Part I

Fundamentals

1 Spectrum management around the world

1.1 The uses of radio spectrum

1.1.1 Introduction

The use of radio spectrum is at the heart of almost all aspects of daily personal, business and government activities. Life without the services reliant upon spectrum would be unthinkable – either no or very limited TV, radio, Internet, air travel, mobile phones, and much, much more. In this section, we provide an overview of the key uses of radio spectrum, their current allocations, and their likely future needs. As an illustration, Figure 1-1 shows the key uses of the spectrum in the UK and their current split of allocations across broad frequency bands.

In interpreting the figure (and recalling that it refers only to the UK) it is, first, worth noting that the usage of all frequency bands will add to greater than 100%. This is because much of the band is shared, and in the chart, if two applications both shared, say, 10% of the band, both would be considered to be using this 10% since it is typically very hard to divide up shared utilization. On this basis, some uses appear overstated: for example, program making and special equipment (PMSE), which is broadly the use of wireless microphones and cameras, appears to have more access to spectrum below 1 GHz than mobile telecommunications, but all the PMSE allocation is shared with broadcasting and PMSE needs to work around broadcasting, giving it little "real" allocation in practice.

In the figure the use is split into four different frequency bands. The advantages and disadvantages of different frequencies are discussed in more detail in the next chapter. Suffice it to say here that the bands below 6 GHz are considered much more valuable than those above and that the band below 1 GHz is especially useful where long-range propagation is required. We now turn to each of the sectors to provide a brief overview.

1.1.2 The public sector

The public sector encompasses all governmental (local, regional, and national) use, which is very varied. By far the largest users in this sector are defense and aeronautics. Other significant users are the emergency services and entities such as maritime safety (e.g. the coastguard) and scientific research. Thus, unlike the categories identified below, public-sector spectrum is put to a multitude of uses.

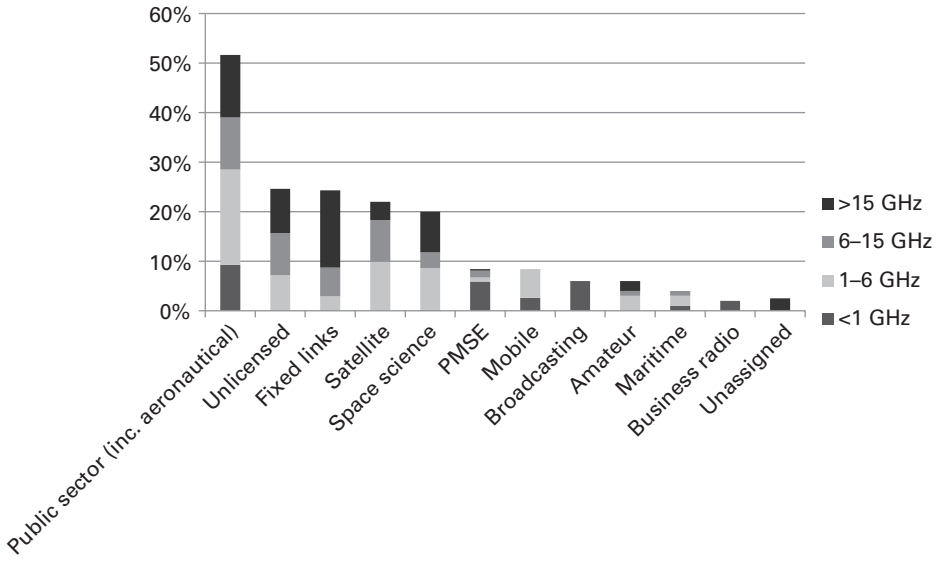

Figure 1-1. Uses of spectrum in the UK. Source: [1].

In most countries, defense services are a major user of radio spectrum. In some ways, this is a reflection of all the other uses – defense has its own "mobile" radio system, its own aeronautical system, its short-range systems, and so on. The actual use of spectrum is often confidential in terms of both the applications each band is used for and the level of usage. Over the last few decades defense use of spectrum has been slowly declining in the advanced economies, as defense needs domestically decline and the value of commercial use has risen. However, in recent years new technologies, such as pilotless drones which require video links, suggest that usage may need to grow to meet these needs. Understanding just how much spectrum should be set aside for defense and policing is extremely difficult and covered in detail in Chapter 12.

Aeronautical use of spectrum is predominantly for radar navigation. There are many different radar systems, from long-range radars that monitor the entire airspace across a country to approach radars at airports and even radars that monitor runways for debris. Planes also use radar for detection of terrain, other planes, turbulence and adverse weather. The accuracy of a radar system is related to the bandwidth of spectrum used and, with requirements for high accuracy, for most aeronautical applications a large amount of bandwidth is dedicated to these radars. Their use generally needs to be standardized internationally so that planes can use the same systems around the world. Other aeronautical applications include the radio links to pilots which sit in the VHF band just above sound broadcasting, data links for passenger in-flight applications which tend to use satellite systems, and radio altimeters which provide height-above-ground information to pilots. Broadly, aeronautical use of spectrum is static, making any changes to the allocation extraordinarily difficult.

The emergency services use spectrum for their own private radio systems. This is broadly the equivalent of a cellular solution for police, fire, and ambulance. By owning it

themselves the emergency services have greater control over coverage, availability, reliability, and features. At present, the emergency services are looking for additional frequencies so that they can increase the data capacity of their system, although it is far from clear whether they will be granted anything globally (there are some exceptions such as in the US[1]). This category of use is sometimes termed public protection and disaster relief (PPDR). It has also been suggested that such users could share with private users of mobile communications.

1.1.3 Unlicensed use

Unlicensed use (sometimes known as "spectrum commons" or as "license-exempt") is a broad set of applications, the best known of which are Wi-Fi[2] and Bluetooth. Unlicensed bands are somewhat like public parks – anyone is allowed to use them as long as they follow the rules of entry; this is discussed in detail in Chapter 8. While unlicensed use appears to have a large allocation of spectrum, it has virtually none below 1 GHz, and much of its allocation is either shared or in bands considered "junk" because of interference from other systems. Unlicensed use appears to be growing rapidly with ever-greater deployment of Wi-Fi, and many new applications such as machine-to-machine (M2M)[3] communications are considering unlicensed bands.[4] Regulators are now looking at whether unlicensed access could be granted into licensed bands on an opportunistic basis – known as dynamic spectrum access or "white-space" access. Deciding how much spectrum should be unlicensed is very difficult as generally market mechanisms such as auctions cannot be used and the future use of a band is hard to predict. Unlicensed bands are often seen as fertile areas for innovation as new technologies and applications can be deployed at low cost and without the need to gain a license [2].

1.1.4 Fixed links

Fixed links transmit data from one point to another using thin beams of radio energy. They are used in places where good-quality copper or fibre lines are unavailable or uneconomic. One major use is "backhaul" from mobile phone cell sites, linking the radio equipment at the cell tower back into the core network of the operator. Other applications include backup links for major cables and provision of telecommunications to remote

[1] The US has tried for many years to engineer a public–private partnership for the delivery of PPDR using the auction mechanism as a tool. The 700 MHz auctions had a reserved component ("D block") with obligations on the private owner to provide PPDR services, but this was unsold in the initial auction. Shared solutions now appear to be emerging through the "FirstNet" initiative.

[2] In 1985 the FCC in the US released the 2.4 GHz ISM band (the industrial, scientific, and medical radio bands reserved internationally for the use of industrial, scientific, and medical purposes other than telecommunications) for unlicensed access. This led to innovations giving rise to the 802.11 standard otherwise known as Wi-Fi, a low-powered, radio-based local-access network. Bluetooth is a related standard using the ISM band to enable personal-area networks.

[3] Sometimes known as the Internet of Things (IoT), M2M is the transmission of data to and from machines such as smart meters and parking sensors.

[4] For example, see the Sigfox technology deployed in 868 MHz or the Weightless technology deployed in "TV white space."

villages. Fixed-link antennas often look like satellite dishes but are pointed horizontally. Because directional antennas result in narrow, focussed beams of radio energy, the radio signal travels further for a given transmitted power. This allows fixed links to operate in higher-frequency bands where signals propagate less well but there is more spectrum and it is less expensive. The demand for fixed links in advanced economies is approximately static, although there is something of a trend away from longer-range links towards short-range solutions for small cells in cities. This is relatively easy to manage as the shorter links can be moved to ever-higher frequency bands where there is currently much available spectrum. Also, because of their thin beams of energy, fixed links rarely interfere with each other, and other applications can often share the same bands.

1.1.5 Satellite

Satellites are used for a wide range of applications. One is communications to remote users, providing voice and data services to ships and increasingly aircraft over sea. Satellite operators such as Inmarsat are periodically updating the data rates and capacity of their system by launching next-generation satellites. Another major use is satellite TV broadcasting, with households in many countries reliant on satellite for TV reception. Global positioning systems such as GPS and the new Galileo constellation are also very valuable users of satellite radio spectrum. Satellite solutions are also used for backhaul to remote sites, for news-gathering in isolated areas, for emergency communications during disaster situations and more. Satellite requirements for spectrum are under continual pressure, especially in the lower-frequency bands, and generally satellite use is progressively being moved to bands above 6 GHz. Satellite allocations are managed at a global level since the coverage from a single satellite can typically be greater than the size of most countries.

1.1.6 Space science

Another use of satellites is monitoring for scientific purposes. This is often known as "earth observation satellite" and includes satellites for meteorological purposes, for measuring parameters such as sea temperature or various emissions, for scientific missions into outer space, and so on. These systems often need to use specific frequency bands where the monitoring equipment operates best, and need these bands to be particularly "clean" of interference due to the sensitive nature of their instruments. There is slowly growing demand in this area, often for lower-frequency spectrum that is also in high demand from other applications.

1.1.7 Wireless microphones and cameras

In the world of security, entertainment and the media more generally, and sport, the demand for wireless microphones and wireless cameras has grown markedly in recent years. These are used in program making, but wireless microphones are also used very widely elsewhere. These applications require relatively little spectrum because the range

involved is typically short, but they can require interference-free links – for example interference on the wireless microphones used in major stage shows cannot be tolerated. Wireless microphones typically share spectrum with others, often broadcasters. However, this secondary-user status makes them vulnerable whenever the primary use is changed and as a result they are sometimes moved to different frequency bands. The demand for wireless links for program making is growing with the increasing use of wireless cameras embedded in sports equipment and similar, but the spectrum availability is, if anything, declining. The user base is diverse, making it difficult to acquire spectrum through vehicles such as auctions, but the reliability requirements make unlicensed spectrum generally unsuitable. It is rather a "problem child" for which regulators have yet to find a satisfactory long-term solution. Major events like the FIFA World Cup and IOC Olympics give rise to huge spikes in demand for spectrum to support the uses discussed here. To accommodate such demand sometimes regulators have temporarily withdrawn spectrum from other users.

1.1.8 Mobile telecommunications

Mobile, or cellular, telecommunication is one of the most visible users of spectrum. It comprises multiple generations of technology (2G, 3G and 4G/LTE) across many different frequency bands in the 300 MHz–3 GHz frequency range. It is generally considered to be the most economically valuable use of the radio spectrum and demand in advanced economies continues to rise as numerous new data-intensive Internet-based applications emerge. Because of rising demand for data fueled by the Internet and smartphone usage, regulators have had to refarm bands that were previously allocated to uses such as broadcasting. Over the years, ever more spectrum has been found for mobile, most recently at 800 MHz and 2.6 GHz (in Europe) and 700 MHz–2.3 GHz (in the US), and there is likely to be ongoing pressure for further refarming. Spectrum licenses assigned for use by mobile service providers are generally awarded through auction processes that often raise enormous sums for government. To date the largest sum raised in a single spectrum auction was that associated with the German 3G auction held in the year 2000, which raised almost €51 billion. Between 1994 and 2015 the US government has sold spectrum in over 96 different auctions, many of them awarding licenses to mobile operators, including the AWS-3 auction in 2015 which netted the US government $45 billion [3].

1.1.9 Broadcasting

Broadcasting encompasses radio at a number of frequencies, the main one being VHF radio (around 90–110 MHz) and TV at UHF (around 170–240 MHz and 470–790 MHz). The bandwidth required for radio is much smaller than that for TV broadcasting. Terrestrial TV transmissions typically take place from high towers and at very high power levels, providing coverage across large areas of the country, and causing substantial interference. In the last decade TV transmissions have been upgraded from analogue to digital systems in a process known as digital switch-over, which has enabled

more TV channels and high-definition TV broadcasts. In an ideal world, broadcasters would like massively more spectrum, to deliver more channels and to enable more high-definition and ultra-high-definition broadcasting, but it is clear that this is not possible in the current frequency bands. This has resulted in the use of satellite and cable systems to deliver much of the TV content, which has left question marks over the future of terrestrial TV broadcasting in UHF (often known as digital terrestrial television – DTT), especially as there is great demand for this spectrum from mobile networks and others. The debate over the balance between broadcasting and other uses is a critical one for the spectrum community and is discussed in detail in Chapter 11. Because of the large range of TV transmitters, much TV usage is planned on an international basis, for example across the whole of Europe, making any change in this area complex and bureaucratic.

1.1.10 Amateur use

Amateur radio users (sometimes known as "radio hams") are granted access to some spectrum for free to allow them to experiment and indulge a hobby. Historically, such users have been valuable in monitoring transmissions from ships in distress and similar, but with better communications this use is in decline. They have also pioneered new technologies, but with ever-increasing investment needed to realize gains it is unclear whether this is likely in the future. Despite this, their entitlement continues, typically being recognized at an international level. Occasionally there is a desire to reclaim some of the bands set aside for amateurs, but as many of these are at higher and less valuable frequencies this is relatively rare.

1.1.11 Maritime use

Maritime use is for links to ships within communications distance of the shore – typically some 30 miles or so. This covers port use. This is a stable requirement with an increasing demand for data transmission, although some of this can be met using commercial cellular and satellite systems. Maritime radio frequencies are typically harmonized globally.

1.1.12 Business radio

Business radio, also known as private mobile radio (PMR), is used by companies such as taxis, and within airports, universities, business parks, and the like. A business radio system typically comprises a single transmitter, often located at the head office of the company, and radios in vehicles or carried by individuals. It has the advantage of low cost and simplicity, and the "broadcast" nature of transmissions such as "Is any taxi free in the vicinity of location *X*?" can be useful for some purposes. It was long thought that business radio would be progressively replaced by cellular solutions, but demand has held approximately constant, or is even growing slowly in some countries. Systems are often voice-based, although there are also low-data-rate capabilities in some cases.

1.1.13 Unassigned spectrum

Finally, some spectrum is unassigned, either pending assignment through an auction or because a decision on its use cannot currently be made and is better deferred. Regulators aim to keep the amount of unassigned spectrum small since it represents an unused resource. On the other hand, reserving spectrum for future use keeps options open for the future, and this can serve a valuable purpose.

1.2 Why spectrum needs managing

We have seen that radio spectrum supports many different uses and demand across these uses is changing and variable. Furthermore, the technology supporting radio-based services is evolving, and sometimes it eases pressure on demand for spectrum access but often exacerbates demand. With such changes taking place there is a need to manage access to frequency bands. Additionally, leaving frequency bands unchecked and allowing free access would give rise to the potential for much harmful interference, potentially obstructing services and having enormous negative costs for economies. For these reasons radio spectrum has been closely managed for decades, both at a global level through the ITU (a body within the UN) and at a national level.

Spectrum (radio frequency bands below 300 GHz) can be viewed as a natural resource, the value of which (unlike that of land, air, or water, but like that of oil and gas) escaped the notice of the human race for most of its existence. Although the amount of frequency in a given area is fixed, there are in principle limitless ways of dividing its use. This suggests that supply of spectrum is not an issue (unlike oil or gas). However, from a practical perspective spectrum is limited or finite as modern radio engineering systems require a degree of exclusive access at any given moment in time. Across the radio spectrum propagation properties vary and this means that different bands are better suited to different uses.

For much of the period in which spectrum's existence has been recognized, its importance has been marginal, recognized mainly by experts in physics, aeronautics, defense, and security. After the 1914–18 First World War, it began to be used to carry mass-point-to-multi-point radio broadcasts and, after the Second World War, television broadcasts. What finally brought spectrum to prominence was the diffusion of mobile communications, in the form first of voice and now, increasingly, of data. It is estimated that in 2015 there are about 7 billion mobile connections in existence, by means of which about 3.5 billion inhabitants of the planet have mobile voice connectivity.

Soon after the development of the mobile industry, finance ministries began to understand the value of spectrum through a series of auctions for spectrum licenses occurring at the turn of the century. The revenues received in the year 2000 by the German and UK governments in particular, from their 3 mobile licenses, drew attention to the scarcity value of spectrum suitable, and available, for mobile communications. Makers of public policy are now also aware of the contribution which wireless voice and broadband services can make to GDP growth. In the private sector, spectrum trades

between operators, especially in the US, have generated billions of dollars of revenue, in addition to government auction revenues.

As spectrum became increasingly scarce the methods chosen to allocate it have developed. About a century ago, there was a short interlude of open access, in which users generally coexisted without interference. But governments in many countries quickly took control of spectrum for reasons of defense and security (particularly at the time of the 1914–18 world war), and then over the years eked it out for other uses, by means of administrative or "command-and-control" methods. This typically entailed a requirement placed on a would-be private or commercial spectrum user to seek the grant of a highly specific spectrum license, which would detail the use to which the spectrum would be put, the power levels and often the location of transmission equipment, permission often being granted for a short but renewable period. If there was competition to provide a service, the government would decide which applicant was the most worthy. Public-sector users, such as defense forces, usually found it much easier to get access to spectrum: they had the government's ear and faced no competing organization delivering the same services (and so requiring access to the same spectrum).

Despite the built-in resistance to innovative spectrum uses which this system embodied, it was a fairly effective way of dealing with spectrum assignment in a period of spectrum abundance. However, as with other resources, growing demand can trigger a search for additional resources and alternative modes of allocation. This is exactly what has happened in the last decade or so. A symptom has been widespread discussion of what is known as the "coming spectrum crunch" – a prospective shortage of spectrum to meet the burgeoning needs of mobile broadband. The expectation of this event has elicited a number of significant responses in spectrum management:

1. Searching in higher bands for capacity to deal with growing demand, initially at around 3.5 GHz but more recently even in bands above 20 GHz, such as the 60 GHz unlicensed band.
2. Questioning whether the traditional administrative or "command-and-control" approach is adequate to the task of making the best use of spectrum in an era of shortage and accelerating technical progress. The first fully developed explicit proposal for use of an alternative mode of allocation – use of a market for spectrum – was made in 1959 by Ronald Coase, but it took another 30 years for market instruments, initially in the form of spectrum auctions, to begin to take hold.
3. Looking for ways for bands to be shared among multiple users and multiple uses. This has been a most prominent feature of the past decade or so. Technical developments have made it possible for multiple users to have access to the same band without incurring the interference which, formerly, would afflict both transmissions. Sharing has also become a means of dealing with the "overhang" of public-sector spectrum use, which arose from the privileged position of those users of spectrum in the days of spectrum abundance. If it is difficult to persuade public-sector users to give up their assignments, it might be easier to make them share them. And data on spectrum use do reveal extensive underuse of public-sector capacity, in some cases even in peak hours.