systems.
Emerging technologies

The work in this area has covered an investigation of Software Defined Radio, Smart Antennas, Cognitive Radio and wireless Mesh networking. The potential impact of these technologies on the spectral efficiency of future systems is significant. To varying degrees each of these technologies today exist in some form. However, there are still technical hurdles to be overcome.

Software Defined Radio

Many future visions of wireless communications involve multi-modal devices connecting to a wide range of different networks such as 2G, 3G, WiFi and Bluetooth. At present this is achieved by incorporating the chipsets from each of the different standards, e.g. 3G and Bluetooth, into the handset. While such an approach works, it is relatively expensive and inflexible. An alternative is for communications devices to be designed like computers with general purpose processing capabilities and different software for different applications. Such devices could then call up, or download, the appropriate software for the particular communications requirement currently in use.

The underlying architecture needed to achieve this is termed Software Defined Radio (SDR). In the future this flexibility might enable more efficient use of the available spectrum through rapid deployment of the latest radio technologies.

To date the defence industry has been the main sector to explore SDR. It is, for example, being deployed as part of the US Joint Tactical Radio System programme. The cellular industry is now showing an interest in using SDR in base stations. SDR could help to make the equipment more ‘future proof’, allowing operators to more rapidly introduce new technologies and services and allow manufacturers to fix bugs and add new features post-manufacture.

Work commissioned by Ofcom has confirmed the potential benefits of SDR but has found that there are many issues with its implementation. They include difficulties in implementing antennas, the speed of chipsets, the battery power required and cost. This has led Ofcom to conclude that SDR is a promising technology but it will be gradually implemented, starting with devices that are able to download minor protocol changes, likely around 2008, through to devices that are able to make major changes to the radio solutions, which could become available in 2015.

Smart Antennas

Smart antenna technology has the potential to significantly increase the efficient use of spectrum in wireless communication applications.

Simple antennas radiate the communications signal equally in all directions. This is wasteful because only a small amount of the signal reaches the intended user; the signal that is radiated in other directions can also cause interference to other users.

Smart antennas intelligently direct the communications signal at the user. The technology has the potential to increase the range and capacity of transmission equipment and reduce interference with other devices.

Smart antennas have been used for many years, notably in defence radar and sonar. Low volume production of such systems has meant that the cost of smart antenna technology has remained high. Significant advances in, for example, processing power are now bringing the technology closer to being commercially viable in the near future for civil communications applications.
Smart antennas could be used to meet the demand for higher bandwidths in future mobile communications systems which operate in the highly-congested area of the radio spectrum. With many systems running close to their theoretical limits of performance, realising the capabilities of smart antennas offers the prospect of performance improvements without placing more demands on the spectrum.

However, there are a number of issues that are restricting the widespread adoption of smart antenna technology, including:

- technical – mainly hardware constraints;
- business – the current relatively high cost of deployment often outweighs the benefits; and
- standards – standards bodies have been slow to agree a global consensus.

For mobile handsets, smart antenna deployment would be complex and expensive. The business case for this application is uncertain at present. For wireless Local Area Network (LAN) applications where the size, power and processing complexity constraints are relaxed, access points with smart antennas have a stronger business case and early versions are now available on the market.

A semi-smart approach - where the communications signal from an antenna is broadened to a sector rather than a narrow beam - would be simpler and cheaper to introduce. Therefore, the business case is stronger and the technology could be introduced within the next three to five years.

**Cognitive Radio**

Not all the spectrum is in use all of the time. Cognitive Radio is a technology that could make efficient use of unused spectrum, potentially allowing large amounts of spectrum to become available for future high bandwidth applications.

Most of today’s radio systems are unaware of their spectrum environment - they are designed to operate in a specific frequency band. A Cognitive Radio system senses and understands its local radio environment to identify temporarily vacant spectrum to operate in. Cognitive Radio would hop into unused bands of the radio spectrum and hop out again if a primary user of a band required that spectrum.

Although the technology holds much promise its introduction might require a different approach to spectrum regulation – this was discussed in Ofcom’s recent Spectrum Framework Review. There are also technical issues to be overcome to ensure that primary users of a band are protected from interference.

There are currently no Cognitive Radio systems in wide deployment, although some early demonstrations of the technology have been built and some existing systems such as DECT cordless phones make use of much simplified Cognitive Radio principles.

Ofcom’s studies in this area are just commencing and no firm conclusions have yet been reached. The work undertaken into SDR suggests that flexible, multi-protocol, multi-band Cognitive Radio systems are some way off. Handsets employing this technology are unlikely before 2010. In the interim there is the possibility of specific band sharing technologies emerging which would provide a stepping stone towards the full Cognitive Radio vision.
**Wireless Mesh Networking**

In a Mesh network every user connecting to a particular wireless communications network acts as a node, relaying information for other users as well as transmitting and receiving its own data. In Mesh networks, information can be transmitted from one user to another via multiple hops through the nodes. Such a network can contain just a few nodes or thousands, all exchanging data.

The advantages of Mesh networks include:

- new communications networks can be formed without the need for new network infrastructure;
- they potentially make more efficient use of spectrum;
- they can extend coverage of cellular and other networks by allowing terminals on the edge of a coverage zone to relay signals to those who do not have coverage; and
- they can be entirely unplanned.

The military already makes use of Mesh networks for battlefield communications. The technology is now beginning to be adopted to provide commercial wireless services using Mesh WiFi technology. Systems already exist in several US metropolitan areas to provide municipal low cost broadband services or in some cases for improved communications for emergency service crews.

Ofcom’s work has concluded that wireless Mesh networks will work best when they are incorporated with some level of fixed infrastructure, for example connections to the telephone network and the internet, or alongside existing networks, such as cellular. This type of Mesh would support applications such as extending wireless hotspots filling in areas of poor wireless coverage, the provision of broadband networks and internet in rural communities.

**Understanding the use and quality of our spectrum**

If Ofcom is to effectively manage the radio spectrum then it requires detailed information on the quality of spectrum and how it is used.

**Quality information** allows Ofcom to understand the degree to which the spectrum is being “polluted” by interference from sources such as unwanted emitters.

**Usage information** allows Ofcom to understand how intensively the spectrum is being used, helping to judge, for example, whether the licence-exempt spectrum is becoming congested. It might also provide information on which judgements about the introduction of new technologies can be made, or allow Ofcom to quickly detect and locate sources of illegal transmissions, such as pirate radio.

To understand spectrum quality Ofcom has commissioned the development of a portable and automated system which can measure the amount of interference compared to actual signal strengths across a wide band from 100 MHz to 10.6 GHz. This will allow detailed analysis of the spectrum use and levels of interference across the most heavily used and demanded frequencies. It will also allow the interference from new systems which generate noise-like signals, such as Ultra Wideband, to be monitored. This system, called the Autonomous Interference Monitoring System (AIMS), will be tested and completed in early in 2006.

To understand spectrum usage Ofcom has commissioned the design of several prototype Automatic Monitoring Stations (AMS). These are being developed to
demonstrate the feasibility of deploying a network of monitoring systems across the UK to provide real-time information on spectrum usage. Such a system would allow Ofcom to rapidly detect and locate sources of illegal transmissions, such as pirate radio. It would also provide valuable information on how intensively the spectrum is being used and provide information on which judgements on the introduction of new technologies such as Cognitive Radio can be made.

**Enhancing spectral efficiency**

Demands from new communications technology and services are putting pressure on spectrum, which is a finite resource. Therefore, Ofcom’s research programme has examined whether new technology can make more efficient use of this resource.

The work in this area includes:

- investigating whether the spectral efficiency of radar systems can be improved;
- considering whether there is potential for communications applications to be deployed in the little used high frequency bands; and
- examining whether there are opportunities for sharing spectrum.

**Spectrally efficient radar systems**

In the frequency band between 1GHz and 3GHz around 30% of the spectrum is primarily allocated to radar systems. This is largely unavailable to other users of the spectrum but these frequency bands have very desirable properties which could be used to support other communication services, such as cellular telephony, messaging and wireless LANs. Large amounts of spectrum could potentially be freed up for commercial purposes if the spectral efficiency of radar systems was improved, moved to a different frequency band in lower demand, or shared with commercial users.

Carrier Wave radar has been identified as a technology that in the longer term could dramatically increase the spectral efficiency for some radar applications, such as Air Traffic Control. Conventional radar systems use very narrow pulses to accurately detect the range of a target. They operate on relatively broad bandwidths of 10s of MHz. An alternative is to move to a continuous transmission, termed Carrier Wave. In principle, this would allow a bandwidth of just a few Hz, offering extremely high spectral efficiency.

However, there are a number of technical hurdles to overcome before Carrier Wave radars are practicable for deployment. They include the susceptibility of the systems to interference and the accurate measurement of target range.

Carrier Wave is unlikely to be retrofitted to existing radar systems so it must be treated as a new deployment. There are also technological, operational and cost hurdles to be first overcome and incumbent radar operators have little incentive to improve spectral efficiency either with short term or longer term measures. The long replacement cycle for existing radar systems means that a timescale for significant improvements in the spectrum efficiency of radar systems is likely to be 2025 or later.

**Reliable Communications Systems at Frequencies above 60 GHz**

The demand for spectrum in the highly congested lower frequency spectrum bands means that there is now a need to consider the higher frequencies for communications 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.
High frequency systems suffer much greater propagation losses making them unsuitable for long range applications. However, Ofcom’s research has shown that the higher frequency bands could be useful for a range of applications, including:

- Broadband Fixed Wireless Access (BFWA) with very high capacities. This could allow applications such as HDTV to the home to be deployed on demand;
- fixed line of sight point to point links, where link lengths of up to 5km are possible with 99.99% availability, supporting short range backhaul;
- high speed (1GB/s) short range wireless LANs, operating over a range of a few hundred metres. This could be used to provide a wireless access system for large buildings such as exhibition halls; and
- short range repeaters (500m to 1km) with very high data rates of up to 5GHz for applications such as network backhaul. Such systems could be applied to a lamp post mounted system for the provision of high bandwidth backhaul to a city-wide WiFi network.

Ofcom’s research has concluded that higher frequency systems are possible within a five year timescale if technology developments, such as improved power generation, occur as expected. However, device costs may take longer to fall to acceptable levels to allow low unit cost production.

**Improving the sharing of radio spectrum**

Traditionally, radio services in the UK have been allocated spectrum on an exclusive basis to minimise any possibility of interference from other radio users. In certain cases secondary uses of the spectrum are allowed, but only where interference is judged unlikely. More frequency channels could be made available if successful sharing between different services could be achieved.

The research examined innovative methods for sharing the spectrum between multiple services in order to maximise its use. The most promising schemes are:

- beacons, which detect whether it is safe to share in a particular spectrum frequency;
- widespread frequency hopping, where spectrum users move across the entire spectrum allotment; and
- spectrum commons, which are rules and methods used for wireless communications.

The research suggests that there is little regulatory action required in the short term. In the five to 10 year timescale, when some of these technologies and services may be better developed, there may be beneficial courses of regulatory action.

**Overall Conclusion**

We have discussed a number of interesting technologies that promise enhanced spectrum efficiency and improvements in device implementation, but broadly, as we would expect at this stage of research, these are around a decade away from commercial realisation. Much of our research is still ongoing, and while we have researched all the leading contenders for spectrum efficiency improvements there may be other technologies that we are not aware of and new technologies are likely to emerge over time. Given these caveats, we tentatively conclude that unless other technologies emerge which are rapidly developed and deployed, then dramatic enhancements in spectrum efficiency will take a decade or longer to achieve. This is
an important conclusion which will have major implications for spectrum use and research over the coming decade.

This does not imply that no enhancements are possible in the next decade – there are many deployed systems which are not using the most advanced existing technology. For example, upgrading existing 2G networks to 3G would provide a gain of around three-fold in spectrum efficiency. Also, many new services can be introduced without dramatic improvements in spectrum efficiency. Finally, major change in services often take five to 10 years – the same timescales as the emergence of the technologies we have discussed here. Hence, we are encouraged that developing technology will continue to underlie developments in wireless systems.

Next Steps
Ofcom’s research programme has focused on emerging technologies and improving the use of the radio spectrum. In the next 12 months Ofcom’s research will explore:

- possible mechanisms for spectrum sharing between the Government and private sector users;
- the role of licence-exempt spectrum; and
- the continued development of monitoring systems to provide information about the radio spectrum.
Section 1

Foreword

Technology developments are driving change throughout the communications industry at an unprecedented rate, enabling exciting new service capabilities for consumers, and challenging service provider businesses both established and new entrant. Understanding the impact of technology developments on the communications industry is vital to Ofcom’s role as the regulator and competition authority for the sector.

The radio spectrum underpins most forms of communication: from telecoms, to TV and radio broadcasting, and much else besides. This is becoming increasingly the case as people begin to enjoy un-tethered access to converged communications services at home and in the office, and the personal mobility that comes from being able to access those same services when out and about.

At Ofcom, we conduct research to ensure that we are well informed about emerging new technologies and their potential impact on the communications industry. With limited resources, we avoid R&D leading towards the development of specific products and services, which is best undertaken by industry. Instead, we focus on two principal objectives for our research, derived from our duties under the Communications Act 2003:

- enabling optimum use of the radio spectrum; and
- encouraging innovation and investment in wireless communication services to promote the wide availability of a broad range of such services.

Quite simply, we want to play our part in making the UK a leader in innovation and investment in wireless communications.

Ofcom’s technology research programme was re-launched in its present form a little over a year ago. We have resolved to publish an annual report on our technology research to share our results with stakeholders, and to seek your input to the future direction of our research programme. This is the first of those annual reports, and we are planning a number of stakeholder engagement events in the coming weeks where the results can be presented and discussed.

The early results from this year’s research projects have already helped to inform our thinking on a number of key issues. I hope that you will find the results to be of interest, and I would welcome your feedback, either directly to me or to any of my R&D team.

Peter Ingram
Chief Technology Officer
Section 2

The role of technology R&D at Ofcom

Technical research to help shape the regulatory environment

Imagine a world where your mobile phone is your “remote control on life”; a device so indispensable that leaving home without it would be more disastrous than leaving your keys and wallet at home today. Many have set out such a vision where the mobile phone becomes a communicator, an organiser, a wallet and much more. In such a world, your communicator device might check on traffic conditions before you leave on a journey, plan your route, provide navigation guidance, check you in for flights, pay for coffee, enable video calling and store music and video. Broadcast content might be more often downloaded than watched “over the air” and could be viewed using a wide range of devices. Access to such services would be nearly ubiquitous as 2G mobile coverage is today. Benefits would extend widely across society – for example emergency services might be able to download floor plans of burning buildings and send back live webcam images taken from the helmets of firefighters. Core networks might be constructed at lower cost and satellite systems might provide a wide range of high-definition channels.

All of these developments require some combination of radio spectrum and enhancements in broadcasting and fixed networks – the areas regulated by Ofcom. It will be the market, not the regulator that ultimately shapes the future. However, in order to understand how to structure such an environment, Ofcom needs to understand the characteristics of the key technologies used. This report is primarily about the technical research Ofcom has carried out over the last year and some of the implications this has for future visions and regulatory environments.

Technical research directed around key building blocks

To realise, for example, a phone that can download video, pay for coffee and much more, requires the development of a number of underlying technologies. In this example some of the advances needed might include:

- the development and deployment of a mobile broadcast system such as DVB-H or DMB;
- multi-modal phones that are able to seamlessly connect to a range of different networks such as cellular outside, WiFi within the airport and perhaps Ultra Wideband (UWB) at the coffee shop;
- underlying core IP networks able to handle a wide range of different data types in a secure environment; and
- enhanced user interfaces on mobile devices, perhaps including voice recognition and flexible displays.

Some of these technologies are not directly relevant to the areas that Ofcom regulates – for example better user interfaces on mobile devices. But many are. Some of these building blocks can be further explored. Take multi-modal phones; developing these might require:

- the development of Software Defined Radio to realise the support of multiple different standards;
- novel antennas able to provide good reception across the wide range of different frequency bands; and
• more efficient use of licence-exempt spectrum to enable multiple uncoordinated networks to work together within a single building.

Underlying many of the areas is the efficient use of radio spectrum. Most visions of the future foresee dramatic increases in the amount of information sent wirelessly. However, the areas of the radio spectrum that can be used for these kinds of transmission expand slowly. Only by making better use of the radio spectrum can the visions be achieved. For example, broadcasting content to mobiles may require greater spectrum efficiency, provided perhaps by Mesh systems or using adaptive antenna technology. Providing new services, such as high speed nomadic solutions, may require a new standard such as WiMax coupled with breakthroughs in spectrum efficiency.

By understanding these building blocks Ofcom can determine how technologies and services might develop and shape regulation. Hence, Ofcom’s technology research and development programme is focussed around understanding and furthering the fundamental building blocks for a whole raft of new technologies and services.

The timescales involved for such technology developments to move from discovery through to mature commercial application and adoption are invariably long, often several decades. Ultra Wideband technology, for example, originates from work undertaken in the 1960s, although it was not until the last decade that developments have occurred which could enable widespread, low cost commercial adoption. Whilst Ofcom’s studies into emerging technologies often take a 10-year view before widespread commercial adoption, regulatory action can also operate on a long timescale, therefore it is important to understand longer term developments and their impact to inform Ofcom’s regulatory stance.

A technical research programme biased towards spectrum

Ofcom regulates spectrum, broadcasting and telecommunications. However, the research programme is biased towards radio spectrum. There are a number of reasons for this:

• Spectrum is a key input for broadcasting and telecommunications. Satellite and terrestrial broadcasting uses spectrum directly and broadcasters make widespread use of spectrum in making programmes. Cellular telecommunications systems use spectrum to link to customers and even fixed telecommunications networks make widespread use of spectrum in deploying wireless fixed links to provide backbone communications links. Hence, researching spectrum helps Ofcom understand many of the key drivers across all areas of regulation.

• The way that Ofcom regulates fixed telecommunications and broadcasting requires less technical research. Spectrum is a scarce resource which needs to be carefully allocated and where interference is forever present. Regulatory issues in fixed telecommunications networks centre mainly around interconnection and open access — areas where economic analysis is often more critical than technical research. In broadcasting, the regulatory issues are either directly related to spectrum or associated with content where market research, rather than technical research, plays a key role.

• The bulk of Ofcom’s technical research funding is specifically targeted at enhancing spectrum efficiency. Under the Spectrum Efficiency Scheme (SES) Ofcom receives £5 million a year from the Treasury to use for technical research into ways to enhance the efficiency with which spectrum is used, or pay compensation to clear spectrum bands.
The research programme does not represent the totality of the studies that Ofcom undertakes in the technology area. There are, for example, studies underway looking at particular regulatory issues that require immediate resolution, such as Ultra Wideband interference. The programme described here takes a longer term view, focused on spectrum related issues.

Segmenting the different types of technical research

Under the overall objective of maintaining a clear understanding of technology trends and regulatory implications, our technical research programme is divided into a number of key strands:

- **Understanding and furthering emerging technologies**, such as Software Defined Radio and Smart Antennas. As discussed above, this is important in ensuring an appropriate regulatory environment to enable future developments.

- **Enhancing spectrum efficiency**, for example looking at options for improving the use of spectrum by existing radar systems. This is important in helping ensure there is sufficient spectrum to allow for the growth in usage envisaged.

- **Understanding the state and use of the spectrum**, by monitoring its quality and usage. This is important in providing input information in looking at ways to enhance efficiency and in ensuring that the spectrum resource is not becoming progressively more polluted by interference.

The technical R&D programme in overview

Between September 2004 and September 2005 Ofcom spent of the order of £4.94 million on technical research. Ofcom completed five research programmes and started 17 more which will bear fruit in the coming year. At the time of writing, Ofcom has 22 on-going research projects. This report focuses on those projects that had completed by September 2005, or were sufficiently close to completion to allow key conclusions to be drawn out. It also reports on some work recently initiated to give insight into the ongoing programme.

Ofcom does not conduct research in-house but makes use of external resources. During the year Ofcom’s projects involved 40 separate companies. The consortia comprised 14 university departments, 25 private commercial organisations and one government funded research institution. With one exception, all of these were primarily based in the UK. As well as ensuring the best possible team is available to conduct the research this helps an exchange of information and networking across the technical community in the UK.

This report focuses on a subset of our studies which have produced material of particular interest. Final reports of all R&D studies undertaken are available on the Ofcom website\(^1\) and the complete list of the studies which make up the Ofcom R&D programme can be found in Annex A.

The key projects that we are reporting on here are:

- evaluating Software Defined Radio primarily for mobile applications;

\(^1\) Ofcom technology research website. Found at www.ofcom.org.uk.
• evaluating Smart and semi-Smart Antenna technologies for mobile and wireless LAN applications;
• evaluating wireless Mesh technologies for mobile applications, considering whether Mesh can enhance spectrum efficiency and the applications where it can be most beneficial;
• investigating an “enhanced spectrum commons” approach by use of politeness protocols to improve the spectral efficiency of licence exempt devices;
• next generation Unattended Automatic Monitoring Systems for radio monitoring;
• development of novel and existing ideas for the improved sharing of the radio spectrum, considering the applications to which these could be applied.
• investigating ways to improve the spectral efficiency of radar systems in the L and S bands;
• investigating use of the frequency range at 60GHz and above for communications applications, considering combining millimetre wave and optical systems to reduce weather outages; and
• evaluating interference cancellation technology for improved spectral efficiency in communications systems.

The structure of this report
The bulk of this report is structured according to the segmentation set out above, with sections covering the research in each of the three areas of emerging technologies, enhanced spectrum efficiency and understanding the state of the spectrum. In each section an overview of the key research projects undertaken is provided, showing how they fit into possible future uses of the spectrum and drawing out their key conclusions. The final chapter draws together the different strands to discuss overall, how future usage of the spectrum might evolve and resulting future research directions.

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. 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. The consortia who have been engaged in research for Ofcom are listed in Annex A.
Section 3

Emerging Technologies

This section provides a summary of the research Ofcom has conducted into what we judge to be the most important emerging technologies. The technologies impact both on devices, for example mobile handsets and wireless access points, and also on the methods by which we access the radio-spectrum. A common thread running through of many of the research projects in this section is an examination of technology that could improve spectral efficiency. This section first gives a short background to the themes of device technology development, radio access technology developments and demand for spectrum, and then a description of the projects that we have underway in this area.

Device technology developments

Many of the visions for the future rely on wireless devices with much greater functionality than is available today. For example, the ability to provide navigational information and communicate with home, office and travel networks while maintaining basic communications on cellular systems will require multi-modal devices.

At Ofcom the R&D programme is focused on the spectrum-related aspects of such devices. We want to understand how multi-modal devices will develop and what regulatory issues this will raise. We are less concerned with, for example, advances in display technology. While these are critical to enable lightweight functional devices, they are unlikely in themselves to lead to regulatory issues or enhancements in spectrum efficiency.

As a result, areas of key interest to Ofcom are:

- enhancements in device design and implementation that will provide the flexibility to enable truly multi-modal and flexible handsets;
- advances in antenna technology needed to enable much greater data rates to devices; and
- the ability of devices to become better aware of their environments and modify their radio transmission behaviour as a result.

Radio access and network technology developments

Emerging technologies also change the way we access the radio spectrum and network devices together. For example UWB provides a fundamentally different way of accessing the radio spectrum to that available to existing devices with the potential for very high data-rate, short range applications such as distribution of wireless HDTV. Mesh networking potentially allows devices to be networked in an ad-hoc fashion, allowing the coverage of existing planned networks to be extended, or as a means of providing coverage in areas where infrastructure cannot be deployed cost effectively.

Again, Ofcom is interested in the implications for spectrum efficiency and regulatory action that may result in improved use of the spectrum or facilitating technology.
Key areas of interest are:

- technologies, such as politeness protocols, that could help to make the best use of license exempt spectrum, the spectral efficiencies that could be gained and the possible cost; and

**Increasing demand for spectrum**

A common objective in these research studies is enhancing the efficiency with which spectrum can be used in order to support our vision of future wireless devices accessing high data rates in the home, office and outside. Greater efficiency is needed because the high level of demand for spectrum in the ‘sweetspot’ band (Figure 1) ideal for many wireless applications could present a barrier to the high data-rate future wireless communications envisioned.

**Radio spectrum in demand – the sweetspot**

Only a relatively small section of the radio spectrum has the ideal properties for many of the wireless communication applications discussed in this report. There are many technical factors determining the ideal frequency for a particular application. Two significant factors for wireless communications applications are the range of transmissions and the bandwidth of those transmissions. There is a relatively small band of the spectrum where both high data rate and long range requirements can be supported, and hence this area of spectrum, termed the sweetspot, is in high demand. Other factors such as the practical antenna size and device costs for manufacture also influence the choice of this frequency range.

This view of limited spectrum is upheld by a recent study undertaken as part of the Cave Independent Audit of Spectrum Holdings, which produced an analysis of the future demand for spectrum. It suggests there could be considerable demand for additional spectrum below 15GHz to support commercial services (Figure 2). The study ‘base case’ suggests that around 2.5GHz of additional spectrum could be required by 2025. The study concluded that spectrum shortages are likely to be a constraint which could prevent the future optimal deployment and growth of a wide variety of services.
Therefore, in many of our studies we aim to establish whether spectrum can be more effectively utilised or used with greater efficiency through asking questions such as:

- Could existing applications successfully work at higher frequencies, freeing up valuable spectrum in the sweetspot?
- Could spectrum in the sweetspot be more effectively utilised, for example through sharing in this band or through Cognitive Radio access?
- Can the spectrum be more efficiently used to support higher data rates, for example through widespread use of smart antennas?
Software Defined Radio

How does it help?
As we discussed in the introduction, many of the visions of future wireless communications involve devices connecting to a wide range of different networks such as 2G, 3G, WiFi, Bluetooth and perhaps others. They may even involve devices modifying their behaviour, perhaps as they discover new types of network or as home networks add additional functionality.

The ability of devices to work in multiple different environments is often termed "multi-modal" capability. At present this is achieved by incorporating into the handset the chipsets from each of the different standards, for example 3G and Bluetooth. While such an approach works, it is relatively expensive and inflexible and will likely become more so as the range of different wireless technologies grows. An alternative might be for communication devices to be designed more like computers with general purpose processing capabilities and different software for different applications. Such a device could then call up, or download, the appropriate software for the particular communications requirement currently in use. It could also seek new versions of software, or "patches", in the case where changes had been made to the communications technology. Another benefit might be increased economies of scale, with manufacturers producing a single core chipset for the entire world market and then installing software appropriate for each country, or operator.

The underlying architecture needed to achieve this is often termed Software Defined Radio (SDR). SDR is heralded by some as a significant step in the evolution of radio. In the future this flexibility might enable the more efficient use of the available spectrum through rapid deployment of the latest radio technologies. In the longer term, SDR is likely to be an enabling technology for widespread Cognitive Radio, which promises to bring further potentially significant benefits in the effective and efficient utilisation of the spectrum. Cognitive Radio is discussed later in this report.

Ofcom is researching SDR to:

- understand the likely progress of the technology and the limits of what can be achieved as an input to predicting the likely deployment patterns and timescales for new services; and
- examine whether there might be any regulatory roadblocks for such radical new technology.

Explanation of technology
In a SDR some or all of the signal path and baseband processing is implemented by software, normally in the digital domain. Crucially, the low level functionality of the radio in a SDR can be altered through changes to the software, without any physical changes to the hardware. This would be a significant change from current handsets where almost all functionality is embedded within hardware at the time of manufacture. The result of this is, for example, that if a user wanted to upgrade a GSM handset to GPRS or EDGE capability, they could only do this through buying a new handset.

In theory a software defined radio could comprise of an antenna, analogue-to-digital converters (ADCs) and digital to analogue converters (DACs) for conversion of the signal to/from analogue, and the remainder of the radio would simply be software implemented on a flexible processor chip. In reality the existing technology today does not support direct conversion from the antenna signal to digital at the
frequencies of interest (for example greater than 1GHz) and the chips that exist do not yet offer that level of flexibility at the speeds required.

In its simplest form a SDR might emulate the function of a conventional radio transceiver, replacing some or all of the analogue frequency translation, filtering, modulation and/or demodulation functions with software-defined equivalents. An example of this might be the implementation of a stereo frequency modulation (FM) receiver using no more than a high speed ADC, an FPGA and an audio DAC.

Although such a radio could be built today, this example demonstrates a single function application, at a low frequency, operating across a narrow bandwidth and with a single modulation, exhibiting little of the promised flexibility offered by SDR. To achieve the benefits set out at the start of this section, the technology must deliver greater flexibility, including:

- the ability to handle multiple protocols;
- the ability to handle a broad operating frequency range – for example 200MHz to 2GHz or greater;
- the ability to handle multiple bandwidths; and
- the ability to be reconfigured and updated via over the air software downloads

**SDR Technology Today**

A simplified block diagram of a SDR, implemented using technology available today, is shown in Figure 3. An antenna system is required to handle the air/electrical interface. This might range from a single, passive antenna to an array of ‘active’ antennas which are reconfigurable, controlled by software. The interface between the analogue and digital domains is be handled by analogue-to-digital converters (ADCs) on the receive side and digital-to-analogue converters (DACs) on the transmit side.

Due to limitations in these devices and for the foreseeable future at least, the radio frequency (RF) front-end will still have to be implemented in the analogue domain. Once in the digital domain, a SDR might use a device such as a field-programmable gate array (FPGA) to implement certain ‘high-speed’ functions, such as mixing, filtering and sample rate conversion and/or ‘general purpose’ processors or digital signal processors (DSPs) to implement ‘low speed’ functions. The demodulated data are passed to/received from higher level ‘application’ software, as in more conventional radio architectures.

![Figure 3 A block diagram of an SDR implemented with today’s technology](image)
In the long term SDR is likely to be an enabling technology leading to the emergence of Cognitive Radios (CRs), radios that intelligently combine an awareness of the local radio environment with the requirements of the user to reconfigure themselves dynamically, providing the most appropriate and cost-effective communications link possible.

**Key breakthroughs needed to make SDR a reality**

There are a range of technical reasons why SDR systems cannot be economically realised today. Broadly, these relate to insufficiently fast ADCs and processor circuitry and also to antenna complexity. The extent to which these are constraints depends to some degree the desired application for the SDR. For example, SDR technology is now sufficiently developed that early versions are being deployed in mobile communication base stations, where space and power constraints place less demand on the technology and there is less cost pressure to use the cheapest possible chipset. This allows base stations to be upgraded to later releases of standards such as 3G without the need to actually visit the base station and insert a new card. However for the technology to be similarly realised in a mobile terminal significant technology developments are required for example in battery life, chip design and antenna performance.

Ofcom’s initial work in this area has looked into the developments needed in the different technology areas in order to better understand the likely roadmap for SDR, the regulatory implications and any actions required. Our work has highlighted the following issues which will need to be overcome:

- new types of antennas capable of working across a broad range of frequencies while fitting onto handheld devices will be needed;
- the continual increase in the complexity of new standards is making it ever more difficult to realise SDR requiring powerful signal processing devices; and
- the ability to change the behaviour of the handset leads to a range of possible security and type approval issues.

Each of these is discussed in more detail below.

**Antennas**

Devices of the future might be required to work across, for example, DAB systems operating at 200MHz, GSM at 900MHz, 3G at 2GHz, Bluetooth at 2.4GHz and WiFi at 5GHz. Further, they might be expected to adapt to different frequency bands where services might subsequently be introduced. Covering such a wide range of frequencies with a single antenna that has sufficient efficiency is a considerable challenge, since the antenna gain at a given frequency is fundamentally linked to the physical size of the antenna. To exacerbate the problem, SDR handsets are likely to require wideband antennas in physically small footprints, such as those available in mobile telephones.

It is likely that commercial ‘wideband’ SDRs will be initially restricted to operating in multiple, distinct frequency bands, specified at design time. Looking towards the future, antenna solutions have been identified that might be reconfigured dynamically to adjust the resonant frequency, gain and polarisation of the antenna, thus leading towards the realisation of true wideband antennas for SDR applications.
Reconfigurable antenna technology

Reconfigurable antennas can be tuned to different frequency bands, whilst maintaining sufficient instantaneous bandwidth and efficiency within each band. Antennas in this class do not cover all bands simultaneously, but provide dynamically selectable narrower instantaneous bandwidths at higher efficiencies than conventional antenna designs. An example of a reconfigurable antenna is the shorted patch antenna. This type of antenna may occupy an area of a few square cm and be tuneable across a number of bands up to a few GHz.

Figure 4a A shorted patch antenna

Two other examples of reconfigurable antennas are shown in Figure 4b. These rely on changing the antenna shape and size to match it to the frequency of operation rather than electrically tuning it as above.

Figure 4b Dipole antenna with switchable arm lengths (left) & array of switchable diodes to control antenna shape

Reconfigurable antennas are a promising but relatively immature technology, not currently employed in practical radio systems. One particular advantage is that in principle they can maintain constant beamwidth across a wide bandwidth, unlike conventional antenna technologies. This avoids problems with the antennas becoming more directional at higher frequency bands and hence increasingly needing to be oriented towards the transmitter.

When considering the vision of highly flexible, true wideband SDRs, it was concluded that the existing state of the art antenna design is insufficient to realise practical SDR systems. However, emerging, novel antenna solutions and state-of-the-art modelling suites, which allow antenna design to become an integral part of the system design, might provide significant advances in the capabilities of antennas for SDR applications in the future.

Security

Security is a key issue in any wireless communications system. However, SDR introduces some unique security challenges, especially when considering SDRs that can be reconfigured across the air interface. Whilst over the air updates bring
potential security benefits such as ensuring that devices are kept up to date with the latest security developments, there are also concerns which must be addressed. Key amongst these is the possibility that a new software download will cause the device to behave inappropriately. This might be because of a bug in the code, or because of malicious behaviour such as the introduction of a virus. If this caused, for example, SDR devices to move to emergency service bands and transmit at high power levels, the results could be life-threatening. To date, this sort of behaviour is prevented through type-approval mechanisms which ensure that a device conforms to standards. If future, it may be necessary to pre-approve each possible combination of hardware and software and then to ensure that devices are only able to download approved software. This will require regulatory work within the standards bodies that deal with type approval.

Another example of a potential concern is that if a software download were intercepted, an intruder might configure their terminal with the intercepted software and masquerade as the intended user and be able to listen in on transmissions, download software onto unauthorised hardware platforms or make use of services for which the intended user was being charged. To prevent situations like this, user authentication is a key issue in SDR security.

Technologies already exist to enable the secure implementation of SDRs. However, standardisation will be a significant obstacle; it is essential that procedures are standardised to ensure compatibility between equipment and to help simplify the potentially daunting task of managing SDR software. Ofcom is already working within the European bodies responsible for type approval where work items relating to these issues are being considered.

**Device capabilities and operating speeds**

One of the major hurdles for SDR is that very high clock rate chips are required to perform all the real-time processing needed. These processing requirements are currently a limiting factor. Simple multi-band and multi-mode systems have been demonstrated using SDR, implementing for example mobile and wireless LAN and PAN standards. However some of the newer standards, such as 802.11a, are more complex and have yet to be fully implemented on SDR platforms. At present, such complex standards can only be fully implemented on ASICs.

New wireless standards are continuously evolving in complexity to support higher data rates through supporting techniques such as beamforming and MIMO. Since new standards are ever more complex than the old ones, the processing capabilities needed are continually rising, perhaps faster than Moore’s law enables devices to improve. If this continues SDR functionality may never “catch up” with evolving standards.

Even if the processing speed needed can be achieved, power consumption is likely to be a significant hurdle to the widespread adoption of SDR technology in handset design. High speed devices tend to require high levels of battery power, yet battery capacity is currently only improving slowly.

Hence, in conclusion, these factors may restrict SDR to a subset of standards, or to a subset of platforms, for example laptops, or there may actually be a mix of ASICs and DSPs utilised to provide multi-modal capability.
Conclusions, timescales, role of technology
We started this section on SDR by noting that SDRs might simplify the implementation of multi-modal devices and bring additional flexibility by allowing patches and enhanced functionality to be downloaded to the terminal. We also noted that SDR might be an enabling technology for Cognitive Radios and perhaps other advances in spectrum usage.

However, we then showed that there are many issues with the implementation of SDR including the difficulties in implementing antennas, in the speed of chipsets, in the battery power required and in the cost, particularly of handsets. This leads us to conclude that SDR will be gradually implemented, starting with devices able to download minor protocol changes, likely around 2008, through the devices able to make major changes to the radio solutions they deploy around 2015.

Even by 2015, completely flexible operation is not likely due to fundamental limits in the antennas that may be deployed on terminals relative to the wide range of frequencies different radio standards occupy. It is more likely that SDR handsets will be designed to be configurable for groups of applications with similar antenna requirements.

The strongest commercial drive towards SDR would appear to be for base stations by the network operators. The advantages include the prospect of more ‘future proof’ equipment and the potential ability to rapidly introduce new technologies and the latest services. There are advantages also for the manufacturers of network infrastructure equipment to adopt SDR technology, such as the potential to get products to market faster, and continue development, fixing bugs and adding new features, post-manufacture. The group with perhaps the weakest drive towards SDR is that of the handset manufacturers. The factors that tend to drive the design of the latest handsets (for example size, weight, power consumption) generally conflict with the characteristics of current SDR technologies. The push for SDR handsets will need to come from the improved multi-modal capability that is available.

Regulatory issues must be carefully considered with the introduction of radios that can be reprogrammed after manufacture. In a SDR, the characteristics of the transmitted waveform are defined in software, as are the structure and formatting of the physical and logical channels. Changes to the software have the potential to modify the characteristics of the transmitted signal and the interoperability with other users. This is the subject of further work within international regulatory bodies.

Overall, this research has suggested to us that the emergence of SDR will take some years. This would imply that:

- the development of new standards or upgrades to existing standards will continue at its current pace, often being constrained by device replacement timescales; and
- approaches to transmission which might use SDR as an underlying technology, such as Cognitive Radio, will either take some time to emerge or will need to seek an alternative technological platform.

Because of these timescales the regulatory implications are unlikely to be immediate. Nevertheless, we will continue to work within European bodies in order to progress more flexible type approval regimes that can be used with SDR when it eventually emerges.
While there is much research and development work required within industry, this work has not revealed any obvious areas for Ofcom to conduct further research into SDR. We will continue to monitor developments against the timescales and roadmaps set out in the full report on SDR and periodically reappraise whether there is any need for us to conduct further research.
**Smart Antennas**

**How do they help?**
Smart antenna technology has the potential to significantly increase the efficient use of the spectrum in wireless communication applications in comparison to the existing methods in use. Through intelligent control of the transmission and reception of signals, capacity and coverage in mobile wireless networks can be significantly improved.

Ofcom is researching this area to:

- identify the key obstacles to the development of widely deployed smart antenna systems, and understand the breakthroughs needed to overcome these;
- identify the areas and applications for which smart antennas will most likely be first deployed; and
- analyse the regulatory issues involved in smart antennas to inform our regulatory stance.

**Explanation of technology**
The simplest form of antenna simply radiates the communications signal in all directions equally.

**Smart antennas – spatial diversity for improved spectral efficiency**
The ability to distinguish between users in a communications system is essential. The most common multiple access schemes currently employed are frequency division multiple access (FDMA), time-division multiple access (TDMA) and code-division multiple access (CDMA). These schemes separate users into the frequency, time and code domains, respectively, giving three distinct degrees of diversity.

A smart antenna system can be used to add increased spatial diversity (sometimes referred to as SDMA) to reduce interference between users and consequently increase user capacity through dynamic adaptation of the antenna's radiating properties. Through directing the antenna beam precisely at the user the transmitted power is efficiently used in comparison to a sectored antenna, and the interference situation reduced.

**Figure 5a TDMA (left), FDMA (centre), CDMA (right)**

**Figure 5b Sectored operation (left) versus smart antenna (right)**
This is wasteful in that only a small amount of the signal reaches the intended user and furthermore the signal radiated in other directions can cause interference to other users.

An improvement on this situation is to use a sectorised approach at a base station where the 360 degrees of coverage is split into for example three sectors of 120 degrees. Each sector is served by an antenna which focuses the radiated signal across just its 120 degree sector. This leads to an increase in the frequency reuse and therefore the efficiency with which the spectrum is used, leading to a higher capacity network. This is the current scheme in use in most mobile networks.

A further refinement would be to use antennas with highly focused beams which are narrow enough to be directed at a single user. Although these beams would now need to be constantly redirected if the user is moving, this would lead to a highly efficient use of the radio spectrum. This is one of the major drivers behind smart antennas. The second significant driver is that as well as directing the beam toward the intended user, the technology also allows interference from unintended users to be suppressed.

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**Smart antennas – beamforming**

A phased array antenna comprises an array of separate radiating ‘elements’ whose signals, when added together, form a beam. Flexibility and control over the beam shape is achieved through the beamforming process by altering the amplitude and phase of the individual elements.

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**Figure 6 Sectored operation (left) versus smart antenna beamforming (right)**

Phased arrays provide maximum signal in the wanted direction through steering the main beam in a chosen direction whilst ‘nulls’ can be steered in the direction of unwanted transmitters simultaneously. Thus, the antenna can be adapted to give high sensitivity to the signals received from one user whilst suppressing those from other users.

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**Current state of the art and our research**

The underlying techniques of smart antennas are not new. Adaptive antennas have been utilised for many years, notably in the defence domain in radar and sonar applications. However low volume production has required bespoke signal processing and antenna equipment to be constructed for these applications generally at great expense. Commercial drivers generating significant advances in for example processing power and antenna technology are now bringing this technology closer to being commercially viable in the near future for civil communications applications.
However there are a number of issues that are hampering widespread adoption of smart antenna technology into current and near term systems. Broadly these fall into technical, standardisation and business issues.

**Technical**

The incorporation of antenna arrays in wireless systems is a formidable technical challenge on its own. On the base station side, space and other hardware constraints limit the number of antennas than can be supported. Each extra antenna requires its own RF chain resulting in the associated cost of extra power amplifiers, cabling, synchronisation / calibration units, and other hardware. Furthermore, the processing of the signals prior to being sent from the antennas requires new ASICs (Application Specific Integrated Circuits), which, besides their complex design, add to the power consumption and real estate requirements of the base station.

The most challenging case for smart antennas is mobile handsets which tend to become ever smaller and cheaper, leaving less and less space for antenna arrays. Smart antennas work best if the antenna elements receive signals that are as different from each other as possible. This is achieved by spacing the antennas some distance apart. Clearly, as handsets become ever smaller, the ability to space antennas apart decreases. The use of new materials and cross-polarised antenna patterns, and the invention of sophisticated embedding techniques will be crucial in allowing the incorporation of antenna arrays in mobile handsets.

**Smart antennas and MIMO**

MIMO processing uses multiple antennas to increase the data capacity of a wireless channel. A data-stream is split into two or more smaller streams, each of which is radiated through a separate antenna. Multiple data-streams are transmitted through the same channel that would ordinarily be used for just a single data-stream. Signals from each of the spatially separated transmitter antennas follow multiple routes, termed multipath, to the receiving antennas where they are recombined using complex processing to form the full capacity data-stream.

![Figure 7 MIMO schematic](image-url)

The success of the increased data capacity of a MIMO system is dependent on the spatial separation of the antennas, and thus there are practical difficulties with small platforms such as mobile handsets.

**Standards**

Standards issues also represent a significant hurdle. Standards bodies have been slow to adopt multiple antenna technologies due to the complex technical and practical issues involved and the difficulties in reaching a global consensus amongst major players.
Business

Finally on the business and market side, the translation of the technical advantages of smart antenna technology into financial profits in the market place remains a challenge. Broadly, to date, the additional cost of smart antennas has been greater than the benefits achieved in terms of increased revenue from more efficient spectrum usage. Further complexities in the business case exist such as the timescales for adoption of new mobile handsets that are required for the new technology.

Our work in the area of smart antennas is split into two strands:

- an investigation into the conventional notion of smart antennas, i.e. beam switched and adaptive beamforming approaches, looking at the factors impacting on widespread deployment of the technology, the likely applications; and
- an investigation into a ‘semismart’ antennas approach which looks at a cost effective method of adapting the sectorised coverage of base stations, rather than beamforming to direct pencil beams at mobile handsets.

Smart antennas

Here we have investigated the potential gains available and the impediments to widespread adoption. The work undertaken has considered a range of wireless systems to determine those for which adaptive smart antennas are most suited, and those for which alternative approaches would be more appropriate. A number of general conclusions have been drawn from this, in particular, that adaptive smart antennas are best employed in relatively low multipath, interference limited environments, where their ability to direct both beam and nulls give the greatest system benefits.

Adaptive smart antennas have been trialled and implemented commercially, but usually within large infrastructure systems, such as mobile telephone base stations. Even here, the physical size and cost of the antenna systems are clear concerns and tend to:

- limit the number of elements in the antenna array, each of which are spaced nominally at half wavelength intervals; and
- make higher frequency systems more attractive, where the wavelength is shorter and so antennas can be both smaller and mounted more closely.

A consequence of a small antenna is that it would only be able to produce a relatively broad beam and nulls. The number of array elements also limits the number of nulls that may be independently steered towards interfering sources.

A prototype IEEE802.11a wireless LAN has been constructed to understand the benefits a smart antenna approach might bring when antenna size is limited. Here using an adaptive antenna with beam steering would improve the range, encouraging more usage, and relieving the congested 2.4GHz band. As the number of users increases, interference would be controlled by the null steering capability.

Initial estimates suggest that providing the additional functionality would add a few dollars to the cost of the chipset in production. The demonstrator employs an array of four elements, each being connected to a downconverter and I/Q detection stage. The type of element and array geometry may be chosen to suit the installation. At present a square array of dipole elements is used, providing 360° coverage.
adaptation is performed by applying phase and amplitude weighting to minimize the errors in known training data.

Figure 8 shows the prototype hardware. Construction of the prototype is complete and performance evaluation is underway.

![Prototype 802.11a access point adaptive smart antenna](image)

**Figure 8** Prototype 802.11a access point adaptive smart antenna

**Semi-smart antennas**

As discussed above, there are many difficulties still facing the deployment of smart antennas. Because of this Ofcom is also supporting investigations into a different approach which promises to bring some of the benefits but with a reduced complexity. The approach is based around using the antenna to optimise sectored coverage rather than developing a narrow steerable beam.

![Semi-smart antenna base stations co-operatively adjusting coverage to cope with traffic demand](image)

**Figure 9** Semi-smart antenna base stations co-operatively adjusting coverage to cope with traffic demand

This approach is of much lower complexity than conventional smart antennas and has a minimal impact on the cellular system architecture. The term semi-smart antenna has been coined to denote its inherent low complexity. The basic idea behind the proposed load balancing scheme is to shape cellular coverage according to the traffic needs. The traffic demand of the heavily loaded cell is decreased to
match the available capacity by contracting the radiation pattern around the area of the peak traffic, while adjacent cells expand their radiation patterns to compensate for coverage loss as shown in Figure 9. Semi-smart antennas provide the required coverage shaping capability.

Figure 10 shows a considerable capacity improvement is achievable when using four antenna elements instead of one. Adding more elements has shown little improvement in comparison to the four elements. The primary system level simulations (using the load balancing strategy) have shown capacity improvements of around 20% in the uplink and 5% in the downlink.

In contrast to other approaches where smart antennas are employed, in this approach the only knowledge required is the location of clusters of mobile users, and the traffic load and capacity of each cell. Invariably the movement of clusters is much slower than the movement of the individual mobiles, and the wide azimuth antenna beams used make the system relatively insensitive to the speed of movement of individual mobiles. Since only the location of mobile clusters must be determined – rather than the location of the individual mobiles – a much longer update period (typically 30 seconds) can be used between pattern changes than is required to steer pencil beams to individual mobiles. The significance of the longer update period is that it greatly reduces the requirements on the hardware implementation of the semi-smart antenna; there is not only less data to handle, but it can be processed more slowly with no loss in performance.

**Conclusions, timescales, role of technology**

Future mobile communications systems are likely to demand much greater capacity. This must be delivered in a highly congested area of the radio spectrum. With many systems running close to their theoretical limits on performance, utilizing the
capabilities of smart antennas offers the prospect of performance improvements without placing more demands on the spectrum.

Various smart antenna techniques may be used, including adaptively formed beams, multi-antenna diversity (such as MIMO) and the semi-smart approach. To some degree these approaches are complementary, some being most appropriate for large, costly infrastructure systems, others working best with various degrees of multipath.

In the case of mobile handsets smart antennas offer increased capacity. However smart antenna deployment looks complex and expensive for handsets, with an uncertain business case at this stage.

For the wireless LAN application where the size, power and processing complexity constraints are relaxed, access points with smart antenna technology have a stronger business case and indeed early versions are now available on the market. A low cost solution system could comprise only a small number of antenna elements, since the requirements for fidelity, parts count and processing load are comparatively small. However such a system has a more limited interference cancellation capability. Further work will determine whether such an antenna would offer significant system improvements at low cost, though the business case looks strong for beamforming smart antennas in the near term. This would produce useful benefits in the future for unlicensed spectrum which faces increasing demand and thus interference.

A semi-smart approach applicable to both mobile base stations and to wireless LAN access points might provide some useful, though smaller, gains in spectral efficiency. Capacity gains of around 20% for uplink have been shown using this approach. This approach has a reduced complexity and associated reduction in cost, providing a more substantial business case in a three to five year timescale.
Cognitive Radio

How does it help?
Investigation of spectrum utilisation suggests that not all the spectrum is in use for all of the time. Cognitive Radio (CR) is one technology which offers the potential to make efficient use of this unused spectrum, potentially allowing large amounts of spectrum to become available for future high bandwidth applications. The long term vision of Cognitive Radio technology is one in which handsets would automatically make use of underutilised spectrum across a broad frequency range, allowing the high bandwidth requirements of the future set out in our vision to be realised.

Although the technology holds much promise, it is a radical departure from the existing methods of spectrum regulation. Complications exist from both a technical and a regulatory standpoint with the introduction of this new technology. On the technical front, the “hidden terminal problem” must be overcome to ensure that primary users of a band are protected from interference. On the regulatory side consideration must be given as to the most appropriate mechanisms to allow CR. These issues were discussed in our Spectrum Framework Review published in 2005.

Over the coming year we are undertaking a study to investigate the issues surrounding introduction of CR technology and to develop a simple demonstrator system. The study will address areas such as:

- identifying applications which could potentially share or partially share spectrum (in space and/or time);
- quantifying the gains in spectrum efficiency and utilisation that would result from the CR approach, and estimating the increased level of activity possible and the consequential economic benefit;
- considering the regulatory impact of CR and what actions could be taken to facilitate deployment and maximise the benefits of the technology; and
- identifying simple, low cost, and potentially nation-wide control mechanisms which can be easily adapted to today’s deployed technologies.

Explanation of technology
A Cognitive Radio system could enable devices to operate efficiently in multiple different frequency bands of the radio spectrum, including those with existing users. Such a radio would hop into unused bands of the radio spectrum and quickly hop out again if a primary user of a band required that spectrum.

Most of today’s radio systems are not aware of their radio environment - they are designed to operate in a specific frequency band using a specific access system. A Cognitive Radio senses and understands its local radio environment to identify temporarily vacant spectrum to operate in. This ability in principle allows Cognitive Radios to coexist with primary users of a band. CRs can stop transmitting when the primary user requires access to the spectrum, potentially switching to a different band to provide continuous service.
The hidden terminal problem
A cognitive radio user might make a measurement and not spot any activity on a piece of spectrum. However, there might be a legitimate user of that spectrum behind the next building, transmitting to a tower on the hill. Because the building is between the users, the cognitive radio user does not receive the legitimate signal and so concludes the spectrum is unoccupied. But because both users are visible to the tower on the hill, when the cognitive radio user transmits its signal it is received as interference at the tower.

This problem is solved by the tower on the hill transmitting a signal indicating whether the spectrum is free. A terminal then requests usage of the spectrum, and if granted, the tower indicates that the spectrum is busy. Such an approach works well but it requires central management by the owner of the band. Hence, it becomes a choice of the owner of the spectrum as to whether they wish to allow this kind of access and if so under what conditions.

A CR has three broad inputs:

- an understanding of the communications requirements of its user;
- an understanding of the radio frequency environment in which it is operating; and
- an understanding of the various network and regulatory policies which apply to it.

The CR can then make autonomous decisions about the means by which it accesses spectrum. By using this autonomy, and reacting dynamically to changes in any of the three inputs, a Cognitive Radio might make efficient and flexible use of the available spectrum.
Spectrum Utilisation

Studies undertaken by Ofcom have investigated the usage of the radio spectrum. These measurements appear to indicate that there are many areas of the radio spectrum which are not fully utilised in different geographical areas of the country.

Figure 12 Spectrum occupancy measurements in a rural area (top), near Heathrow airport (middle) and in central London (bottom)

There are some caveats which must accompany the figures, for example some low level signals may not have been picked up and thus activity levels will be indicated as lower than is truly the case. Nevertheless, such measurements indicate the potential gains that might be accrued from a system which was able to sense its radio environment and utilise it effectively.

Current state of the art and our research

CR is an emerging technology. Currently there are no systems in wide deployment employing the technology, although some early demonstrations of the technology have been built and some existing systems such as DECT cordless phones make use of much simplified CR principles.

Our research in this area will establish the likely timescales for deployment of practical applications employing CR technology, bringing together the existing work in the different underpinning technology areas such as wideband antenna development and SDR.

Conclusions, timescales, role of technology

Our studies in this area are just commencing. We thus have no firm conclusions at this stage. However, the work undertaken into SDR suggests flexible, multi-protocol, multi-band Cognitive Radio systems are some way off yet. Handsets for example employing this technology successfully seem unlikely inside a 2010 timescale.

In the interim therefore we conclude that there is the possibility of specific band sharing technologies emerging, which in technology terms are a stepping stone towards the full CR vision which allow some specific instances of spectrum sharing. These are likely as the incumbent operators who are not making full use of their spectrum resource realise the financial benefits that may be accrued in a liberalised spectrum market.
Understanding the timescales, the progress being made in addressing the technical hurdles, and the regulatory action that can be taken, for example investigating the benefit of allocation of bands to CR technology, are all important to ensure Ofcom has an informed basis on which to make decisions regarding this technology.
Ultra Wideband

Ultra Wideband (UWB) is a promising technology in the short range or PAN domain. It promises very high data rates which will support a wide range of applications, for example the wireless distribution of high definition TV around the home.

UWB as a technology is well developed and has already been regulated in the US by the Federal Communications Commission (FCC). It has already been the subject of a consultation document by Ofcom, considering its introduction in the UK and a number of studies have been undertaken and are underway to establish the impact introduction of UWB may have to various specific existing services, such as FWA, 3G and radio astronomy. These have included an assessment of:

- the economic value of UWB to the UK;
- the impact of UWB on BFWA;
- the impact of UWB on the 2.5-2.69GHz band; and
- the impact of UWB on radio astronomy.

These are available on the Ofcom website.

As the technology is relatively close to commercial reality we have not considered it further here, although as a theme it features in several of our R&D studies, for example the AIMS project discussed later which aims to measure the quality of the spectrum over a number of years and monitor the impact of technologies such as UWB.
Mesh networks

How do they help?
Mesh networks have the potential to bring several advantages to wireless communications services, namely:

- they can allow the formation of a new type of network where users exchange information without the need for network infrastructure. As well as allowing a different commercial model it is often claimed these are more spectrum efficient; and
- they can extend coverage of cellular and other networks by allowing terminals on the edge of the coverage zone to relay signals to those who do not have coverage.

An often quoted vision of mobile communications describes the future as the integration of all mobile and wireless nodes (for example cellular, WLAN, PAN etc) with an IP core. One potential application of Mesh technology would be to provide another route, alongside WLAN and 3G etc, into such a core network.

Ofcom is researching Mesh networks to:

- identify the theoretical determinants and metrics of spectral efficiency for both high frequency (line of sight) and low frequency (non-line of sight) Mesh systems;
- investigate the capacity constraints of Mesh networks and examine the hypothesis that for a mobile Mesh the more consumers who use a service, the more capacity the network has;
- investigate whether Mesh systems have any regulatory impact, for example would the wider use of Mesh systems imply that there should be more licence exempt spectrum?; and
• examine the key problems in the delivery of fixed and mobile Mesh systems, understand what is required to resolve these and what the timescales for widespread adoption of Mesh might be.

Mesh Attractions
Perhaps the largest attraction of meshes is that they can be entirely unplanned. This is useful to the military and to disaster recovery teams who desire this ad-hoc networking capability for fast deployment and flexibility in situations with little fixed infrastructure. It is less clear what this benefit brings to the roll-out of a mass market mesh network, although for a service provider or regulator, the lure of a network which promises no planning phase must be high and thus merit investigation.

Another strongly attractive feature is in coverage, where they can offer complimentary performance to that of cellular systems. Meshes have the ability to provide coverage in cluttered environments such as the urban environment. A chain of mesh nodes can ‘hop’ around corners in an urban environment in a way the cellular point to multi-point systems cannot.

Figure 14 Cellular versus mesh networking coverage. (a) Cellular blast through and over approach, (b) Mesh hopping around approach

Explanation of technology
In a Mesh network every user connecting to the network acts as a node, relaying information for other users as well as transmitting and receiving its own data. In this way information can be transmitted from one user to a distant user via multiple hops through the other users.

Figure 15 Communication through a wireless Mesh network

Such a network can contain just a few nodes or potentially thousands of nodes exchanging data. An example might be a home network where all devices (such as laptops, TVs, DVD players and MP3 players) are able to communicate or an entire office WLAN.
Mesh networks can be broadly categorised into two types, defined here as “extra-Mesh” and “intra-Mesh” depending on whether traffic stays within the Mesh or flows out into other networks.

Clearly, the vast majority of traffic which is of commercial significance to network / service providers today would be classed as extra-Mesh traffic, with an interface to the public telephone network and the internet. It should be noted that even in the case of intra-Mesh traffic, there may be associated network management and/or billing traffic which must flow to a Management Centre and so is extra-Mesh. Thus, in practice one is very likely to always require a hybrid architecture supporting intra- and extra-Mesh traffic types to varying degrees. Hence within the area covered by a Mesh there would be Access Points providing a route to the infrastructure resources.

Some application examples of Mesh are listed below. All but the first two are access Meshes rather than pure Meshes, since they require external network access. It is important to note that much published literature addresses only the isolated pure Mesh case.

- Military, emergency and disaster relief activities which cannot depend on infrastructure.
- Sensor networks
- Hotspot extension of urban public wireless access
- Rural Community Networks Lecture hall or convention hall networks
- Integrating PAN devices (for example PDA phones) into the WAN
- Home networks

**Current state of the art and our research**

Mesh networks have existed for some time in military applications where deployment of infrastructure is not possible. Here Mesh networks offer an ad-hoc network for battlefield communications and sensing which can be quickly put up and pulled down.

The technology is now beginning to be adopted to provide commercial wireless services. Commercial systems are now available for provision of city wide broadband wireless access using Mesh WiFi technology. Systems exist in several US metropolitan areas to provide municipal low cost broadband services or in some cases for improved communications for emergency service crews.
One of the most important claims made for Mesh networks is that they provide a greater capacity for a given amount of radio spectrum than a conventional network. The reasoning is usually along the lines of *each new user brings additional capacity to the Mesh*, or *each new user effectively becomes a base station*. The difference between network capacity and the user throughput here is important. Statements such as these need critical examination to understand the true benefits in likely applications, separating the practical reality from the ‘something for nothing’ type of mythology.

The work we have commissioned in this area is addressing questions such as:

- Are Meshes more spectrally efficient than alternatives?
- Can Meshes enable the use of higher frequency bands, and/or support services-types that alternatives cannot?
- Are Meshes practical, and what are the enabling technologies?

Our work in this area will cover both fixed and mobile Mesh applications. The work presented here concentrates on mobile Mesh applications, though some of what is said will apply to the fixed case also.

The work has shown that in discussing the performance of Mesh systems care must be taken since the type of Mesh used and its application can lead to very different conclusions regarding the performance that may be expected.

**Capacity and scalability - Do customers self-generate capacity in Mesh?**

There are huge attractions to having ‘self generation of capacity’ in a radio network. Notably, that the network is self-sustaining and that it could avoid the so-called ‘tragedy of the commons’. Such a tragedy relates to the days when common land was used for the grazing of livestock with free access for all. The danger is that free access to a finite resource can result in that resource being fully consumed or compromised further such that it loses its usefulness to all. What then, if each user were somehow to add grazing capacity as they joined the common?

The hypothesis that in a Mesh network the subscriber base self-generates capacity is crucial for understanding the likely applications and performance of Mesh systems. To establish whether this hypothesis is valid in practical applications, four published approaches supporting this standpoint have been reviewed. Each presents a
coherent argument based on its stated assumptions, however those assumptions do not translate well to practical applications. The assumptions were:

- unbounded latency for network traffic;
- unbounded requirements for spectrum; and
- confinement of nodes into localised groups in a large Mesh.

These assumptions place a significant limit on the applicability of the self generating capacity.

The work has concluded that for a pure Mesh, subscribers cannot self-generate capacity at a rate sufficient to maintain a target level of per-user throughput regardless of network size and population. The only viable ways scalability can be achieved are by providing additional capacity either in the form of a secondary backbone (fixed) Mesh network – so forming a “Hybrid Mesh”, or an access network – so forming an “Access Mesh” as shown in Figure 16(b). In these two configurations scalability is possible and has similar characteristics to that of a cellular network.

![Figure 18 Hybrid Network: Intra-Mesh traffic with Infra-structure support](image)

The conclusion from the work undertaken is that Meshes have no especially good properties with respect to scaling. In particular as node density and geographic size increase, the traffic rate available to any particular user decreases. The implication of this is that Mesh networks should not be chosen over cellular networks on the basis of capacity alone.

This work shows that this lack of scalability can only be overcome by either adding additional capacity in the form of a hierarchical network or containing the end-to-end traffic flows to localised regions within the network.

All current theory and measurement of ideal, novel and practical Meshes conclude that ad hoc Mesh networks comprising only peer-to-peer communication links do not scale well with increasing node population unless there are specific limitations on the density of nodes, the propagation environment and the traffic models.

Additionally there exist practical MAC and routing challenges which further push for Meshes which have a low hop count – and hence localised traffic flows.
Underlying causes of limited capacity

Transmissions from nodes in a mesh extend beyond the wanted range to a wider ‘interference zone’, as shown below. Other nodes wanting to communicate within this interference zone must use other elements of time/bandwidth resource. Given that this is a finite resource this can lead to bottlenecks in communications across these interference zones, particularly as node density rises.

![Figure 19 Mesh node interference (each colour represents a different frequency channel)](image_url)

Clearly it is advantageous to keep this area, shown as small as possible. This confirms the conclusion of other researchers that short hop lengths and high propagation attenuation factor are conducive to high throughput capacity of the network.

Spectral efficiency of mesh networks

There is a theoretical basis on which Mesh networks can be more spectrally efficient than point to multi-point (PMP) systems. However the work undertaken has brought together practical issues with the theory and concludes that there seems little reason to believe that practical Meshes will be intrinsically more spectrally efficient than traditional PMP networks and that any preference for implementing a Mesh should be based on other benefits such as coverage or lack of infrastructure.

It should be noted that it is difficult to answer such a hypothesis without consideration of the details of the system. For example there are many possible deployment scenarios varying in range, numbers of subscribers, traffic flows etc. Additional complexity arises from the fact that real systems comprise not just a topology, but a whole range of components such as protocols, radios, antennas etc. Consideration of just one element may be misleading. A particular case in point is the use of directional antennas: some deployed Mesh systems claim great spectral efficiency but this efficiency arises solely from the use of highly directional antennas rather than the use of the Mesh architecture per se.

Mesh vs Cellular: A comparison of spectral efficiency

To exemplify some of the spectral efficiency issues the work has compared a cellular system to the ‘Access Mesh’ in which all traffic flows to/from some central gateway, applicable to the majority of commercially significant applications (for example telephony, internet access).

If deploying a cellular system the approach would be to site a base station at some appropriate central position with enough power/sensitivity to meet the required objectives. If a fixed rate service is offered (for example a GSM call) then the worst case users, those furthest from the base station in terms of path loss, set the link...
budgets. The data rate put through the channel (or alternately the width of the channel) is dictated by this worst-case link budget. The spectral efficiency can then be simply calculated as user bit rate per channel bandwidth per unit area of cell.

Now consider the introduction of hopping, i.e. a Mesh system. In principle the worst that can be done is the same as the cellular system, since it can default to a one hop service to all users. In fact users near the base station or access point it will probably use a single hop. For further away users, however, it is possible to improve the delivered bit rate by transferring the data in a number of hops. A simplistic argument concludes that overall this implies that twice as much data can be transferred using two shorter hops, see Figure 20.

![Figure 20 Two hops versus one hop data rate improvement](image)

Within limits, theoretically, the more hops used the greater the improvement. It follows therefore that higher bit rates can be delivered to the more remote users in the area of coverage, and thus the spectral efficiency will be increased relative to a cellular system.

However, practical issues have a severe impact on the above conclusions:

- in general the hops won’t be of equal length, nor will they form a straight line, causing increased overheads associated with the routing and an increased path-length, requiring greater transmit powers. If the distribution of users is ‘clumpy’ rather than even then this will exacerbate routing problems;
- the theoretical quadrupling of data rate assumed will not hold if higher order modulation schemes are used; and
- the introduction of hopping brings a requirement for routing, even leaving aside the need for route discovery; this adds an overhead that will diminish spectral efficiency.

Perhaps the most significant practical issue relates to link budgets. The theoretical argument above implicitly assumed that node-node links have similar link budgets to node–base station. In the case of a mobile service this is most emphatically not the case. Handset to handset communication is greatly disadvantaged relative to base station to mobile communication in the following ways:

- being closer to the ground the signal will propagate less distance;
- the antenna systems of a base station/access point can have a higher gain those of a mobile due to the usually more relaxed size constraints; and
- base stations can operate with less regard to power consumption compared to mobiles. This allows them, for example, to use modulation schemes such
as high order QAM that can carry many bits/Hz but that demand highly linear, and thus power-hungry transmitter amplifiers.

The aggregate effect of these differences means that the range of mobile to mobile hops will be much less than that of the base station to mobile links for the same transmit power, receiver sensitivity, and channel bandwidth. This means that several mobile-mobile hops are required just to regain parity with the capabilities of a more powerful base station.

A simplified analysis of an example case comparing the above telephony example for the cellular and Mesh cases suggests that the spectral efficiency of the access Mesh is around a third of that of the cellular case. The implication is that the Mesh is not particularly suitable for a service such as telephony on the basis of spectral efficiency alone.

As a final point: whilst the capacity of a cellular system can within limits be expanded post-deployment, Mesh systems are less flexible. For a Mesh, the network capacity is a function of the capability of the nodes. Operators/suppliers must therefore take a view at deployment time as to the long term subscriber density and desired services and issue nodes that can support these. As performance depends on the subscriber's equipment it cannot be easily upgraded as required. It follows therefore that nodes may have to be substantially over-dimensioned from the outset - with associated R&D and product cost implications.

**Do directional antennas bring benefit to Mesh networks?**
Utilising higher gain antennas are postulated as a mechanism for increasing spectral efficiency due to reduced mutual interference and hence greater spatial reuse of frequency. This is the primary mechanism which is in use for increasing the spectral efficiency of fixed Mesh networks.

Network capacity can be improved through the use of directional antennas. However for handheld devices the extent of directionality (beamwidth) is limited due to the product’s small physical size in relation to wavelength. But, more significantly, the high sidelobes levels associated with such small antennas (coupled with degradations due to body effects etc) severely limit the improvements in spatial reuse that would otherwise be possible.

Primarily because of the sidelobe problem, the potential gain in spatial reuse offered by directional antennas diminishes with high propagation losses such as are found in an urban environment. Considering the propagation environment likely for urban applications: theoretical gains of circa \( x^3 \) are likely to reduce to \( x^2 \) because of antenna / RF practicalities, and are likely to be further reduced to possibly little more that \( x1.5 \) when MAC and control issues are factored in.
**Increasing antenna directionality for mobile handsets**

If we consider an idealised antenna (having negligible side lobe responses) we have a simplistic interfering / non-interfering alignment of beams as illustrated below.

![Interfering and Non-interfering beams](image)

**Figure 21 Interference model for directional antennas**

For a network of randomly deployed nodes equipped with such antennas, the theoretical upper limit on the improvement of throughput capacity is as large as $4\pi^2/\alpha\beta$. (where $\alpha$ and $\beta$ are the beam widths of the transmit and receive antennas respectively).

For mobile/hand-held products in the bands of interest here (vis below 6GHz) the minimum achievable antenna beam width is likely to be in the region of 90°, giving an upper bound on capacity improvement from the idealised antenna of 16. However, for any practical antenna, and more-so for mobile/hand-held products in the bands of interest here (0.5-3.5 GHz) there will be finite side lobe responses which will seriously erode the above potential gains.

Considering the practically likely case for a mobile handset of 90° beam widths with -13dB side lobes this implies a capacity gain in the region of x3.3 compared to the theoretical gain of x16 for the zero-side lobes case. As beam width is reduced the side lobe level dominates performance, thus indicating that there is little benefit in decreasing beam width without equal attention to reducing side lobe levels.

**Conclusions, timescales, role of technology**

Our work in this area addresses the role that Mesh networking will play in support of our vision of future wireless devices providing high bandwidth connections at home, in the office and outdoors.

The work concludes that Meshes work best for the scenario of connections to extra-Mesh services such as the telephone network and the Internet. This type of Mesh will support applications such as extending hotspots to wider areas, provision of broadband networks and internet to rural communities, or provision of wireless networking at lecture halls or conventions.

Such Mesh networks therefore will require infrastructure for deployment in the form of access points to connect to the external network. The work concludes that Mesh networks can scale and provide a sustained level of service as new users join as long as the density of such planned access points is kept sufficiently high. This represents a form of ad hoc network in that users may join in an ad hoc manner, but the infrastructure itself must be planned and scaled, very much like cellular networks. Such Meshes will not be as quick to deploy as pure intra-Meshes, however will still be quicker to install than any new wired or cellular system, so will still have clear benefits as an alternative in some applications. An example application might be deployment to cover a new industrial park or a temporary conference event. Thus we
view Meshes as likely to play a role in our vision of increasingly mobile communications, supporting the ability for mobile devices to increasingly connect to broadband networks at any location.

For a pure Mesh network where there is no infrastructure to provide connections to external networks such as the internet, the benefits of rapid set-up and tear down are accrued. It is in this area that Meshes were originally used in defence applications and are likely to find further application in emergency service operations where planned infrastructure is unavailable. However, for this type of pure Mesh subscribers cannot self-generate capacity at a rate sufficient to maintain a target level of per-user throughput regardless of network size and population. Thus this type of Mesh is unlikely to find widespread commercial application.

The work has shown that Meshes are not an improvement in spectrum efficiency in practical cases in comparison for example to cellular networks. Improvements in spectral efficiency of a Mesh network can be made through the use of directional antennas, however this is likely only to be available to fixed Mesh applications. In the mobile case small handset sizes preclude the benefits of spectral efficiency.

Improved utilisation of the spectrum is possible however since many of the applications for Mesh networking can be efficiently deployed at the higher frequencies outside of the congested high demand spectrum.
Enhanced Spectrum Commons

How will it help?
In our vision of how devices might be used in the future, licence-exempt spectrum plays a key role. It could be used for WiFi networks, in the airport for example, for short range communications such as paying for the coffee, for linking devices together, such as synchronising communicators and laptops, and much more. However, the growing popularity of licence-exempt spectrum might eventually lead to increased interference and eventually limited usefulness – the so-called “tragedy of the commons”. This project is looking for ways to avoid this outcome.

Through specification of some rules and methods used for wireless communications in a license exempt band, often termed an enhanced commons approach, it may be possible to improve upon the device’s robustness to interference. The resultant improved spectral efficiency and possibly higher power transmissions could allow for increasing growth in usage without excessive interference.

Ofcom’s work in this area will:

- identify technical approaches that may be adopted and the operational rules/methods for these approaches; and
- explore the regulatory options and the potential benefit that may be accrued.

Explanation of technology
Licence exempt bands have seen a major increase in use over the last few years for mainly short range data communication devices. The limited regulatory controls placed on the bands at 2.4GHz and 5GHz have proved very popular with the radio industry and end-users alike and have led to a wide variety of cost-effective radio standards (for example 802.11, HiperLan, Bluetooth) and the associated applications being developed for these bands.

The reason that the regulator has been able to lightly regulate these bands successfully is that it specifies a low EIRP level which limits range and hence the possibility of interference to other users. However this also limits the use of these bands for some applications to a degree that might be unnecessary if other controls were imposed by the regulator.

Current state of art and role of our work
Several examples of more advanced mechanisms for limiting interference already exist:

- a carrier sense capability is mandated on all equipment in the UK operating in the light-licence Band C at 5.8GHz. This means fixed services such as BFWA avoid interfering with existing radar services in this band;
- some Bluetooth implementations avoid frequency hopping onto carriers that are used by 802.11b/g bands and so avoid mutual interference between the two systems in the same area. This enables short range Bluetooth devices such as phones and laptops to interoperate with WiFi wireless LANs; and
- individual 802.11 devices avoid interference using a carrier sense multiple access collision detect (CSMA/CD) approach that increases reliability and lessens the ‘hidden-node’ problem.
Our work in this area will extend this more generally to look at what would be possible in a politeness protocol controlled (PPC) band where the regulator specifies how all devices should behave in detecting and avoiding mutual interference. These ‘politeness’ protocols should inter-work for all devices using a band and would be expected to allow greater range and / or capacity than can be achieved by controlling interference by limiting EIRP alone. In this way, it is expected that the benefits inherent in licence exempt spectrum can be extended to a large number of other applications.

Work will identify operational rules/methods and their application in both a predetermined and dynamic fashion, identify potential applications, quantify increases in spectral efficiency, and the trade offs and costs of use of such protocols in future politeness protocol controlled spectrum.

This study will undertake an analysis of the optimum politeness protocols that could be used in such a band and use modelling to determine the effect of the politeness protocols on the spectrum efficiency that can be achieved, the capacity and the cost impact on devices. From this we can infer what politeness protocols are most economically efficient in terms of spectrum use and in allowing new radio services to develop.

Regulatory options will be considered such as:

- the spectrum bandwidth that will be required;
- what frequency band should be used to support the identified applications;
- whether this spectrum needs to be contiguous;
- what guard bands will be required to protect adjacent services; and
- whether PPC spectrum could interface with other spectrum uses;

We expect this work to identify suitable technical approaches and regulatory options for creating an enhanced spectrum commons band, and estimate the potential benefit such a band may bring.
Section 4

Understanding the use and quality of our spectrum

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.

- **Quality information** allows us to understand the degree to which the spectrum is being “polluted” by interference from sources such as unwanted emitters, or possibly in the future from devices such as Ultra Wideband transmitters. It might allow us to modify the rules governing unwanted emissions or to modify the parameters of UWB if the noise floor was seen to be rising rapidly.

- **Usage information** allows us to understand how intensively the spectrum is being used, helping us to judge, for example, whether the licence-exempt spectrum is becoming congested or whether the basis on which we have made assignments is not in line with actual usage. It might provide important information to make a judgement about the introduction of new technologies such as Cognitive Radio. Finally, it might allow us to more rapidly detect sources of illegal transmissions, such as pirate radio systems, and quickly locate them.

We are conducting two primary areas of study in support of these duties, which are outlined below.

To understand spectrum quality we have commissioned the development of a portable and automated system which can measure the amount of interference and noise compared to actual signal strengths across a very wide band from 100 MHz to 10.6 GHz. This will allow detailed analysis of the spectrum use and levels of interference and noise across the most highly utilised and demanded frequencies. It will also allow the interference from new technologies such as UWB to be monitored. This system which we call the Autonomous Interference Monitoring System (AIMS) is discussed in the next section below.

To understand usage we have commissioned the design of an Automatic Monitoring Station (AMS) that can be deployed in large numbers to monitor the radio spectrum and detect interfering radio signals with sufficient accuracy to localise and identify the source of the interference. It is expected that this work will lead to a demonstration of the concept to the point of producing one or more prototypes and the determination of the cost of deploying, maintaining and operating such a network in the UK. The second part of this section of the report discusses the background and requirements of this system and presents the initial findings of the work.
Autonomous Interference Monitoring System

The AIMS system will allow the measurement of the amount of interference and noise compared to actual signal strengths across a broad frequency range. The system is expected to be deployed for a number of days at locations of interest around the UK. The system will be unmanned during deployment, operating autonomously until the system is collected and data retrieved. This will allow spectrum usage and quality measurements to be made at a range of urban, suburban and rural locations. These will be repeated at regular intervals to monitor quality, usage and the impact of new developments over time.

The AIMS comprises the following main components:

- **Ultra Wideband antenna.** This will be omnidirectional, vertically polarised and cover the frequency range 100 MHz to 10.6 GHz. It is being designed and built by Queen Mary University London (QMUL). A Low Noise Amplifier (LNA), with a noise figure of approximately 3 dB, will be integrated into the antenna to ensure a low system noise figure of less than 4 dB across the entire frequency range.
- **Receiver subsystem.** The receiver subsystem comprises a spectrum analyser, RF switch, noise source and other ancillary equipment. The bulk of the analysis will be based on processing the I/Q outputs of the analyser.
- **Analysis software.** This will comprise an emitter database, test editor, calibration database, DVD viewer plus the remote desktop functionality of Windows XP.

![Figure 22 Autonomous Interference Monitoring System (AIMS) schematic](image)

Design of a suitable antenna which can operate successfully over the required frequency range is a significant challenge. Advanced electromagnetic simulation has been used to design a novel antenna concept which can meet the challenging performance requirements for the AIMS system. From this concept a compact, Ultra Wideband antenna has been designed and built. The antenna is close to omnidirectional across the full frequency range, and incorporates an integral Low Noise Amplifier (LNA) to ensure a good system noise figure.
Signal Analysis

Another major challenge in the AIMS system is to design and develop the signal analysis software that will allow the system to measure the signal and (interference + noise) characteristics for the huge diversity of modulation types in use across the frequency range of 100 MHz to 10.6 GHz. These range from simple analogue transmissions to highly complex, digitally modulated signals. The growing trend towards more spectrally efficient, noise-like signals means that it is becoming harder to distinguish signals from noise in many cases. The intention is to handle as many of the current signal modulations as possible, and also identify algorithms that may be used for future signal modulations such as UWB.

Two fundamentally different approaches could be taken in the design of a system like AIMS. The first approach is to build a receiver that is capable of demodulating all known signal types. With the current rate of change in the communications world, it is believed that such an approach cannot be practical, as it would be prohibitively costly to maintain. Many proprietary modulations do not become publicly available for considerable time after their deployment and even the standard protocols can have many subtle variations. It was therefore decided to use the alternative approach of finding demodulation algorithms that can measure powers in a wide variety of cases with little reliance on a priori knowledge.

The main areas of work have been concerned with:

- estimations of the carrier level and the background interference + noise level C/(I+N);
- Automatic Modulation Recognition (AMR); and
- UWB signal detection and analysis.
Work to date has shown that the automatic analysis of interference and noise levels is a complex area of research, with very little published literature available covering the methods to be used in wide band spectrum monitoring applications. A wide variety of algorithmic approaches have been studied, with a view to identifying a generic, robust and accurate method of measuring carrier, interference and noise powers. No single algorithm can meet the needs of the wide variety of signal modulations expected whilst also offering optimised performance.

An approach using a fourth order Method Of Moments algorithm has been chosen as a baseline which gives reasonable performance for a wide variety of modulation types. Whilst this algorithm is robust and generic it has a number of limitations such as an inherent requirement for the carrier to be significantly higher in power than the interference and noise. Thus, although this approach should operate well, it will not be able to distinguish those carriers that are working close to the interference plus noise power.
It is recognised that the latest digital modulation schemes are complex and that there is a growing trend for these to resemble noise signals in many ways. This trend means that automated modulation recognition algorithms relying on statistical moments or constellation recovery cannot meet all the needs of AIMS. Therefore in parallel more advanced techniques have been identified and are being further developed that will address such signals, including UWB. These advanced algorithms will be introduced into the AIMS system as they are proven and tested through simulation and testing against measured data.

**Automatic Modulation Recognition (AMR)**

The latest digital modulation schemes are complex and that there is a growing trend for these to resemble noise signals in many ways. This trend means that AMR algorithms relying on statistical moments or constellation recovery cannot meet all the needs of AIMS. It would be ideal if it were simple to add new modulations to the system after delivery with minimum support.

A concept for a generic AMR method has been proposed which entails using signatures derived from the eigenstructure of recorded or simulated signals. An example of a typical signature is shown. A neural network is trained on the eigenvalue signatures. This framework would allow AIMS to be retrained by Ofcom personnel as new modulations are introduced, rather than having to get the system reprogrammed.
UWB noise measurement

One of the challenging tasks of the AIMS system is to measure levels of UWB signals. This is the subject of ongoing research where some promising methods have been investigated. One method for a Multi-Band Orthogonal Frequency Division Multiplex (MB-OFDM) UWB signal is discussed here. The figure below shows how the MB-OFDM signal would appear to the AIMS receiver.

![Figure 28a A multi-band OFDM signal detected at the AIMS receiver](image)

It has been found that the method of moments algorithm may be configured differently to allow it to detect the UWB pulses as a carrier. Once this is complete a useful amplitude probability distribution (APD) can be obtained, shown below. This would allow useful information to be obtained about the UWB level.

![Figure 28b An APD of the above signal showing an estimate of the UWB signal](image)

Conclusions, timescales, role of technology

The design of this system is well underway. Novel and advanced algorithms have been implemented which will allow the system to analyse state of the art signals and monitor interference and noise levels. The system design is suitable for rolling upgrades to the software ensuring algorithms can be employed to maintain analysis of state of the art signals.

Initial measurements with the system will begin early in 2006. A programme of measurements will be established to allow long term analysis of the spectrum, allowing the impact of new developments such as UWB for example, to be quantified.

This system will feed valuable information into our regulatory decision making, for example giving information on the impact of spectrum liberalisation, understanding the effect of ever increasing proliferation of electronic devices, particularly those with high clock rate electronics, such as PCs, and monitoring the impact of low noise communications technologies such as UWB.
Automatic Monitoring System

Ofcom currently has two programmes which utilise unattended equipment for spectrum management and interference resolution purposes:

- the remote monitoring and direction finding (RMDF) system currently consisting of 24 sites with the capabilities to detect signals and their direction of arrival from 20 MHz to 3 GHz; and
- the Unattended Monitoring System (UMS) currently with 28 sites capable of providing occupancy information from 20MHz to 3GHz.

These systems have been deployed separately because the RMDF systems are optimally sited on high ground so that they have the highest chance of receiving an interfering signal, whereas the UMS systems are optimally mounted in city centres where they only receive local signals and so can accurately map the usage in that city.

However, a fully comprehensive network, capable of monitoring the radio spectrum and detecting interfering sources over a large part of the country will need far more monitoring stations than currently in the network. An estimate of the number of stations required for covering much of the urban, suburban and some of the rural area is 2000, although this will be investigated in detail as part of the study. These will have to be automatic in operation, have means of downloading reports of interfering sources automatically or on request and be relatively cheap to purchase and maintain to ensure the network costs are not prohibitive.

A feasibility study is underway to investigate a system which will meet the UK radio-spectrum monitoring future needs. The study will develop a specification for a system and a monitoring station will be developed, modelled and experimental development units constructed and tested in the field. The output of this work will allow Ofcom to make a decision whether to proceed to deploy such a network in the future.

Current state of art

Existing automatic monitoring systems typically use signal location based on direction finding (DF) techniques. This requires multi-element antenna arrays which are generally quite large and bulky, particularly for operation at HF and VHF.

The work has reviewed the wide range of automatic monitoring systems currently available or in use globally. It has found some limitations in the commercially available automatic monitoring systems such as:

- a limited capability against modern signal types such as TDMA and CDMA where the signals can effectively be stacked on top of each other;
- reduced performance in multipath environments which limits their use in urban or metropolitan areas; and
- reduced performance with co-channel signals and limited classification capabilities in dense signal environments.

Very few of the systems that were reviewed offered any integration with existing databases of license holders and license types. This is a useful feature as it will help operators to determine quickly whether particular transmissions are licensed or not. In a dynamic spectrum trading environment, it could be otherwise difficult for operators to determine the validity of unusual transmissions.
The system proposed in this research study aims to address a number of the issues listed above through utilising an entirely different approach. The system will use a time direction of arrival (TDOA) approach based upon a network of affordable monitoring units. The TDOA technique calculates the received time differences between simultaneous captures of the same signal at three or more different locations. By knowing the exact positions of the sensors, these time differences can be translated into lines of position on the earth’s surface. The point of intersection of these defines the position of the emitter.

The technique is based on a correlative processing technique, which is able to cope with co-channel signals (such as CDMA, TDMA and interferers), and has the flexibility, via software upgrades, to handle more complex waveforms as they become more widely used. Similarly, the flexibility of a software approach mean that results could easily be linked back into an existing database of license holders, enabling the identification of new unlicensed transmissions quickly in a geographical area.

For emitter location a number of sensor units need to be deployed in a cellular structure over the region to be monitored. The size of a cell is dependent upon the location accuracy and sensitivity required by the user. The sensors in turn connect to Command and Control units. These define sensor tasking, the cell structure, and allowing viewing of sensor output. Sensor locations are shown on a map which displays status and allows easy connection to the sensors output. This technique benefits from improved sensitivity over the more convention direction finding (DF) technique, and can be used with low profile, inconspicuous antennas rather than the large arrays normally associated with DF at these frequencies.

Modelling of the monitoring network has been undertaken to establish the expected performance. Figure 30 shows and example of the expected location accuracy over a
15km square for a 1W transmitter in the VHF terrestrial radio broadcast band with sensors located at the corners of the top and left sides.

Figure 30 Performance prediction of location accuracy of the monitoring system

The prototype hardware and software design and manufacture are now nearing completion and system trials will be taking place over the next few months to prove the capability for a range of signal types and frequencies.

Figure 31 Automatic monitoring system – prototype hardware
Conclusions, timescales, role of technology

The study is concentrating on de-risking and identifying the benefits of novel techniques to address the AMS problem. The aim is to combine the new technology with conventional features available in current systems to develop a prototype and design for a future network of AMS sensors.

A TDOA based system is expected to have significant cost benefits due to:

- use of low cost antennas;
- single channel architecture; and
- less stringent siting requirements.

Work so far has concluded that construction of the AMS systems and network is feasible, though further cost and performance modelling are required. Once the feasibility study is complete, if a positive result is attained, we expect to undertake further exploratory work before taking the system forward and recommending procurement of the monitoring network.
Section 5

Enhancing the efficiency of existing systems

In this section we consider projects looking at existing uses of the radio spectrum and asking whether there are more efficient ways to achieve the same service. Ofcom is undertaking this work because in some 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.

Some parts of this work are complementary to the Cave Independent Audit of Spectrum Holdings which is looking at enhancing incentives for public sector organisations to use their spectrum holdings efficiently. Here we consider the technical options available while the Cave audit will look at broadly economic incentives.
Spectrally efficient radar systems

How will they help?
In the frequency band between 1GHz and 3 GHz around 30% of the spectrum is primarily allocated to radar systems and is largely unavailable to other users of the spectrum. These frequency bands have very desirable propagation properties, and could be used to support other communication services, such as cellular telephony, messaging and wireless local area networks. Potentially large amounts of spectrum could be freed up for commercial purposes if radar systems can be improved in terms of their spectral efficiency, moved to a different frequency band in lower demand, or can share the spectrum with commercial users.

Ofcom is researching this area to:

- demonstrate the practicality of techniques which will
  - improve the spectral efficiency of radar systems,
  - allow radar systems to operate in different bands; and
- establish a cost benefit analysis, determining the costs of modifying and re-certifying existing radar systems or deploying new systems, and comparing them to the value of the spectrum released for other commercial applications.

Explanation of technology
In the L (1GHz – 2GHz) and S (2GHz – 4GHz) bands civil radar is extensively used in the UK for aeronautical and maritime surveillance on both fixed and mobile platforms. In addition there is extensive military radar use in these bands. The military uses of radar fall into two types: those that replicate the civil use and those that are exclusively military and have no civil application.

How does a radar system operate?
Radar systems send out radio pulses in a given direction to detect targets. The angle of the target is determined from the antenna pointing direction. The range of the target is measured from the time taken by the transmitted pulse to be reflected back from the target and received as an echo at the antenna.

Signals returned from distant targets such as aircraft can be extremely small due to the distance of the target and dispersion of the transmitted energy. To compound this, the signal must complete with that from other interfering signals such as reflections from the land and weather, termed ‘clutter’.

Figure 33 A typical air traffic control radar system

Radar systems send pulsed signals to detect and locate targets of interest. Applications such as air traffic control (ATC) and military applications generally require the robust detection and localisation of targets at long distances. The primary performance requirements are thus good detection performance and accurate
localisation, usually expressed as range and angle. These performance requirements coupled with a desire to minimise costs determine some significant factors to which we give some background below:

- choice of frequency of operation; and
- interference to other radars and wireless communication systems.

**Choice of operating frequency**

The choice of frequency for a radar system such as an ATC radar system is primarily driven by detection performance, angular accuracy and cost. The L and S bands have traditionally been used for radar due to their favourable propagation properties allowing good detection range performance, coupled with the ability to achieve reasonable angular resolution and the low relative equipment costs compared to higher frequency bands.

![Figure 34 (a) Choice of operating frequency for a radar system is a compromise between several factors determining performance at practicable size and cost. (b) Effective radiated power (ERP) of different radio systems, showing the very high ERP of radar systems in comparison to typical communications and broadcast signals](image)

In general the higher the operating frequency the higher the required transmitted power. However the study will address the question of whether there is scope for performance criteria to be met at higher frequencies than the L & S bands traditionally chosen.

**Interference to other radars and other systems**

The transmitted bandwidth of a pulsed radar is relatively wide, up to tens of Megahertz. This is partly due to the requirement to determine accurate range of targets. However sidebands and spurious emissions are also generated due to the nature of the high power RF sources required. This is exacerbated by the high cost and long service life of typical radar systems, which results in older, lower performance technology remaining in use. In addition, in order to maintain detection performance on fluctuating targets, such as aircraft, radar systems typically use two or more transmit frequencies separated by many tens of Megahertz. Such frequency diverse operation is necessary to meet detection requirements and leads to a wide operating bandwidth. The broad transmitted and operating bandwidth and emissions in combination with the extremely high radiated powers that are typically required for target detection give the potential for significant interference with other systems operating in adjacent bands and with other radars, leading to a low frequency re-use factor – and in some cases no frequency re-use whatever.

**Current state of art and our research in this area**

Ofcom has conducted previous work in this area. An earlier SES study considering radar systems within the 1-16GHz band identified techniques that could potentially improve the spectrum utilisation of radar systems considerably. Short term solutions identified include
• improving the interference emissions of systems for example through the use of sharper cut-off filters in existing radars
• improving the spectral re-use between systems through the use of waveform coding

In a longer time frame, the work estimated that the use of continuous wave (CW) and long pulse length radar systems could reduce the spectrum used in certain applications by up to 90%.

Further work has been commissioned to follow up on these findings. The work will investigate the practical issues remaining which must be addressed to implement these recommendations and use the expertise of radar manufacturers to establish the indicative costs of implementing the solutions, for example system redesign costs and re-certification costs for ATC modifications.

Initial work in this area has covered:

• a study into the practical problems of generating high power coded waveforms using travelling wave tube or alternative devices, in order to increase radar frequency reuse; and
• analysis of the practical issues in deploying a CW radar system, for example investigating the susceptibility of such systems to deliberate or accidental jamming and investigating techniques that could be employed to recover range information from CW radar.

**High Power Coded Waveforms for Radar Systems**

Coded waveforms are used in communications systems to give a high degree of spectral re-use. This work is investigating whether such waveforms can be practically applied to a radar system. The study has focused on the generation coded waveforms for the following ATC applications and transmitter systems based on current ATC radars in use in the UK:

• a TWT Terminal Radar in S Band;
• a Solid State Terminal Radar in S Band; and
• a TWT En-route Radar operating in L Band.

The work has established that many of the proposed coded waveform techniques would not be possible to implement on existing radar systems. This is principally due to the necessarily non-linear nature of radar transmitters. However the work has identified some coded waveform techniques, which may be implemented on some newer radar systems.

The spectrally efficient coded waveforms considered fall into two types:

• those that can be used to generate a radar-pulse with the minimum RF bandwidth whilst still meeting the minimum performance requirement of the radar; and
• those that allow radars to operate with a waveform that minimises the interference to radars of a like type, thus improving spectral efficiency by reducing the frequency reuse distance.

This work is ongoing, although initial work suggests that some significant gains in spectral efficiency could be made by strategies for shaping the radar pulse. In older systems this would decrease the detection performance of the radar. New systems
could be designed appropriately to meet detection range requirements. Further work will establish the performance and cost implications of such a modification.

**CW Radar**
Conventional radar systems use very narrow pulses to accurately detect the range of a target. They have relatively broad bandwidths of the order of 10s of MHz, since fundamental physics dictates that the narrower a pulse of energy is in time the broader its spectral envelope. As the spectral envelope is reduced, the resolution of the range measurement is degraded. The maximum bandwidth reduction possible would be to move to essentially a continuous transmission, termed CW operation. This would allow in principle a bandwidth of just a few Hz to be achieved, offering extremely high spectral efficiency, but at the cost of losing the ability to measure target range.

![Figure 35 Range resolution as a function of bandwidth](image)

However, such CW radars require a number of technical hurdles to be addressed before they are practicable. These are chiefly:

- the susceptibility of such a narrow bandwidth system to interference;
- the accurate measurement of range with such a system; and
- issues of deployment of a network of CW radars that can operate efficiently as a multistatic system.

**Range measurement with CW radar**
Range measurement can be obtained from a CW radar through two routes. Firstly by relaxing the constraints on CW operation, increasing the bandwidth of the signal from just a few Hertz, to a wider, but still narrowband signal. This allows measurement of range, for example through frequency modulated CW operation (FMCW). This method cannot regain the accuracy required for an ATC system without increasing the signal bandwidth back to that of current systems, hence gaining nothing in spectral efficiency. However a coarse range measurement can be obtained.

The second method is to utilise a multi-static radar system. In a multi-static radar system multiple receivers are used to detect the target from different geographical locations. Triangulation of the different measurements of target angle from the different locations yields an estimate of the target’s range. Increased location accuracy can be made through incorporating measurements of the target Doppler (radial velocity) and of the target range – assuming an FMCW radar is used as outlined above.
Multi-static Radar Systems

Multiple static receivers are dispersed around the target, as shown, and are tuned to receive the scattered CW signal using a narrowband receiver. Each receiver is able to measure the angle of arrival of the scattered signal from the target and the measured angle of arrival at each receiver is then passed to a central control (CC) for processing via a data link. Using this information and the known positions of the receivers, the CC is able to use triangulation to provide an estimate of the 2D target position by drawing lines of bearing through each receiver.

The work has created simulations in order to rate the range measurement capability of CW systems in four scenarios:

- target location is made on the basis of angular measurements alone
- target location is made on the basis of both angular and Doppler (radial velocity) measurements;
- target location is based on angle, Doppler and also on range information (assuming FMCW radar); and
- super-resolution techniques are employed to improve the measurement accuracy further.

The study is currently analysing these options and will recommend a system solution for an ATC application. The performance of the system will be modelled and indicative costs established.

Above and beyond the technical hurdles, there are likely to be significant cost and time implications in adopting this different location technology. These would mainly be associated with de-risking activities such as flight trialling, performance measurement, certification and acceptance, and with de-commissioning current monostatic primary radar systems.

Conclusions, timescales, role of technology

In the frequency band between 1GHz and 3 GHz around 30% of the spectrum is primarily allocated to radar systems and is largely unavailable to other users of the spectrum. Improvements in the spectrum efficiency of these systems or relocation to other lower value areas could free up valuable radio spectrum to support other
communication services, such as cellular telephony, messaging and wireless local area networks.

Short term measures which were identified in previous work as possible mechanisms for improving spectral efficiency, whilst feasible, may not be cost effective or timely to deploy into older systems, however may be effective as part of the design of newer systems.

In the longer term, CW radar has been identified as a potential technology for dramatically increasing the spectral efficiency for some radar applications, such as ATC. This is unlikely to be able to be retrofitted to existing systems. Therefore it must be looked at as a new deployment. There are technological, operational and cost hurdles in the development of a CW based system that can achieve the ATC requirements. In addition, there is no incentive for this to be the case for procurement programmes, and is only likely to be considered with an incentivised spectrum pricing structure.

Ongoing upgrades of the ATC network of radars to new solid state based transmitters will increase spectral efficiency to a degree, though this is driven by improved radar performance rather than improving spectral efficiency of a system.

The continuing work in this area will estimate costs of the various system enhancements and new deployments. These will determine the feasibility of measures to improve the spectrum utilisation of these radar systems and provide an assessment of the increased value and services that could be made.
Reliable Communications Systems at Frequencies above 60 GHz

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 outlined in our vision and could also release spectrum at lower frequencies for other purposes.

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

Ofcom is researching this area to:

- examine the higher frequency bands between 60GHz – 100GHz, identifying the potentially useful bands;
- investigate the regulatory and economic issues involved, for example the implications of licensed versus licence-exempt use, in order to gain an understanding of the approach most likely to encourage innovation and usage of these bands; and
- identify key obstacles to the usage of these bands, the breakthroughs required and the timescales which applications in these bands may be expected to emerge.

Explanation of the technology
High frequency systems suffer much greater propagation losses making them unsuitable for long range applications. This is especially true at 60GHz where an absorption band exists due to the resonance of the oxygen molecules in air. An example of this is shown in Figure 37 which shows the margin achieved for a typical line of sight system on a 5km path operating with a data rate in excess of 100 Mbps.

![Figure 37 Radio propagation at high frequencies. Clear air margin (dark blue) achieved for of a line of sight system on a 5km path operating with a data rate in excess of 100 Mbps. Also shown are the reduction in margin which occurs in rain (yellow 0.01% time & magenta 0.1% time), fog (cyan, 200m visibility) and turbulent conditions (purple, 0.01% time)](image-url)
As well as the reduced levels of signal propagation, equipment is currently more expensive in higher frequency bands; but as costs fall, use of these bands becomes an interesting prospect.

The 60GHz band itself has unique characteristics as it combines the potential for large information bandwidths with the rapid attenuation caused by the oxygen absorption band. This makes it possible to reuse the same spectrum in closely spaced systems. However, as these frequency bands suffer severely from rain attenuation, their usefulness on their own for outdoor systems may be limited.

**Potential Applications**

Our analysis is that at these high frequencies applications need to operate over short paths (under 10km), and to take advantage of the high antenna gains and directivities which can be achieved at these frequencies. This rules out systems where long range is required such as satellite or HAPS systems, or where non-line of sight paths are experienced, for example personal communications and home networks.

However, the analysis has shown that the bands could be useful for a range of applications:

- Broadband fixed wireless access with very high capacities such as 150Mb/s. This could allow applications such as HDTV to the home to be deployed on demand;
- fixed line of sight point to point links, where link lengths of up to 5km are possible with 99.99% availability, supporting 150Mbps data rates for short range backhaul;
- high speed (1GB/s) short range wireless LANs, operating over a range of a few hundred metres in a line of sight environment. This could be used to provide a wireless access system for a very large building such as an exhibition hall or a space such as a sports stadium or car park; and
- short range repeaters (over 500m to 1km) with very high data rates of up to 5GHz for applications such as network backhaul. Such systems could be applied to a lamppost mounted system for provision of high bandwidth backhaul to a city wide WiFi network. This application could be considered as a wireless alternative to cable modem distributions through hybrid fibre coaxial networks where the cost of digging trenches can be avoided.

Two promising candidate applications are now the subject of further detailed investigation and demonstration. These are:

- wireless local area networks providing a 1Gbps capacity through millimetre wave access points; and
- very high capacity backhaul for either Mesh or branch and tree networks, operated in conjunction with very local wireless distribution services at lower frequencies.

**Investigation and demonstration of combined Free Space Optics / 64GHz wireless link**

Free Space Optics (FSO) technology uses light, typically infra-red, transmitted through lasers to delivers high speed data communications. Previous work commissioned by Ofcom has suggested that FSO and millimetre links can be used in
combination in order to provide reliable high frequency communication links for applications such as campus networking and last mile links.

Neither of these systems on their own is suitably robust to the propagation conditions to be able to provide a continuous link. Frequency bands above 60GHz suffer severely from rain, resulting in low availabilities of a link using these bands. Free Space Optical systems are similarly affected by the presence of fog and mist and suffer even lower availabilities. However, FSO systems however 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.

**Demonstrator FSO/64GHz Fixed Link**
A technology demonstrator has been installed exactly as if deployed on a commercial basis to provide connectivity between two network routers operating at Gigabit and 100BaseT data rates over a distance of approximately 450m in line-of-sight.

![Figure 38 Demonstrator FSO/64GHz fixed link communications system](image)

As the installation is intended to mimic a commercial deployment, network monitoring was established to generate alarms in the event of excessive latency and network link failures. CCTV cameras have been set up to enable real time visibility of both the equipment and the link path. This visual inspection is date and time stamped so can be correlated against any significant meteorological events that could affect the links.

A demonstrator system has now been commissioned with the objective of deploying a 64GHz radio system in a commercial environment to examine its performance and economic viability.

The work has demonstrated that an operational range of sub 1km for wide bandwidth connectivity using 60GHz radio is practicable. A hybrid system such as this can provide a true carrier grade (99.999%) wireless link over sub km ranges, and provided installation is simple and rapid would appear to have multiple applications in campus networking and “last mile” environments.

**Conclusions, timescales, role of technology**
At the start of this section we noted that millimetre wave communications systems at frequencies above 60 GHz have the potential for very high capacities, with more than 10 GHz of bandwidth available. We are studying this area to consider whether new applications such as high speed WLANS and short range fixed links for backhaul are viable at these higher frequencies, and if so when.
The work undertaken has shown that there are a number of viable applications which could utilise these high frequency bands. Some of the most promising are:

- High speed wireless local area networks of 1Gbps;
- Very high capacity backhaul for either Mesh or branch and tree networks; and
- BFWA.

The work has demonstrated the practicality of a dual frequency FSO/64GHz combined communications system deployed in a commercial environment. The system has demonstrated that there is the potential to provide very high availability for such an application. The system offers high spectral efficiency since it has a high frequency re-use factor by using the oxygen absorption band to suppress long distance mm wave transmissions.

The work leads us to conclude that higher frequency systems are possible within a five year timescale if the technology developments such as improved power generation occur as expected. However an appreciable cost decrease in cost of production of these systems is required to see wide commercial use. The most significant factor determining this occurring is the production of low cost mm wave component devices. Whether or not this will happen is likely to be driven by the demand for significantly more spectrum to provide wideband wireless services and applications.

Further work will establish whether the provision of more licensed or licence-exempt spectrum in this area will promote better utilisation of the higher frequency bands, by for example giving more regulatory certainty which could encourage the production of low cost devices.
Improving the sharing of the radio spectrum

How does it help

Core to supporting our vision for future wideband wireless communications systems and novel applications and services is the provision of access to broad bandwidths of radio spectrum. At the frequencies of interest for typical communications systems this bandwidth is a scarce resource. More frequency channels could be made available if successful sharing between different services could be achieved. Examples of this might be a wireless LAN sharing some radio spectrum with a broadcaster.

In an earlier section we discussed Cognitive Radio. This is one particular approach by which spectrum access could be shared in the future. This study aims to look at other innovative methods for sharing the spectrum between multiple services in order to maximise its utilisation and to enable provision of new services.

Ofcom is researching this area to:

- establish the degree by which the spectrum efficiency and utilisation could be improved by using such methods; and
- evaluate the risks of increasing the sharing of the radio spectrum in terms of how new services in the band will affect quality of service so as to determine where maximum benefit lies to the UK in terms of increased services and increased interference.

Explanation of approach

Traditionally, radio services in the UK have been allocated spectrum on an exclusive basis in a particular area in order to minimise any possibility of interference from other radio users. In certain cases, secondary uses are allowed, but only where interference is judged unlikely due to geographical or long-term temporal separation of the two services.

Although this allows a predictable quality of service, it can result in cases where spectrum is not being used in a specific area at a particular time. For a TDMA system this means unused timeslots and for a CDMA system this means unused codes, giving spectral inefficiency in the frequency allocation system. For some services, where the radio service in a particular area is only being used intermittently, this inefficiency can be large.

Using modern digital radio techniques, several other ways have been suggested in order to improve on this situation. In particular, radios could intelligently choose when to transmit to avoid other transmissions, they could use novel coding techniques to spread the energy and so avoid undue interference or they could use a beacon signal to indicate when they can transmit. All these techniques might, however, reduce the quality of service experienced by the licence holder.

State of the art and our R&D in this area

Sharing already occurs in various ways, for example through the use of multiple WiFi and other devices in license exempt bands, or usage of the same spectrum for satellite and terrestrial applications. There has been much work looking into the sharing of specific applications or services. Our work focuses on identifying general existing and novel sharing schemes and quantifying their performance and cost/benefit and technical feasibility against a wide range of possible applications.
Conventional sharing strategies

Conventionally bands are shared between services either on the basis of sharing in time or sharing it geographical separation. Sharing in time could be on the basis of regular sharing of time-slots, or through one service using time where another service does not require use of the band. Geographically sharing is achieved through sufficient separation of services to enable concurrent operation without interference.

The work has undertaken a detailed analysis of sharing strategies. It has concluded that few novel sharing schemes seemed to be feasible with currently deployed radio systems. However a number of schemes may be viable for future systems designed specifically to facilitate sharing. We have evaluated possible schemes on the basis of:

- the amount of spectrum that might be made available;
- the risks of increased interference with existing users; and
- the trade-off between increased multiplicity of radio services or increased reliability of radio services.

The most promising schemes are:

- beacons transmitted from receivers;
- coordinated beacons managing requests;
- widespread frequency hopping;
- spectrum commons; and
- spectrum commons, where devices move if interfered with.

These sharing schemes are outlined below and are now undergoing detailed modeling to establish their benefits.

Beacons transmitted from receivers

The beacons concept is based on the idea that it is only possible to be certain that it is safe to share a frequency if we know what interference we generate at the receivers in the sharing system rather than knowing the power level received from the transmitter. To that end it is proposed to equip each receiver in the primary system with a beacon transmitter that operates in a separate band (Figure 39). The secondary system transmitters that wish to share spectrum overlapped with that used by the primary system receiver are furnished with beacon receivers. By examining the power of the beacons received from the primary system receivers, the secondary system transmitters can determine whether and at what transmit power they may safely share the frequency. The concept is based on providing a standard for the beacon waveform to which all users of the controlled spectrum must conform.

Figure 39 Beacons at each receiver in the primary service managing requests from the secondary service
**Coordinated beacons managing requests amongst multiple services**

These kinds of beacons are equipments scattered amongst the different users of the spectrum (Figure 40). In order for the beacons to facilitate spectrum sharing between disparate systems they must have mechanisms for achieving:

1. monitoring requests for spectrum from users from all systems using the beacons;
2. sending responses to these requests; and
3. keeping track of utilisation of spectrum.

(1) & (2) above could be achieved through beacon receivers having the ability to receive according to any of the radio standards used by the different systems in the shared band. This would require little hardware modification to existing radio systems in the band, but complex multi-standard beacons. Alternatively a new standard could be created specifically for transmission of requests to beacons. All radio systems wishing to transmit in this band would need to conform to this standard, thus require hardware modification of existing systems. However, in the future new radio systems can be added provided they conform to the standard.

Two variants of this kind of beacon-based sharing scheme will be modelled:

- beacons make assignments solely on basis of received signal strength and hence estimated path loss; and
- beacons include knowledge of the location of the source and/or destination in making assignments.

**Widespread Frequency Hopping**

Widespread frequency hopping involves users hopping across the entire spectrum allotment, with the potential for interference averaging in space, time and frequency dimensions. However, widespread frequency hopping may induce movement from interference-free channels to channels where interference occurs. This is a result of a lack of etiquette but may not have a significant impact due the effect of widespread interference averaging across multiple dimensions. The precise nature of this effect is likely to be a function of system(s) load and this will be investigated and compared with the related sharing schemes.

**Spectrum Commons**

Spectrum Commons, or free-for-all spectrum sharing represents independent systems operation with no co-ordination or control. This is an important sharing
mechanism because it represents the simplest way in which different systems and services can use the spectrum, with no local or centralised coordination and minimal etiquette. This therefore forms a benchmark against which improvements are sought in terms of sharing scheme performance. Clearly there is no incentive to adopt a sharing scheme whose performance falls beneath that of free-for-all sharing.

**Spectrum Commons: Move if Interfered**
Spectrum Commons - move if interfered, extends the free-for-all approach by imposing simple etiquette in response to link failure due to interference. The precise effect of rules to change transmission channel is of particular interest. This scheme is clearly responsive but whether there is a better mechanism than simply moving to other channels is worthy of investigation. This is likely to be a function of system(s) load and modelling will focus on this.

**Conclusions, timescales, role of technology**
Our work in this area has concluded that few novel sharing schemes seemed to be feasible for sharing between existing commercial technologies and services. It should be noted that the Cave Independent Audit of Spectrum Holdings is considering sharing between commercial and non-commercial users. There are different issues which apply in this instance, for example the incentives for optimal spectrum usage, and thus we might reasonably expect a different outcome.

However considering the cost/benefit for possible future commercial technologies and services several candidates were identified with potential for sharing. Further work will model these potential candidates in detail and will establish the likely cost/benefit of implementing the solution in practice. In addition, future work will aim to examine what degradation of existing quality of service levels would be tolerable to users in order to increase the number of radio services available.

Our work here suggests there is little regulatory action required in the short term. In the longer term five to ten year timescale there may be beneficial courses of regulatory action.
Section 6

Conclusions

Summary of research projects

We started this report by setting out a vision of how communications systems might evolve in the future and noting that this would require advances such as more efficient use of spectrum or advanced device technologies like SDR. We also noted that advances in technology often took a decade or more before they achieved widespread usage, and hence we did not expect rapid developments in the areas we were researching.

In looking at potential technologies that might be used to deliver these services we concluded that:

- **SDR** faces a number of difficult barriers to implementation, particularly in the handset. Full SDR implementations are likely to be deployed in a timescale of 2015 or later.
- **Smart antennas** may be too expensive to be worth deploying in most applications in the near term. A modified approach termed semi-smart antennas might be deployed within the next three to five years, bringing more modest gains in spectrum efficiency.
- **Cognitive Radio** also faces many hurdles, not least because it might be based on SDR. Basic single-band Cognitive Radio handsets might become available by 2010. More complex handsets that can work across multiple bands, capable of significantly greater gains in spectral utilisation, are likely in a timescale of 2015 or later.
- **Mobile Mesh** systems can be implemented now, but the spectrum efficiency benefits are not strong and Mesh will likely be limited to specialised applications.
- **Politeness protocols** may reap benefits in enhancing spectrum efficiency in licence-exempt spectrum – further work is underway.
- **Enhancing the efficiency of radar systems** could result in significant gains in spectral utilisation. This will take some time because of the lack of simple technological upgrades and the long time span for equipment replacement. A timescale of 2025 is realistic before more spectrum efficient radars are deployed. There may be scope for accelerating this timescale if incentives which encouraged more spectrally efficient operation were adopted.
- **Systems could be deployed above 60GHz** within five years for some applications. There are few technology hurdles, although device costs may take longer to fall to acceptable levels.
- **Novel ways of sharing spectrum** are likely to yield benefit if implemented with the advent of new standards. The timescale for this is 2015, or possibly longer.

There are a number of interesting technologies that promise enhanced spectrum efficiency and improvements in device implementation, but broadly, as we would expect at this stage of research, these are around a decade away from commercial realisation. Much of our research is still ongoing, and while we have researched all the leading contenders for spectrum efficiency improvements there may be other technologies that we are not aware of and new technologies are likely to emerge over time. Given these caveats, we tentatively conclude that unless other technologies emerge which are rapidly developed and deployed, then dramatic enhancements in spectrum efficiency will take a decade or longer to achieve. This is
an important conclusion which will have major implications for spectrum use and research over the coming decade.

This does not imply that no enhancements are possible in the next decade – there are many deployed systems which are not using the most advanced existing technology. For example:

- upgrading existing 2G networks to 3G would provide a gain of around three-fold in spectrum efficiency;
- changing the “rules” for licence-exempt bands might improve their efficiency of use of spectrum; and
- enhancing planning guidelines in areas such as fixed links may bring gains even without any change in the underlying technology.

The ability to significantly enhance spectrum efficiency, but only in the medium to longer term, will have some impact on the vision set out at the start of this report. Because capacity will not increase rapidly, it seems unlikely that there will be orders of magnitude reductions in the cost per bit transmitted. This will make it more difficult for applications that transmit high data rates over wide area systems, such as watching individual video streams over cellular, to succeed until the enhancements discussed here become available. The slow development of broadband antennas might delay the arrival of multimodal terminals that are able to work on many different networks. Conversely, some elements of our vision only require low data rate or short range transmission and so will be unaffected by these findings.

Future research programme

These results have implications for our future research programme. Broadly, we do not currently see value in conducting further research into the novel technologies that we have reported on here. Instead, over the coming year we see merit in researching:

- Possible mechanisms for sharing between Government and private sector users, as might be identified by the Cave Independent Audit of Spectrum Holdings. Such sharing might be achieved more quickly than the advances in technology discussed in this report and hence provide additional capacity at an important time.
- Further exploring the role and optimal organisation of licence-exempt spectrum. If efficiency is not set to grow then it seems likely that there will be increased pressure on the licence-exempt spectrum. Enhancing the efficiency of use of licence-exempt spectrum could therefore be very valuable.
- Continuing with our development of monitoring systems able to provide greater degrees of information about the radio spectrum. These will be important in assessing potential gains from sharing, Cognitive Radio and other similar approaches. The information they provide us with will allow us to search for under-utilised spectrum and consider ways to enhance utilisation. Finally, it will enable us to understand whether the capacity of existing spectrum is being compromised by rising interference levels and to set in train any necessary corrective action.
Annex A

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.

2004/05 R&D projects and consortia

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### 2005/06 R&D projects and consortia

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Annex B

Glossary

2G  Second-generation mobile network for example GSM. 2G refers to spectrum within the 880-915 MHz, 925-960 MHz, 1710-1785 MHz or 1805-1880 MHz bands.

2.5G  Second-generation enhanced mobile. Enhanced 2G networks, for example GPRS.

3G  Third generation of mobile systems. Provide high-speed data transmissions and higher supporting multimedia applications such as full-motion video, video conferencing and Internet access.

3GPP  Third Generation Partnership Project. A cooperation between regional standards bodies to ensure global interworking for 3G systems.

802.11  A family of specifications developed by the IEEE for wireless LAN technology defining communications between wireless LAN devices. The WiFi protocol is a subset of this standard.

ADSL  Asymmetric digital subscriber line. A technology that enables high-speed data services to be delivered over twisted pair copper cable, typically with a download speed in excess of 256 kbit/s, but with a lower upload speed.

Adaptive antennas  An antenna, usually consisting of an array of radiating elements, in which the antenna pattern can be adjusted to steer the main beam in a given direction, or to place nulls in the antenna pattern to reduce interference.

Analogue  An analogue signal is any continuously variable signal. Such a signal could be used to encode for example a voice transmission. Analogue is often also used to refer to the devices for transmission, reception or processing of analogue signals.

Analogue to Digital Converter (ADC)  A device for converting an analogue signal into a digital signal.

Antenna  A passive device designed to radiate and receive electromagnetic energy.

ASIC  Application specific integrated circuit. An integrated circuit which has been designed for a specific use, for example specifically to implement a wireless protocol for a mobile phone.

Assignment  Authorisation given by licensing authority for a radio station to use a specific radio frequency or channel under specified conditions.

Band  A recognised frequency range or a recognised group of frequency ranges where each range has a defined start and end frequency.

Bandwidth  The extent of frequencies occupied by signals. Measured in terms of Hertz (Hz). Higher bandwidth signals allow more information to be transmitted in a given amount of time.
**Base station**
A radio transmitter and receiver installed by an operator to provide a communications service typically used in mobile cellular networks to communicate with cellular terminals (for example phones).

**Beamforming**
A process of combining the signals to or from an array of radiating elements which make up a phased array antenna to form a beam pattern. This may be fixed, or adaptive, using digital techniques to modify the antenna pattern.

**BFWA**
Broadband FWA.

**Bluetooth**
A radio standard for short range communication in the license exempt band at 2.45 GHz between devices such as mobile phones and computers.

**CDMA**
Code division multiple access. A technology for digital transmission of radio signals occupying the same frequency and time allocations, but separated by unique transmission codes with spread spectrum techniques.

**Cellular**
A mobile telephone service provided by a network of base stations, each of which covers one geographic cell within the total cellular system service area.

**Channel**
One of a number of discrete frequency ranges utilized by a base station to transmit and receive information from cellular terminals (such as mobile handsets).

**Cognitive Radio**
A type of radio which is able to utilise unused areas of the radio spectrum.

**Communications Act**
The Communications Act 2003, which came into force in December 2003.

**Continuous Wave (CW)**
CW radar refers to radar which transmits continuously rather than the more usual pulsed radar. CW radars occupy very small bandwidths, down to a few Hertz, and thus are highly spectrally efficient. However this limited bandwidth causes a number of limitations in performance.

**Coverage**
The range or area covered of a mobile cellular network.

**dBW**
A dBW is a convenient unit to express a power in relation to a reference level of 1 Watt. dBW = 10*log (Power in Watts).

For example 20dBW = 10^(20/10) Watts = 10^(2) Watts = 100 Watts

**DECT**
Digital Enhanced Cordless Telecommunications. A European standard for digital portable phones for home or corporate use. Operating at 1900MHz.

**Digital**
A digital signal is a signal that is both discrete and quantized. Representation of information such as voice or data is by encoding the information into the signal using digits 0 and 1. Digital systems typically achieve higher capacity than analogue systems.

**Digital Audio Broadcast (DAB)**
DAB is a standard for broadcast of digital audio signals for radio. It has been adopted in the UK and other countries.

**Digital Multimedia Broadcast (DMB)**
DMB is a standard for sending multimedia data such as radio and TV to mobile devices. It is a competing standard with DVB-H, based upon the DAB standard.
Digital Signal Processor (DSP)
A micro-processor specifically designed for undertaking common digital signal processing tasks in speedy optimised fashion, generally allowing a signal to be processed in real time for an application such as a mobile phone or mp3 player.

Digital to Analogue Converter (DAC)
A device which converts a digital signal to an analogue signal.

Digital Video Broadcast (DVB)
DVB encompasses a number of internationally accepted standards for digital television transmission, maintained by the DVB Project, an industry consortium. Specific types include satellite (DVB-S), cable (DVB-C), terrestrial (DVB-T) and handhelds (for example mobile phones) (DVB-H).

Doppler
The Doppler effect is the apparent shift in frequency an observer perceives who is moving relative to the source of a signal. For example in a radar system the Doppler effect can be used to measure the velocity of a target.

DSL
Digital subscriber line. A technology for bringing high-bandwidth information to homes and small businesses over ordinary copper telephone lines.

Dual-mode (also tri-mode)
Handsets that can work with more than one different standard and/or at more than one frequency.

EDGE
Enhanced Data rates for GSM Evolution. An interim technology moving toward 3G for providing data rates up to 384 kbit/s.

EiRP
Equivalent isotropic radiated power is the maximum power out of the antenna in a given direction (usually a few degrees down to the horizontal). The antenna acts to focus the radio beam, like a lamp reflector, therefore the maximum power will appear in a particular direction. The power in other directions, such as vertically downwards is sometimes significantly less.

Ethernet
A protocol for interconnecting computers and peripheral devices at high speed.

Exchange
Part of a telephone network that routes telephone calls to the destination.

FDD
Frequency Division Duplex. One technique used for wireless communications where the up link and down link are at different frequencies.

FDMA
Frequency division multiple access. A cellular technology that has been used in the first generation analogue systems (i.e. NMT, AMPS).

Fixed line
A physical line connecting the subscriber to the telephone exchange.

Fixed Links
Communications links between fixed points. Such links may be unidirectional or bidirectional, and may be point-to-point or point-to-multipoint.

FPGA
Field Programmable Gate Array. A silicon chip which can be reprogrammed after manufacture unlike most standard chips.

Frequency band of operation
In the UK the following frequency bands are used for public cellular telephony: 380-385 MHz TETRA, 390-395 MHz TETRA, 410-415 MHz TETRA, 420-425 MHz TETRA, 876-915 MHz GSM, 921-960 MHz GSM, 1710-1871 MHz GSM, 1805-1876 MHz GSM, 1900 – 1980 MHz 3G, 2110 – 2170 MHz 3G.
Frequency Modulated CW (FMCW)

An FMCW radar differs from a CW radar in that the transmission frequency is modulated. This modulation of frequency broadens the spectral bandwidth of the radar, but allows measurement of target distance.

Frequency Range

Any formally recognised division of the radio spectrum defined in terms of a start and end frequency (or centre frequency and bandwidth).

Frequency

The number of complete cycles of an electromagnetic wave in a second measured in units of Hertz (Hz)

FWA

Fixed Wireless Access radio link to the home or the office from a cell site or base station, replacing the traditional local loop.

GHz (Gigahertz)

Thousand million Hz (cycles per second). Example 2.2 GHz = 2,200,000,000Hz

GPRS General Packet Radio Service

A 2.5G mobile standard typically adopted by GSM

GPS

Global positioning system. A system for providing position information using a constellation of satellites launched by the United States Department of Defense.

GSM

Global System for Mobile communications. European-developed digital mobile cellular standard. The most widespread 2G digital mobile cellular standard

Hotspot

An access point to a wireless local area network (WLAN). Provided for example in a café to allow access to internet services by a customer laptop.

HAPS

High Altitude Platforms. A communications system could utilise platforms at high altitude to support a base station for communication with for example mobile handsets.

Hz

Hertz. The frequency measurement unit equal to one cycle per second.

High Definition TV (HDTV)

HDTV is a standard for transmission of higher resolution digital TV.

HiperLan

A European WLAN standard, alternative to the IEEE 802.11 standard.

Integrated Services Digital Network (ISDN)

A Network based on the existing digital Public Telephone Network which provides digital links to Customers and end to end digital connectivity between them.

Internet Service Provider (ISP)

ISPs provide end-users, and other ISPs, access to the Internet. They may also offer their own content and access to online services such as e-mail.

I/Q

In phase and quadrature. A common means of representing data symbols in communications systems is with in-phase (I) and quadrature (Q) signals.

L band

The band of frequencies between 1GHz and 2GHz.

Licence

A formal authorisation under section 1 of the Wireless Telegraphy Act 1949 for a customer to use radio equipment under certain restrictions
Licensee
A person or organisation to whom a licence is issued.

Local Area Network (LAN)
A computer network that is typically used in a single building such as an office.

Maximum licensed power
In EiRP dBW per channel. The maximum licensed power is the maximum power any one antenna is allowed to transmit per channel. In practice, most transmitters would operate substantially below this limit.

Medium Access Control (MAC)
A sublayer of a communications system in which defined protocols ensure that signals sent from different stations across the same channel don't collide.

MIMO
Multiple Input Multiple Output. Refers to a system which employs multiple antennas to increase the data capacity that a channel can support. MIMO is a recent technology which is not yet widely deployed. Future standards which include MIMO technology, for example 802.11n, promise to bring significant improvements to channel data capacity.

MHz (Megahertz)
A Million Hz (cycles per second). Example 900 MHz = 900,000,000 Hz

MNO (Mobile Network Operator)
For example Vodafone, O2, Orange, T-Mobile, or '3'.

Monostatic
A radar system where the transmitter and the receiver are positioned in the same location. Most radar systems are of this type.

MP3
MPEG-1 Audio Layer-3 A standard for encoding and compressing audio files such as songs.

Multi-band OFDM (MB-ODFM)
An implementation where a frequency band is divided into multiple sub-bands, and OFDM modulation is used to transmit information in each sub-band.

Multimedia Message Service (MMS)
MMS enables users to send and receive messages with formatted text, graphics, audio and video.

Multistatic
A multistatic radar has a transmitter in one location and one or more receivers in separate locations. This is different to a typical radar system which is monostatic.

MVNO (Mobile Virtual Network Operator)
an organisation which provides mobile telephony services to its customers, but does not have allocation of spectrum.

Nomadic
Nomadic access or nomadic computing. Ability of a user to access data or information from a network while they are in a state of motion.

Ofcom
Ofcom is the regulator for the UK communications industries, with responsibilities across television, radio, telecommunications and wireless communications services.

Orthogonal Frequency Division Multiplex (OFDM)
OFDM is a highly efficient wireless communications modulation scheme, allowing large amounts of data to be transmitted in a small bandwidth. OFDM is used in many communications systems, for example ADSL, Wireless LAN, DAB and UWB.
Packet
Block or grouping of data that is treated as a single unit within a communication system.

Packet-based
A system of network in which data is transmitted and received in packets of data.

PAMR
Public Access Mobile Radio.

PBR
Private Business Radio (previously known as Private Mobile Radio). A private radio service installed and operated by businesses and public sector organisations to provide mobile communications for their own workforces. A base station is installed by each organisation on a suitable site providing local coverage, and used to send or receive short messages concerning the business of the organisation to, from or between, mobile units.

PDA
Personal digital assistant. Handheld device such as an organiser or diary, often with more sophisticated computer functionality such as spreadsheets, word processing or email.

Personal Area Network (PAN)
A PAN is a short range network for connecting devices, for example synchronising your phone with your computer or handsfree headset. Bluetooth is an example of a PAN communications protocol.

PMR
Private Mobile Radio (PMR), see PBR.

Point-to-multipoint
Fixed link having at one end a multi-directional antenna for communication with multiple users over or relatively small area.

Point to Multi-point (P2MP)
A central antenna, or base station, broadcasts to several receiving antennae, or terminals.

Primary Assignment
The initial allocation of spectrum by the regulator to the market.

Protocol
A specification for transmission and reception of data.

PSTN
Public Switched Telephony Network, the telecommunications networks of the major operators, on which calls can be made to all customers of the PSTN.

RFID
Radio frequency identification. A system of radio tagging to provide identification data for goods in order to make them traceable.

Roaming
A service allowing subscribers to a cellular network of one operator to use their handsets on networks of other operators or in different countries.

RX
Receive

S band
The band of frequencies between 2GHz and 4GHz.

Safety of life services
Services provided by organisations who use radio spectrum to protect the lives of individuals, such as the emergency services.

Sidelobe
Any antenna radiates power both in the wanted direction but also in other directions. Power tends to vary in a lobed structure with angle. A directional antenna radiates power in a desired direction, termed the main lobe. It also
radiates power in other directions, usually at a significantly lower level, termed the sidelobes.

**Software Defined Radio**
A type of technology that implements much of the functionality of a radio in software to provide highly flexible and adaptive radio systems. Potentially an enabling technology for Cognitive Radio.

**SMS**
Short Message Service. A service available on digital networks, typically enabling messages with up to 160 characters to be sent or received via the message centre of a network operator to a subscriber’s mobile phone.

**Spectrum Efficiency Scheme (SES)**
A Treasury scheme aimed at improving the efficiency with which the radio spectrum is used in the UK.

**Spectrum**
A continuous range of frequencies of electromagnetic radiation (for example, radio waves).

**Spread spectrum**
A technique in which a signal is transmitted in a bandwidth considerably greater than the frequency content of the original information. This can be used for multiple access and/or multiple functions. This technique decreases the potential interference to other receivers while achieving privacy and increasing the immunity of spread spectrum receivers to noise and interference.

**Subscriber**
Any person who is party to a contract with a provider of services, for example mobile voice services.

**TCP**
Transmission Control Protocol. A transport layer protocol that offers connection-oriented, reliable stream services between two hosts. This is the primary transport protocol used by TCP/IP applications.

**TDD**
Time Division Duplex. A technique used for wireless communication where the up link and down link use the same frequencies but are separated in time.

**TDMA**
Time Division Multiple Access. A digital cellular technology that divides frequency into time slots. It is the prevalent technology of 2G.

**Time Difference of Arrival (TDOA)**
A method of measuring the position of a signal source by comparing the time of reception at multiple receivers.

**Transmission Control Protocol/Internet Protocol (TCP/IP)**
The suite of protocols that defines the Internet and enables information to be transmitted from one network to another.

**Transmitter Power**
Specified in terms of Effective Isotropic Radiated Power (EiRP dBW) per channel.

**TX**
Transmit

**UMTS**
Universal Mobile Telecommunications System. The European term for 3G mobile communications system which provides enhanced range of multimedia services (for example, video, high speed Internet access)

**UWB**
Ultra Wideband. A technology that spreads a signal thinly over a wide range of frequencies.
**VHF**
Very High Frequency (30 - 300 MHz).

**Voice over IP (VoIP)**
The conveying of voice messages over Internet Protocol.

**VPN**
Virtual private network. A method of encrypting a connection over the Internet. VPNs are used extensively in business to allow employees to access private networks at the office from remote locations.

**Wide Area Network (WAN)**
WAN refers to a network that connects devices over long physical distances. Where a LAN would likely be used within a building such as an office, a WAN might connect a user over larger distances, for example a 3G cellular network.

**WiFi**
Wireless fidelity. A mark of interoperability among devices adhering to the 802.11 specification for Wireless LANs from the Institute of Electrical and Electronics Engineers (IEEE).

**WiMAX**
WiMAX is a standard that provides high-throughput broadband connections over longer distances than for example WiFi. Examples of use include "last mile" broadband connections, hotspots and cellular backhaul.

**Wireless local loop**
A wireless last mile connection between an operator and the end user, rather than a wired connection such as copper twisted pair.

**WLAN**
Wireless local area network. Also known as Wireless LAN. (See LAN). For example a wireless LAN might be implemented using WiFi, rather than a traditional Ethernet LAN for a building network.