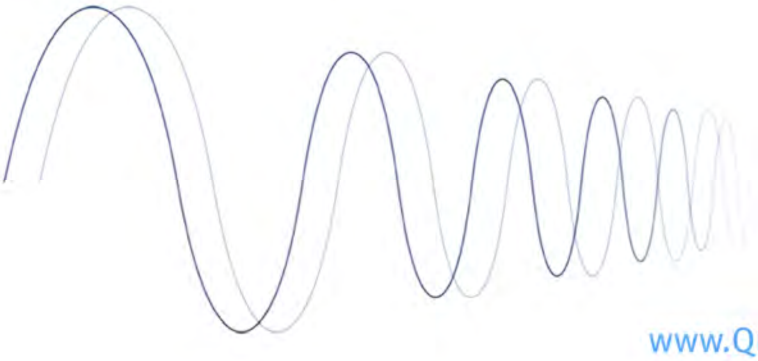
Quotient Associates

Technologies and approaches for meeting the demand for wireless data using licence exempt spectrum to 2022

Final Report

Final Report to Ofcom, January 2013



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0 EXECUTIVE SUMMARY

The objective of this study was firstly to develop an improved understanding of the demand for spectrum by wireless data applications in the main licence exempt bands, and secondly to perform a first-order identification of any areas where demand is likely to be in excess of the anticipated supply, over the next ten years.

An additional objective arose over the course of the study, which was to make a fresh assessment of the framework used to consider the balance between licensed and license exempt spectrum, taking into account recent publications and the uncertainties involved in the accurate assessment of relative economic value.

Applications

First of all, it was necessary to identify those applications which were likely to present a high demand in future. A total of almost 20 wireless data applications were initially identified over eight industry sectors. It was found that these could be re-categorised and reduced to four key applications groups which were

- Wireless broadband;
- Internet of Things;
- Intelligent Mobility;
- Connected Healthcare.

Wireless broadband using Wi-Fi in licence exempt spectrum at 2.4 and 5 GHz is growing rapidly and there is a broad base of evidence which shows this will continue over the next ten years. Drivers of such growth include Wi-Fi offload and private Wi-Fi. Reported measurements show that 80% of UK mobile phone data traffic is already carried by Wi-Fi.

Our analysis showed that beyond this undisputed trend, there are two likely drivers which will cause a further doubling of the bandwidth requirements of two key applications, based on the properties of the network architectures employed.

Firstly, considering the indoor situation, there is already a trend to stream real time content to a device from the Internet. An upcoming trend is screencasting, which involves 'casting' a portable device's screen to a higher resolution display. This is supported by the Wi-Fi Alliance's Wi-Fi Direct specification, which is currently being rolled out. If a user chooses to stream from the Internet and screencast concurrently from the same device, then two Wi-Fi channels will be consumed; one from the home AP and one from a soft AP on the screencast channel. This doubles resource requirements.

Secondly, considering outdoor Wi-Fi hotspots, there is a trend to denser and more contiguous coverage. This leads to an increased need to backhaul. Where that backhaul is carried in-band, perhaps via a mesh arrangement as is popular in UK installations today, the Wi-Fi network will need the capacity to carry the access traffic as well as to cope with self backhaul of the same traffic. This could double resource requirements.

A possible respite from demand at 2.4 and 5 GHz comes from WiGig at 60 GHz. This could take over video distribution from Wi-Fi within a home. Its other key application is docking and 'instant backups' for laptops and tablets.

Other applications within the wireless broadband group include rural broadband which might be delivered by TV band white space devices, if sufficient bandwidth can be achieved via future modulation technology improvements. A further application is line-of-sight backhaul links at 60 GHz and above, which are seeing renewed interest due to the growth of the small cell movement.

Our Internet of Things application group includes the general category of 'smarts', which includes smart meters, smart homes and smart cities (in which we also include M3N – Metropolitan Machine Mesh networks and Wireless Sensor Networks). This group also includes RFID, and it is RFID and smart meters where we see the greatest demand in future.

However we note that short range device (SRD) demand has been predicted for some time and plans are already in place within ETSI to reduce application fragmentation and increase capacity in the UHF SRD band. It is anticipated that more spectrum will be allocated for low power SRD use at 870-876 MHz (e.g. for smart meters) and to high powers SRDs at 915-921 MHz (e.g. for RFID). These bands are available since they have not seen use by Private Mobile Radio. The increased future availability of sub-1 GHz SRD spectrum may substitute for the demand for white space spectrum, especially for those applications which do not need the range and bandwidth of TV white space devices and would benefit from avoiding the extra complexity involved in working via a geolocation database.

In terms of Intelligent Mobility, aspects which relate to the Informed Personal Traveller have been included in the wireless broadband group. This sector may also have a demand for driverless transit communications in future, or road user charging, but the former is likely to be geographically restricted and the latter has appeared to be stalled for some time due to non-technical considerations. We note that the Intelligent Transport Systems band at 5.9 GHz has been little used since its creation several years ago.

Connected Health includes two key components, namely Medical Body Area Networks (MBANs) and Low Power Active Medical Implants (LP-AMI), which are both in the process of seeking globally harmonised spectrum adjacent to the 2.4 GHz band. MBANs in the USA have provided a good example of cross-sector industry co-operation driving workable rules for spectrum sharing[1].

Technologies

Our review of technologies was necessarily dominated by considerations of the many and widely varied facets of 802.11. As well as the expected higher speed, general purpose 5th generation WLAN, 802.11 targets in-room microwave links for video distribution and laptop instant docking via WiGig. Working groups within 802.11 have not been contemplating making Wi-Fi perform any faster as 802.11ac is already Gb/s capable. Instead they have focused new effort on very low power operation for the Internet of Things, and on 'White-Fi', for white space operation. The Wi-Fi Alliance and the Wireless Broadband Association are producing complementary specifications to better enable cellular- Wi-Fi handoff and seamless authentication (if not yet seamless IP sessions).

5 GHz will become the key Wi-Fi band with its new, wide channels of 80 and 160 MHz. Such wide channels are feasible only at 5 GHz and indeed are not specified outside this band. Such wide channels will consume the available spectrum quickly, with perhaps no more than three or four 80 MHz channels available. Built into the 802.11ac draft is a technique to fall back to narrower channels in times of congestion. In this way, legacy Wi-Fi is treated fairly with respect to medium access. On the other hand, 11ac users will necessarily see their speeds throttled at these times, which would likely defeat the

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[1] However we note that a desire for 2300 MHz LTE spectrum conflicts with MBANs outside the USA.

purpose of running an 11ac system. The only way around this bottleneck is to add more spectrum.

Spectrum

Fortunately we believe that more spectrum may be made available at 5GHz. It is important that any new spectrum is contiguous with existing allocations, since there would then be the greatest possibility of creating a workable number of independent 80 MHz channels. We show via a simple analysis that it is desirable not to be restricted to only three or four channels in a dense deployment due to compromised carrier-to-interference ratios (a self-interference effect which worsens with the increasing modulation complexity of higher data rates). It is instructive to note that a key reason that Wi-Fi works at 2.4 GHz with only three channels in a dense environment is that the back-off algorithm will relentlessly schedule packet retries, but this is not efficient operation.

Considering 5 GHz, we identified that if two extension bands were created by suitable sharing mechanisms, plus the UK fixed wireless broadband band C were opened to general purpose Wi-Fi, then 70% more spectrum could be realised, making room for perhaps eight or more 80 MHz channels in the 5 GHz band. We show several examples of the various processes by which sharing arrangements have come to fruition in recent years. On the whole they are more complex that in the past, but the benefits can be considerable. We believe that sensing based approaches like Dynamic Frequency Selection may have to give way to alternate approaches such as geolocation, registration, dependent station enablement and combinations of these, in order to guarantee compliance with more challenging sharing requirements. Such approaches could additionally enable a new middle ground of licensing between licensed and license exempt, in the form of tiered sharing rights. It would be appropriate to introduce any tiered sharing rights in new spectrum bands rather than retrospectively.

Overall, we found that 5 GHz Wi-Fi is the application which is likely to see excess demand over the next ten years unless action is taken. Timescales for compatibility work are often long and the coexistence studies at 5 GHz may be quite challenging as aeronautical services are involved. We therefore recommend the prompt initiation of any such processes.

We did not find that other licence exempt bands were in comparable danger of excess demand. This is in large part to the plans already in place to revise and extend UHF SRD spectrum[2]. Not only will this satisfy UHF SRD users, it may also offer a substitute for TV white space spectrum, which is presently shrinking as TV allocations themselves shrink. Other substitute effects will include 5 GHz for 2.4 GHz, which should benefit lower speed Wi-Fi users who remain at 2.4 GHz as much as it will benefit SRD users at 2.4 GHz. Loading of 5 GHz for very high speed point to point data links can be alleviated by working at 60 GHz or higher instead. Backhaul links are highly directional with excellent frequency reuse and are unlikely to exhaust spectrum at 60/70/80 GHz. However adoption of these microwave frequencies may rely on tri-band Wi-Fi chipsets to gain economies of scale in the case of 60 GHz indoors; and lowering costs for line-of-sight links at 70/80 GHz outdoors.

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[2] We note that there is a potential interference issue from future 800 MHz LTE into the UHF SRD bands, which is presently under discussion.

Economic framework

In our complementary investigation in which we revisited the economic framework for assessing license versus licence exempt decisions, we reviewed the state of the art in methods and approaches to assess economic value and thus support decision making.

We noted that although the need to assess congestion effects is quite widely appreciated, as is the need to understand band usage rather than simply band allocations, both these needs are poorly supported in terms of the input data available. This ultimately leads to them not being adequately considered in practice. Moreover it became clear that social value assessments have a large role to pay in assessing and comparing value. Unfortunately it is these very social values which have proved so difficult to quantify. As an initial step towards tackling this problem we have suggested the use of comparisons based on marginal utilities. This will help the case of applications with high utility but with a small number of users. Presently these applications appear to be unfairly over-looked in the assessment process.

We presented an initial framework which seeks to address the present shortfalls in the economic valuation process. This includes a short case study detailing how the framework might actually be applied in practice, including a suggestion to apply relative scores to parameters that cannot be easily quantified. There is much work to be done towards such a new framework approach.

Conclusions

Our conclusions from this study may be grouped into several areas. In terms of applications and technology

- We see Wi-Fi, smart meters and RFID as the strongest growth applications;
- Wi-Fi technology for wider channels will target the 5 GHz band only and this will become the key Wi-Fi band. 80 MHz channels will be important for handheld devices with single antennas;
- With 80 and 160 MHz channels, Wi-Fi will be Gb/s capable and no faster versions are currently planned by 802.11 working groups;
- 802.11's future direction includes very low power for Internet of Things applications, 'White-Fi' for white space operation and country specific Wi-Fi extensions.

In terms of future spectrum needs

- The planned increase to the spectrum available for UHF SRDs in Europe should go a long way towards redressing the relative paucity of sub-1 GHz licence exempt spectrum which has put Europe at a comparative disadvantage to the USA for example, especially with respect to innovative solutions such as smart meters;
- An increase in the spectrum available to WLANs at 5 GHz is needed. Unlike SRDs we are not aware of firm plans to investigate this at the present time;
- We have suggested how 70% more contiguous spectrum could be released at 5 GHz by investigating sharing in two extension bands and allowing RLANs in UK band C. This would likely mean that eight or more 80 MHz channels would be available over the 5 GHz band.
- Shared RLAN spectrum at 5GHz would absolutely need to be verified by compatibility studies. This could be an involved process, so any such studies should start without delay.

- More spectrum for SRDs and 5GHz WLANs is expected to reduce pressure on the 2.4 GHz band and white space spectrum;
- We do not expect to see an excess demand for spectrum at 60 GHz and above.

In terms of sharing

- We expect increasingly complex sharing mechanisms will be needed and we have given examples of how such approaches are already beginning;
- More complex sharing schemes will allow the creation of a middle ground between the extremes of licensing and licence exemption. Such tiered sharing or soft licensing could be introduced in new bands;
- Sharing schemes based on sensing such as Dynamic frequency Selection may have to give way to combinations of alternative approaches such as geolocation, registration and dynamic station enablement, for example;
- Although sharing technologies will need to be specified to have the desired effect, the underlying communications services may still remain technologically neutral.

In terms of the framework needed to assess economic value and hence licensed versus licence exempt decisions

- We note that congestion and actual band usage are key inputs to the process, but information on these aspects (including for example the costs of congestion) is often lacking and hence they are often not fully accounted for in evaluations;
- The social benefits of an application can have a very large effect on value, but this is one of the most challenging values to quantify;
- We have suggested an outline for a new framework approach which includes aspects such as marginal utility for socially attractive applications which may have high utility for a small number of users, and a scoring system for parameters which are difficult to quantify.

1 FUTURE WIRELESS DATA APPLICATIONS

In this Chapter we first present the wider background to this work.

1.1 Introduction

The policies pursued by a regulator can have a major impact not only on the sectors for which it is responsible but also on society and the economy. This is true even if the regulator's underlying philosophy is based on letting the market make as many decisions as possible, both because the regulatory regime influences the way the markets operate and because there are wider national interests over which Ofcom policies can have an influence. At the same time Ofcom policies do not act in isolation, but rather their impact is shaped by other government policies, by the economy and by the way that society behaves and reacts to change.

In setting and reviewing its policies, including its spectrum management policies, a regulator needs to understand the implications of its policies as future developments unfold, and to understand how its policies may affect these future developments. As part of this process a regulator needs to understand how technologies are likely to develop, and how their development will affect and be affected by the associated economics and their use by society.

We note that Ofcom believes that in principle there are two reasons for allocation spectrum licence exempt use[3].

- Because the economic value of doing so is greater than the economic value if the spectrum were licensed;
- Because congestion is unlikely and hence the cost of licensing is unnecessary.

Clearly as licence exempt usage increases, so it is likely that the economic value will increase on the one hand, but the potential for congestion may also increase on the other hand – thus potentially limiting the economic value which may be realised. This trade-off and especially how it might be best managed, including consideration of new technologies and spectrum, is at the core of this study.

1.1.1 Previous Ofcom licence exempt work

Ofcom's License Exempt Framework Review (LEFR) statement in 2007, which itself followed the Spectrum Framework Review (SFR) of 2005, was supported in part by research studies carried out in 2006 and 2007. For example Quotient led the Higher Frequency License Exempt (HFLE) study which was co-ordinated via plenary sessions with sister projects looking at Application Specific Licence Exempt (ASLE) spectrum, the Economic Value of Licence Exempt bands, Polite Protocols and Wireless Last Mile.

In brief summary, the LEFR reported the following

- The contribution to the economy of licence exempt spectrum is significant;
- The Application Specific Licence Exempt approach was seen to be an inefficient use of spectrum compared to a commons[4];

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[3] See Ofcom Spectrum Framework Review.

[4] Notwithstanding issues of safety which take precedence.

- Politeness rules are desirable in a commons;
- Light licensing has a role, notably where transmitters are at fixed sites;
- Use of higher frequencies (e.g. >40GHz) is unlikely to experience congestion and thus licence exemption or light licensing is appropriate;
- Very low power devices, such as Ultra-Wideband (UWB) are likely to be suitable for licence exemption;

The LEFR expressly indicated that there was no proposal to introduce any conclusions retrospectively, i.e. into existing bands, but that future bands, including those created by re-farming, should be subject to consideration. One reason for this is that an entire band and its legacy applications would need to be addressed and potentially modified. For example, in the case of politeness protocols, there would be little advantage in having only some applications using such protocols, while other in the same band did not. In fact this is the situation with Wi-Fi today, where self co-existence is good, but there are little or no mechanisms for active politeness with other protocols, not even with other IEEE 802 protocols. Furthermore where Wi-Fi is passively polite, other band users such as video senders are not, putting Wi-Fi at an unfair disadvantage.

The lack of fair sharing and issues of congestion affect the economic value of the band. For example, an assumption used in Ofcom studies in the past is that the value of a band may rise as the number of users increase, until such a point where congestion occurs and the economic value tends to a constant.

Further work on licence exemption resulted in a statement identifying Spectrum Commons Classes as a general policy approach in 2008. This brought together much of the thinking of previous years, and introduced the concept of 'Indicator Values' to gauge the interference potential of an application. Nonetheless, implementation details were found to require significant optimisation on a band-by-band basis. Once again, no proposal was made to make such Classes retrospective and it was noted that such work could usefully be pursued and harmonised at the European level.

Work on cognitive devices produced a statement in 2009. This was followed by a consultation on geolocation the following year, drawing on Ofcom commissioned research[5]. Licence exempt operation of cognitive devices exhibits significant differences compared to traditional operation in the usual licence exempt bands, but many of the same considerations also continue to apply. It should also be borne in mind that the introduction of white space devices in the TV bands (or any other new licence exempt spectrum) could lead to a reduction of congestion in the 2.4 and 5 GHz bands. The cognitive statement once again noted that European co-ordination was appropriate in this area and was being sought via SE43.

1.2 Licence exempt usage today - review

The use of Licence Exempt spectrum is an integral and essential part of UK society and its economy. The economy, of course, could not operate as we know it without spectrum and our 2006 estimate of its contribution put this at 3% of UK GDP[6]. Further we agree with many in the field that in more recent times licence exempt usage appears to be generating an increasing contribution. Licence exempt usage spans a number of sectors and

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[5] "Locating wireless devices where GPS may be unavailable", Quotient Associates for Ofcom, 2010.

[6] "Economic impact of the use of radio spectrum in the UK", covering licensed and Licence Exempt spectrum, Europe Economics for Ofcom, 2006, www.ofcom.org.uk

encompasses technologies which are on the whole short or moderate range. We show examples in Table 1-1.

	WLAN (Wi-Fi)	***Gigabit WLAN***	***Video sender***	***Fast WPAN (Bluetooth)***	***Slow WPAN (ZigBee)***	***SRD/RFID***
Example bands (UK)	2.4, 5 GHz	60 GHz	2.4, 5 GHz	2.4 GHz	868 MHz, 2.4 GHz	433, 868 MHz, 2.4 GHz
Consumer / Entertainment	Home Broadband Access Mobile social networking Audio streaming	HD Video streaming	Home security Baby monitoring Video streaming	Headsets USB cable substitutes Body Area Networks Sports and leisure	Home automation Sensor networks New ISO 14543 low energy/ harvesting	ePayment Remote controllers
Business	Public Wi-Fi Hotspots Cellular data traffic hand-off Intranets HANs for smart metering[7] Asset tracking		Retail Security	Headsets USB cable substitutes	Smart buildings Sensor networks Process control	Stock control Asset tracking Industrial control
Transport	Traveller Internet Access		Passenger monitoring (public transport)	Intra-vehicle connectivity		eTickets eLuggage
Location Services	Wi-Fi SSID					RTLS[8], proximity
Health	Intranets Asset tracking			Medical Sensors Body Area Networks		Medicine identification

Table 1-1 Examples of licence exempt applications per sector versus technology

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[7] HAN = Home Area Network

[8] RTLS = Real Time Location Systems

The use of licence exemption in terms of the number and variety of end uses is ever increasing. In recent times, notable additions to the applications list of Table 1-1 have included, for example

- cellular hand-off to Wi-Fi, where users temporarily leave the cellular network and connect via Wi-Fi at certain hotspots. In recent years there has been an explosion in the demand for mobile data connectivity; it is presently more expeditious and economical for cellular operators to install Wi-Fi hotspots in areas of high and concentrated user demand;
- social networking such as via FaceBook, which from an initial public opening in late 2006, has grown to 900 million users today. More than 50% of users access FaceBook via their smart phones, leading to increased usage of the cellular network and Wi-Fi in hotspots and at home. More than 20% of online time in the USA is spent on FaceBook[9];
- video streaming to tablets, which surpasses FaceBook in terms of data demand as we show below in Figure 1-2.

Applications of interest to this study are those whose spectrum requirements are expected to grow markedly over the next ten years. To identify these we must first identify key applications where market demand is expected to grow[10].

1.3 Future challenges in demand

Several key areas are candidates for future hotspots in the demand for applications using license exempt spectrum. These are

- Broadband data
- Smart metering
- Machine to machine (M2M)
- Web of people and things
- Healthcare
- Intelligent Mobility
- Entertainment
- Wireless sensor networks

We first review each area in turn. Following this we create a limited number of consolidated application groups to take forward in the study.

1.4 Wireless broadband applications

1.4.1 Broadband data growth

The economic value of the UK Internet economy grew to more than £121Bn in 2010, and is predicted to rise to £225Bn by 2016[11]. Both the UK government and the EC have

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[9] NY Times online 15 May 2012, http://www.nytimes.com/2012/05/15/technology/facebook-needs-to-turn-data-trove-into-investor-gold.html?pagewanted=2&_r=1

[10] It should be borne in mind that high market growth for an application will not necessarily translate to a higher demand for spectrum.

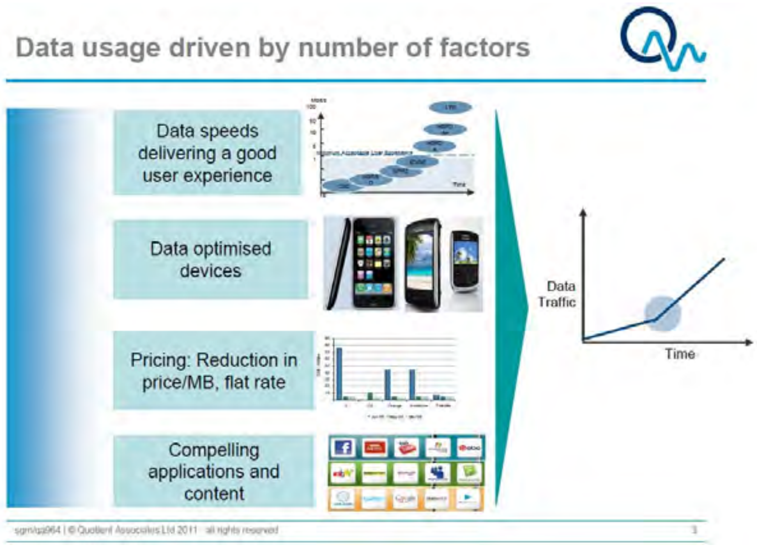
[11] Source: Boston Consulting Group. 2012.

initiatives in place to help achieve the level of connectivity required to support this in the future. For example, DCMS has identified that 500 MHz of spectrum should be released from the public sector by 2020 in order to help cope with the demand and the projected spectrum crunch[12].

In Europe the creation of the Radio Spectrum Policy Program (RSPP) is in support of Europe 2020, including the Digital Agenda which aims to facilitate an advanced digital economy by 2020. Among other goals, this includes broadband connectivity beyond 30 Mb/s for Europeans in 2020, and the introduction of smart grids for energy resource management[13].

At the European level, it is well accepted that more spectrum needs to be made available for such aims to succeed, yet the reality is that much of the finite spectrum available has already been allocated. Because of this, a more flexible approach to allocation and sharing of spectrum is being sought in order to maximise the economic and social value derived from spectrum[14]. A recent workshop described the initial results of an EC study into improving the efficiency of European spectrum usage[15].

It is instructive to consider the drivers of demand for broadband connectivity. Figure 1-1 shows a slide from a representation made to a cellular operator. This shows that a concentration of four simultaneous drivers have come together to create a very sharp up-trend in the demand graph. In many ways broadband is the victim of its own success.


Data usage driven by number of factors

Data speeds delivering a good user experience

Data optimised devices

Pricing: Reduction in price/MB, flat rate

Compelling applications and content

Figure 1-1 Concentration of key drivers for 'Boom' in data demand[16]

The value placed on broadband connectivity by consumers is very high. A recent study by the Boston Consulting Group[17] suggested that a consumer would need to be compensated

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[12] "Enabling UK Growth - Releasing public spectrum" from www.culture.gov.uk .

[13] See, for example "Spectrum for Wireless Innovation in Europe, Digital Assembly workshop, Chaired by Catherine Trautmann, MEP, Brussels 17 June 2011.

[14] The Radio Spectrum Policy Program, http://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/eu_policy/rspp/index_en.htm

[15] "Inventory and review of spectrum use: Assessment of the EU potential for improving spectrum efficiency", European Commission Workshop, Brussels, 10 May 2012.

[16] Source: Quotient Associates presentation to cellular operator client on mobile network economics (unpublished).

[17] http://www.broadbandchoices.co.uk/news/uk-internet-economy-bigger-than-healthcare-and-education-190312.html

by as much as £180 per month to give up internet access. One cannot read across directly from this research to willingness to pay (WTP) for mobile phone use but it is an indication that the value attached to what are still relatively new services of this sort can be well in excess of the average price paid.

Interestingly when asked what they would give up in order to keep their broadband connection, three quarters of people said they would rather give up coffee or chocolate and 65% volunteered that they would rather give up alcohol[18].

The type of application greatly affects the amount of data consumed. At a deeper level it can also be seen that the distribution of data usage between high and average users is also different by application type, as shown in Figure 1-2.

For example, users who use social networking or download applications from app stores, show a gradual increase in usage level from the average to the highest users. In contrast the heaviest users of online video show an exponential increase over users who consume at the average level. Heaviest users might watch 40 minutes of online video per day while the average user might watch 30 seconds. In other words, the top 5% of online video users consume nearly two orders of magnitude greater bandwidth than the average.

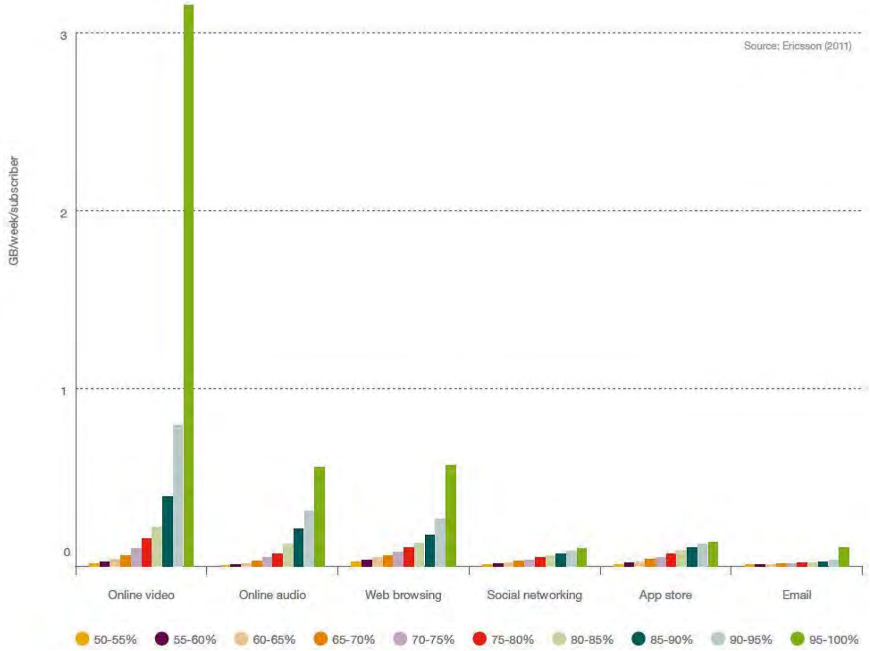

Figure 1-2 Average weekly application traffic for different subscriber clusters of a new Android Smartphone model (high end with large screen) at one specific operator[19]. The vertical scale is GB/week/subscriber. Note that the 95-100% cluster in green denotes the heaviest 5% of users. Users with below average (i.e. 50%) application traffic use are not represented.

This data was collected by Ericsson, who found the data to be independent of smartphone type and concluded that traffic management should focus on online video users as the source of highest demand.

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[18] 17 % of people reportedly said they would rather give up showering.

[19] Ericsson Traffic and Market Data Report, November 2011, www.ericsson.com.

Broadband wireless access to the Internet can be enabled by a number of different approaches using licence exempt spectrum. For the purposes of our study work, we will use the following classes for broadband access.

- Indoor wireless broadband
- Outdoor wireless broadband
- Rural broadband
- Backhaul

We introduce each class in turn.

1.4.2 **Indoor wireless broadband**

This class includes the use of Wi-Fi in the home and office as well as in public indoor sites such as cafes. As with all Wi-Fi broadband access, this approach always involves Wi-Fi plus a separate WAN connection, e.g. Wi-Fi plus ADSL or cable.

Present approach and typical applications

Wi-Fi access points are end-user installed in the home scenario. This may or may not involve some channel configuration on the part of the user, although some newer access points may auto-configure channels In either case, there is no centralised control of channel configuration. This lack of co-ordination may lead to inference with adjacent Wi-Fi access points.

In an office environment, the Wi-Fi architecture and channel plan are often centrally managed by IT staff. Larger installations may use proprietary Wi-Fi enterprise extensions to achieve fast mobility between access points, in some cases fast enough for seamless VoIP. Interference with adjacent Wi-Fi access points is managed within the system.

Indoor Wi-Fi hotspots are also found in cafes and retail outlets. These may be user installed like a home device or may be managed like an office installation.

Factors affecting demand

The rise of IPTV applications, such as iPlayer and LoveFilm on-demand services have increased home broadband demand in recent years and these services require a good connection speed with good QoS; significantly better than that required for simple web browsing. Tablets have also risen in popularity and almost all tablets sold have been Wi-Fi only. In some cases tablet use is replacing mobile phone use for checking email, social networking etc while at home. Tablets are also now viewed as 'the 4th screen' for watching films after cinema, TV and PC.

Demand for Wi-Fi use in the office has been increased by the Bring Your Own Device (BYOD) effect. Employees now expect to be able to connect their personal smartphones to the corporate network to read corporate emails and potentially for personal use[20]. This trend indicates a decreasing reliance on cellular data and wired Ethernet connectivity and a consequent shift to increased Wi-Fi use in the office.

Public indoor Wi-Fi hotspots have seen a surge in popularity as users increasingly expect to be always best connected.

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[20] The security issues this may raise for the corporate network and the privacy issues this may raise for the user are not the concern of this study.

Potential barriers to growth

Especially in the uncontrolled home environment, congestion in areas of high Wi-Fi density may act as a barrier to growth if it leads to poor broadband performance. As well as congestion from other Wi-Fi users, interference from impolite band users such as video senders may also be present in the 2.4 GHz band.

In the office case, although the network may be managed, congestion may still occur at the network edge, plus there is potentially more likelihood of USB 3.0 interference, whose transmission spectrum has significant energy at 2.4GHz[21].

1.4.3 **Outdoor wireless broadband**

Present approach and typical applications

Outdoor Wi-Fi in the UK began as isolated hotspots with fixed backhaul[22] and as such were used nomadically. More recently they are beginning to be installed as managed networks, in some cases with contiguous coverage capability. In either case they may be independent or cellular operator owned, although the independents' business cases generally include arrangements with cellular operators for hand-off. A key use case is hand-off from the cellular network, to reduce pressure on cellular networks.

There also exists an end-user led application of outdoor broadband in the area of community networks. Here a communications hub with backhaul is procured for a previously isolated community and that subsequently the community organises a way to distribute the hub connection around the community, such as by Wi-Fi. This approach has been used for some time in many locations around the world.

Factors affecting demand

Already most (80%) of UK mobile phone data traffic is delivered via Wi-Fi, based on results gathered from the Mobida dedicated smartphone measurement app[23]. This proportion relates to the total Wi-Fi use over all connection methods, i.e. including public, home and office. It is conceivable that over the 10 year time horizon of this study, when solutions for Wi-Fi fast mobility are adopted by the market and a more contiguous Wi-Fi footprint is available, we may see the advent of Wi-Fi only broadband operators in direct competition with today's cellular operators.

Potential barriers to growth

The range limitations of Wi-Fi mean that for wide area coverage an alternative approach such as macro cells will always be needed. Limitations to increased Wi-Fi deployment also come from the paucity of channels available within the presently popular 2.4 GHz band. A move to include the 5 GHz band is already under way as the availability of 5 GHz Wi-Fi increases in user equipment.

At present, hand-off from cellular to Wi-Fi is a break-before-make service, so end user communications sessions are interrupted. This may not impact too noticeably when emailing and web browsing, but it will stall multimedia flows and VoIP will be unworkable. What is required is a hand-over rather than a hand-off, such that IP sessions are maintained. Transparent authentication (e.g. via SIM card) is also required.

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[21] "USB 3.0 Radio Frequency Interference Impact on 2.4 GHz Wireless Devices" Intel White paper, April 2012.

[22] Including fixed wireless backhaul.

[23] "Understanding today's smartphone user: Demystifying data usage trends on cellular & Wi-Fi networks", Informa White Paper, 2012.

1.4.4 **Rural broadband**

Present approach and typical applications

Not spot and rural broadband solutions benefit from longer range technologies, which traditionally is not the realm of licence exempt devices. However, the use of white space devices (WSD) in the TV band may be set to change this. Working at these lower frequencies results in longer range, Figure 1-3. Geolocation database control is required to ensure that interference is not caused to the primary users of the TV bands, leading to a situation where WSDs are opportunistic users of spectrum. WSD networks are not presently commercially deployed in the UK, but initial trials have occurred in Cambridge and Bute to help prove the concept[24].

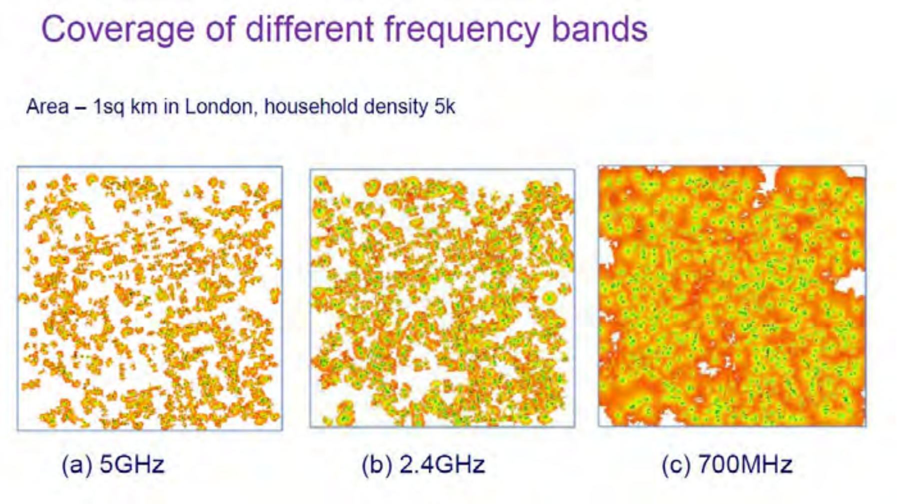

Figure 1-3 Coverage at various frequencies compared[25].

Factors affecting demand

Limited bandwidth in an unused TV channel means a limited connection speed is available per channel. However the creation of any new Internet connections, where none existed before, will help bridge the digital divide even if it does not meet superfast broadband targets. EU project QUASAR has used British Telecom (BT) as a positive business case example of WSD rural broadband provision in the UK, based on reusing BT plant.

Potential barriers to growth

Presently Ofcom does not allow WSDs, but this situation is expected to change in 2013. The limited speed available per channel may be addressed by new modulation technology, as we discuss in the Chapter 2.

1.4.5 **Wireless backhaul**

Present approach and typical applications

Wireless backhaul can be very convenient in cases where access to communications infrastructure is difficult, or where an installation needs to be made in the shortest possible time. Today, point to point wireless Ethernet bridging at 2.4 GHz and 5 GHz is

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[24] See Section 4.3.2.

[25] Michael Fitch, Cambridge Wireless Small Cells SIG, 29th March 2012.

used with 5 GHz presently better for lower interference. An example is O2's London Wi-Fi network where Ruckus Wi-Fi access points at 2.4/5 GHz are linked by wireless meshing at 5 GHz[26]. This approach was predicted some time ago by EU project BuNGee which outlined 'under-the-rooftops' wireless backhaul links.

Higher capacity can be had at a higher equipment cost by using 'wireless fibre' (i.e. a wireless link with the fibre-like capability) which operates in the lightly licensed 70/80 GHz bands, or the unlicensed 60 GHz band. This is presently of interest to the small cells community[27].

Factors affecting demand

The greater the installation of small cells, the greater the need for backhaul, including wireless backhaul. Demand is therefore expected to grow strongly.

Potential barriers to growth

It is possible that, in future, congestion and potentially range limitations will be a problem in the 5GHz band. This may drive line of sight applications towards microwave frequencies, where limiting technical factors are likely to include tower space and concentration of radio paths in dense areas.

1.5 Sector specific applications

Broadband wireless access, as described in the previous section, is used across all sectors of the economy. However in some sectors licence exempt spectrum use is for more specific data communications needs. We next examine these sectors, which are summarised in Figure 1-4.

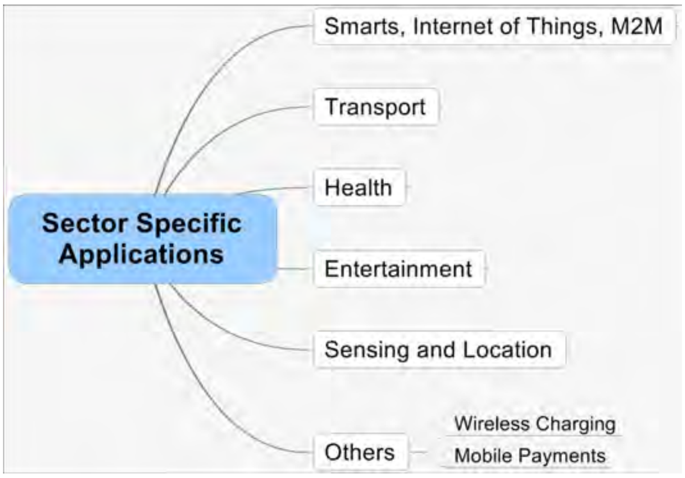

Figure 1-4 Sector specific applications relevant to licence exempt spectrum

1.5.1 Smarts, Internet of Things, M2M

We have used the terms 'Smarts' for the following:

- Smart Meters
- Smart Homes

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[26] http://www.ruckuswireless.com/press/releases/20120730-o2-makes-first-big-move-to-small-cells

[27] "Non-Line-of-Sight Wireless Backhaul for LTE Picocell Deployments", Peter Claydon, Airspan, Cambridge Wireless, January 2013.

- Smart Cities

There is some overlap between these categories and the more general categories

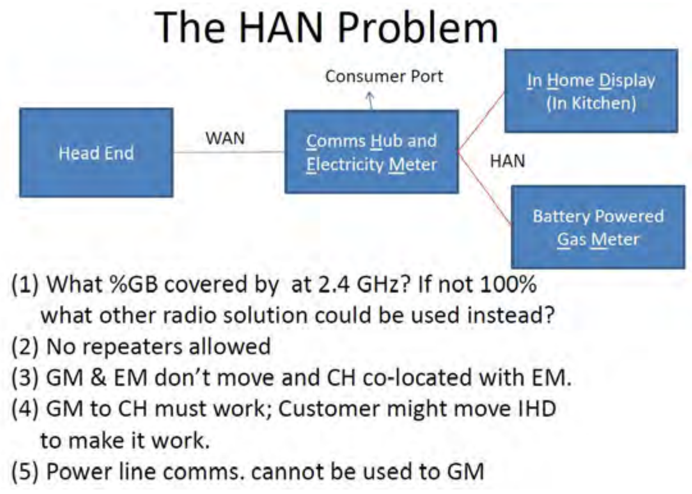
- Machine to machine (M2M)
- Internet of Things (IoT)

We review each in turn

Smart meters

A European Digital Agenda goal is the introduction of smart meters and grids[28] for energy resource management. Similarly the UK Government, via DECC, announced that it has an objective for each UK residence to have a smart meter.

However the smart meter approach across the world is still quite fragmented in terms of the communication technologies needed. Some of this is due to the different geographies encountered and some may be due to lack of standards or spectrum. In the UK a long range communications solution, plus wireless home network (HAN) solution appears to be most favoured, whereas in the USA mesh networking in unlicensed frequencies not available in the UK is gaining traction (915 MHz). The UK (DECC) favours a communications hub approach, as shown in Figure 1-5.



The HAN Problem

(1) What %GB covered by at 2.4 GHz? If not 100% what other radio solution could be used instead?
(2) No repeaters allowed
(3) GM & EM don't move and CH co-located with EM.
(4) GM to CH must work; Customer might move IHD to make it work.
(5) Power line comms. cannot be used to GM

Figure 1-5 UK Home Area Network (HAN) approach for smart metering (GM = gas meter, EM = electricity meter, CH = communications hub, IHD = in-home display)

DECC held a HAN trial over 120 selected homes from Nov 2011 to May 2012, the results of which were described in a recent presentation[29]. The trial considered the used of four licence exempt frequencies

- 169 MHz;
- 433 MHz;
- 868 MHz;
- 2.4 GHz.

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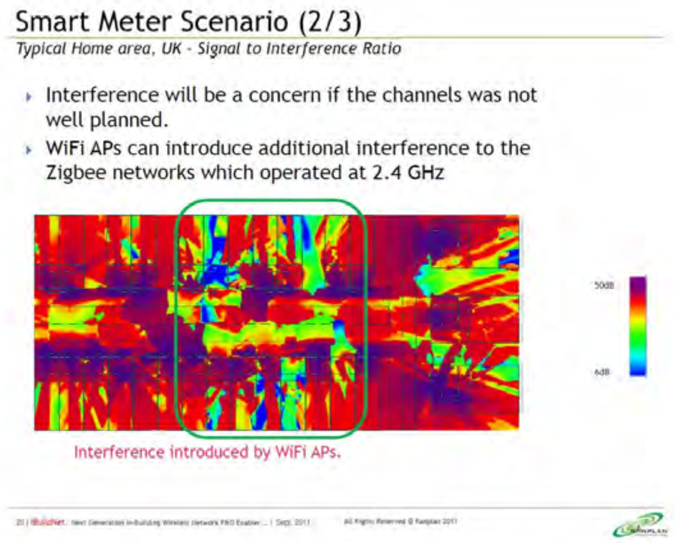
[28] Smart meters give simple visual feedback to the consumer; smart grids add a control element for the grid.

[29] "The Home Area Network Radio Challenge in GB", William Harrold, IET London, 26 April 2012.

No clear winner in terms of frequency band was found via the measurements. The approach was described as employing 2.4 GHz where this was found to work, with the other frequencies in descending order of preference by frequency. Impediments found included path loss due to distance, metallised insulation (foil backed) and metallised windows. Connecting to the gas meter is a particular challenge as it presently has no wiring, so the unit must be battery powered (leading to limitations on the radio) and cannot use power line communications, plus the gas meter is often relatively inaccessible at a property.

In summary, 2.4 GHz is the favoured frequency band for UK smart meter Home Area Networks, with 868 MHz as second choice due to limited bandwidth. The lower frequencies are unlikely to provide the bandwidth required. Whether dual frequency units should be produced is the subject of a current consultation from DECC.

Although roll out was set for 2012, there would appear to be issues on interference which have not yet been fully characterised. As shown in Figure 1-6, a smart meter HAN at 2.4 GHz and ZigBee are not expected to coexist well (this experiment used Wi-Fi as the HAN in order to model interference, but which will not prove practical in the field due to the overheads and power consumption of Wi-Fi).



Smart Meter Scenario (2/3)

Typical Home area, UK - Signal to Interference Ratio

- Interference will be a concern if the channels was not well planned.
- WiFi APs can introduce additional interference to the Zigbee networks which operated at 2.4 GHz

Figure 1-6 Smart meter (Wi-Fi) interference with Zigbee[30].

There is a move in Europe (CEPT SE24) to designate the band 870-876 MHz for smart meter operation. Use of this band is not yet resolved but DECC are aware of this move and have not ruled it out as a UK solution, although progress has already been made with other approaches.

Smart Homes and Smart Cities

Smart homes encompass home automation and remote control, such as control of heating from a mobile phone. Smart cities expand on the scope of this on an industrial scale to include building automation (e.g. HVAC – heating ventilation and air conditioning), sensor networks (to sense weather, traffic conditions etc), traffic light and street light control, for example. Smart cities in particular are very similar to the general

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[30] Wireless Systems in the Home Environment", Richard Langley, U Sheffield, IET London, 26 April 2012.

classification of wireless sensor networks. One specific smart city application is M3N, metropolitan mesh machine networks.

In the main the applications are short range and use ZigBee or Zigbee like protocols in the 2.4 GHz band. We found in earlier work for Ofcom that a greater availability of suitable channels in the 868 MHz band would improve the prospects for smarts and other sensor networks[31].

Machine to machine (M2M)

Beyond 'smarts', the wider area of M2M is gaining much attention, with a notable focus on automotive applications using cellular communications, as shown in Figure 1-7. The detail of the automotive applications are not given in the figure, but we know, from our forward-looking Transport Study[32] for Ofcom, that the most popular applications will include eCall (an eCall vehicle can dial the emergency services automatically), telematics for vehicle manufactures/service centres and driver navigation. Where privacy concerns allow, tracking could also be used for stolen vehicle recovery and driver insurance purposes.

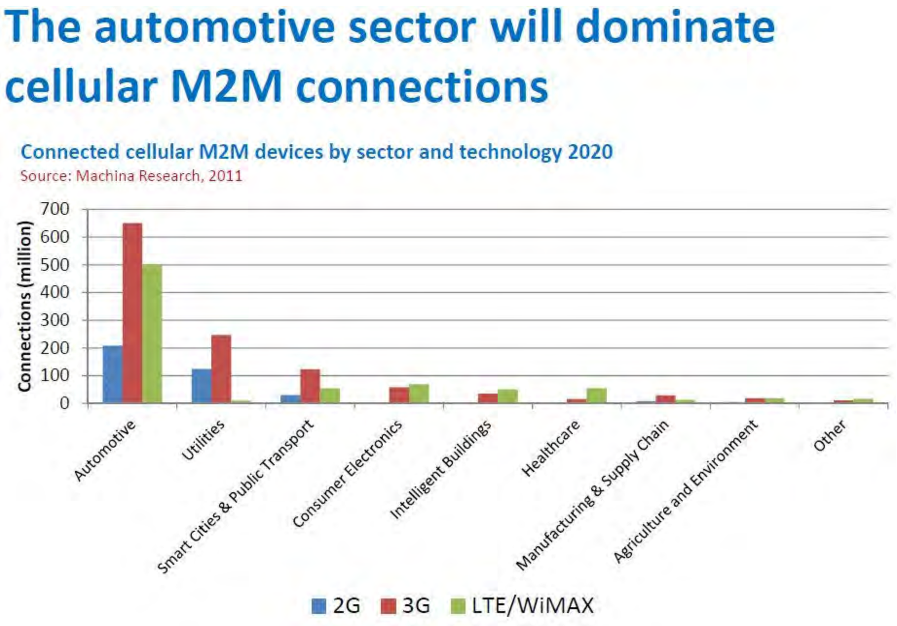

Figure 1-7 For cellular M2M, the automotive sector is predicted to be the greatest user[33].

The rise in demand for cellular M2M in the automotive sector is likely to be mirrored by a rise in the demand for Wi-Fi connectivity. As shown in Figure 1-8, future electric vehicles will have a near-constant need to communication both with a data centre ('CWDC' in the figure) and the driver. Driver communications will be needed both when inside the car and away from the vehicle, such as at home or office where Wi-Fi is likely to be used.

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[31] "Wireless Sensor Networks", Steve Methley, for Ofcom 2008,www.ofcom.org.uk.

[32] "Transport Sector Study, Quotient Associates for Ofcom, 2008, www.ofcom.org.uk

[33] "Realizing the potential of the 'Connected Life'", Machina Research/GSM Association, October 2011, available from www.gsma.com.

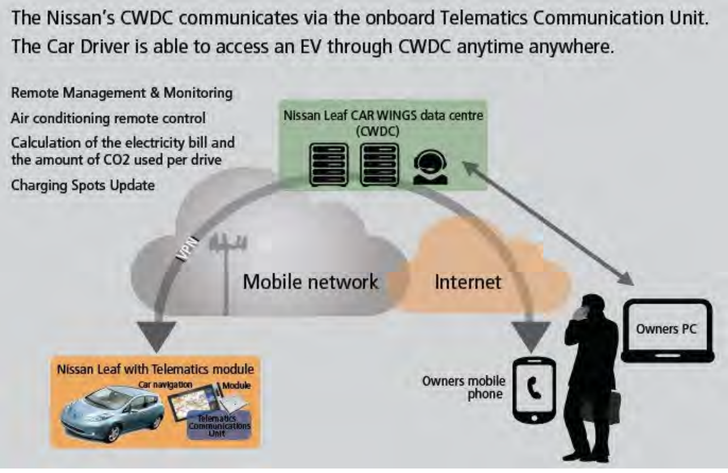

Figure 1-8 Nissan electric car communications network, cellular and Licence Exempt[34]

Although future electric vehicles may have the greatest need for communications based on the limitations of their power source, all vehicles will have a growing need for navigation updates and service telematics, which can both involve large file sizes and are likely to use Wi-Fi when at the home or office.

Internet of Things (IoT)

Many definitions of the Internet of Things exist, but on the whole they have a theme of 'more things being connected'. We can se examples of this today via wireless personal area networks (WPANs) connecting Bluetooth and other devices.

The European Commission estimates that 70 billion devices will be connected by 2020. As shown in Figure 1-9, the trend for connectivity of people and their things is well under way. It is already becoming the norm for a new TV to have a Wi-Fi connection.

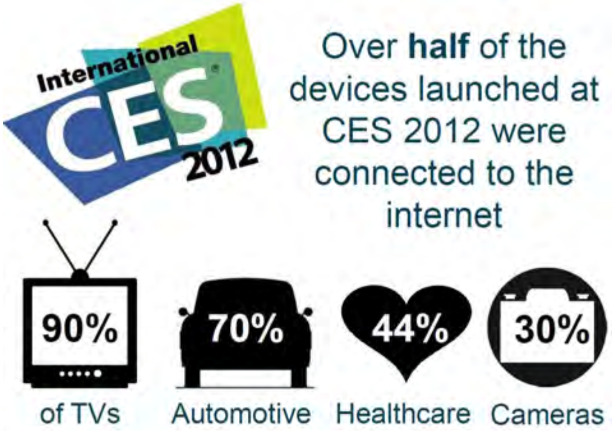

Figure 1-9 New devices show increased Internet connectivity[35]

Interestingly, the increase in Connected Health devices involves a considerable consumer component whose use devices for sport and leisure. It also includes the 'worried well' who wish to monitor their health, but may have no particular condition.

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[34] Nissan case study by the GSM Association, from www.gsma.com

[35] Presentation by Mike Short of Telefonica, using data from GSMA Connected Life press releases, www.gsma.com .

An interesting new area within IoT is wearable technology. Google has showcased prototype 'Smart Glasses', Figure 1-10.

Figure 1-10 Google 'smart glasses' prototype.

A small display is built into the glasses, to provide information to the user. The users may communicate using the glasses via a WPAN of microphones, speakers, cameras and other sensors. Smart watches have also been introduced, for example by Sony. Apple is widely expected to follow suit.

Figure 1-11 Smart watch released by Sony.

IMS research has predicted that the wearable technology market will exceed $6 billion by 2016[36]. Although the applications are expected to be very short range in the WPAN, a wireless WAN connection is very likely to be required in addition. Both are likely to be licence exempt.

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[36] http://imsresearch.com/press-release/Wearable_Technology_Market_to_Exceed_6_Billion_by_2016

Finally, RFID is considered part of this group and we concur with the findings of CEPT studies and industry opinion that RFID will experience high growth over the next 10-15 years.

Potential barriers to growth

Across all the smarts, M2M and IoT, a major limit to growth in Europe is the availability of only one 20kb/s Zigbee channel at 868 MHz. This contrasts strongly with the 10 channels at 30 kb/s available in ITU Region 2. This constrains most manufacturers to release ZigBee based equipment at 2.4 GHz in Europe, forcing a less attractive power/range capability and adding to the congestion at 2.4 GHz. However, for very narrow band low duty cycle proprietary applications, 868 MHz is still used, for example in street light control in the UK.

1.5.2 **Intelligent mobility**

We know, from our forward-looking Transport Study[37] for Ofcom, that the transport sector does not need a great deal more dedicated spectrum in the future, given that the 5.9 GHz band has now been allocated to car-to-car applications[38].

However, based on that study and more recent work on the Informed Personal Traveller, we do expect the transport sector to generate more broadband access to the Internet. This is to provide traveller information, not as a broadcast update, but rather targeted towards an individual traveller's needs. Apart from travel information this is also expected to include eBooking and eTicketing functions. In terms of spectrum, this means more access to cellular and Wi-Fi systems for broadband Internet, especially where these are installed as small cells at points of public transport interchange, such as railway and bus stations, and airports, for example. We have already covered broadband Internet access for the purposes of electric vehicle monitoring in section 1.5.1.

A further trigger which could cause a more specialised requirement than public broadband access for travellers would be the advent of road user charging (RUC). In our 2006 Transport report, we showed that this depended on future decisions by Government, but that public resistance appears to be high. However, if it were to be introduced, we would expect licence exempt spectrum to become in demand for communications where vehicle mounted RUC tags were employed.

Aside from Internet access, Transport applications using license exempt spectrum in future are expected to include driverless transit.

Potential barriers to growth

Broadband Internet access for the traveller is seen to have few barriers to adoption and has begun already, but in spectrum terms this is no different to the broadband Internet access application as described in section 1.4. As such they will suffer the same potential congestion and range limitation issues. Road User Charging would be a specific application with a potentially large demand base, but is still awaiting a political decision.

1.5.3 **Connected health**

Spectrum in the heath sector splits conveniently into that used in hospitals and that used outside.

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[37] "Transport Sector Study, 2008, www.ofcom.org.uk

[38] So far, this band has seen little usage.

Outside hospitals, teleheath (remote monitoring, diagnosis etc), telecare (independent living) and social alarms all require wireless communications. On the whole, teleheath and telecare use licensed wireless WANs for connectivity, i.e. the cellular network. Social alarms on the other hand use SRD spectrum, for example at 869 MHz. Social alarms are unusual in that, despite being a safety of life service, they are licence exempt in a shared band. Nonetheless this has worked well for many years and a reliable 50m indoor range is reported for social alarms at this frequency[39]. Unfortunately the advent of the LTE band at 800 MHz is widely anticipated to be a potential issue for many SRDs. We are aware that measurement work has been commissioned by Ofcom and others in this regard.

In hospital, wireless is used for professional equipment, patient communications and equipment tracking. Wireless used for professional equipment is often licensed and controlled in the hospital environment by qualified hospital staff. However, notable exceptions include spectrum for medical implants, presently using 406 MHz, and some aspects of patient monitoring, presently in the Wi-Fi bands.

Patient communications and asset tracking is normally installed by non-medically qualified IT support groups, and uses license exempt spectrum. We know from our work in location for Ofcom[40], that the network load presented by real time location systems (RTLS) operating in the Wi-Fi band is relatively low, much lower than for normal data communications over Wi-Fi.

Potential barriers to growth

In interviews with manufacturers and the TSB assisted living group, we found that the Telehealth sector is not looking for any significant increase in license exempt spectrum. However, it was stressed to us that the sector is very concerned about loosing performance in the spectrum bands they presently use.

In-hospital monitoring and medical implants are presently seeking more spectrum.

1.5.4 **Entertainment**

In the entertainment area, Intel WiDi is a Wireless Display link, based on Wi-Fi but operates a virtual access point (AP) in peer to peer mode. Apple also has a proprietary peer to peer capability over an existing Wi-Fi network for iPad display mirroring to a TV. In the 5 GHz band the WHDI alliance have promised to produce a generic display mirroring solution. In the 60 GHz licence exempt band there are wireless display links using WiGig and Wireless HD, which offer a much higher data rate, so the delays of compressing video data can be avoided, which can be important for interactive game playing.

Video senders and display links are also used in the home. Ofcom commissioned work in 2006 to examine congestion in the 2.4 GHz band and a major cause of interference to Wi-Fi was reported to be from video senders.

Potential barriers to growth

Potential issues include congestion and interference. Interference in the 2.4 GHz band may arise from other wireless devices, but also from USB 3.0[41]. Congestion may be increased by peer to peer 802.11 based devices at 2.4 and 5GHz.

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[39] Source: interview with a social alarm manufacturer.

[40] "Locating Wireless Devices where GOPS may not be available", Quotient associates for Ofcom, 2010.

[41] See footnote 21, page 18

1.5.5 Wireless sensor networks

In general, wireless sensing covers a wide range of applications, including aspects of smart cities for example, but it also covers more specialist applications such as weather and environmental monitoring, industrial process control and heavy plant monitoring (oil pipelines etc).

Location covers asset tracking which encompasses supply chain stock control, freight tracking, stolen item recovery and more recently on-the-shelf, real time consumer goods pricing. RFID is used extensively in stock control and asset tracking, while asset tracking also commonly employs 2.4 GHz RTLS (real time location system) based on Wi-Fi.

We studied wireless sensor networks (WSN) and location in previous projects for Ofcom[42]. In the former we noted that there was a scarcity of sub 1GHz spectrum for wireless sensor devices using ZigBee, with only a single, narrow channel in the 868 MHz band. We also noted the interference issues between Wi-Fi channels and ZigBee channels at 2.4 GHz and that, often, physical separation was the only solution.

Potential barriers to growth

The UK and Europe suffer from a smaller sub 1 GHz allocation for SRDs than for instance the USA. There are fewer channels for RFID and ZigBee. Ofcom have recently issued a second consultation on the paired band 870-876 and 915-920 MHz, plus CEPT have studied this for smart meter and RFID use. If this band could be shared with SRDs then this would remove a barrier to growth via increasing operational capacity.

1.5.6 Further specific applications

We include two further growing applications for completeness, although they fall outside the scope of this study.

Wireless charging

Wireless charging has been used for consumer goods such as tablets and phone, but also for electric vehicle recharging. However, the frequencies used appear to be around 100 kHz and below. This falls outside the scope of this study due to the low frequency and very short range.

Mobile payment

Mobile payment has been introduced based on near field communications[43], for example in mobile phones and also as separate cards, such as London Transport's Oyster Card. This falls outside the scope of this study due to the very short range.

1.6 Consolidated key application groups

By inspection of the foregoing, we can reduce the number of distinct application groups of interest to just four.

In particular, the aspects of Intelligent Mobility which relate to informed personal travel information can be included within the more general class of Wireless Broadband, as can the whole of the Entertainment application. Wireless Sensor Networks have a high level of synergy with smart cities and the Internet of Things. The Internet of Things also includes all the 'smarts', RFID and devices used in wireless personal areas networks (WPANs).

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[42] "Wireless Sensor Networks" and "Locating Wireless Devices where GPS is Unavailable"

[43] This is differentiated from RFID due to very short range.

In summary our four key applications groupings are

- Wireless broadband;
- Internet of Things;
- Connected Health;
- Intelligent mobility.

We will employ these groups throughout the remainder of the study.

2 TECHNOLOGIES

2.1 Introduction

Technology innovation may involve improvements made to wireless operation within existing bands or may provide an avenue to enable use of new bands which effectively then also become substitute bands for existing licence exempt applications. Technology improvements may result in a reduction in the spectrum needed, such as via improved modulation schemes, but they may also result in an increase in the spectrum required when addressing the need for greater user data bandwidth. Some improvements, such as better co-existence may be best suited for application specific bands or parts of bands, and hence may be most likely to see adoption in new spectrum.

Technology advances may be usefully split into those which occur at lower layers, including physical layer and medium access control, and upper layers, including networking and other functions up to the application layer[44]. Ancillary functionality such as authentication or network discovery may also be part of the higher layers.

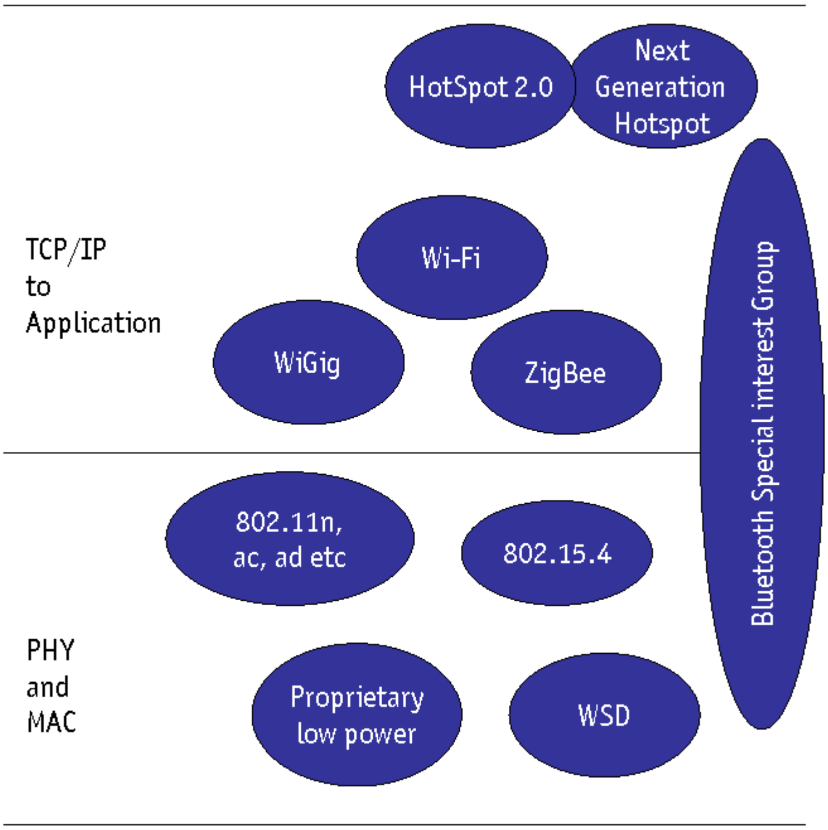

Figure 2-1 Technologies mapped to most relevant OSI layers

Figure 2-1 shows example technologies of interest to this study mapped to upper and lower layers. Making the distinction is useful, as often standards do not specify all layers; IEEE 802 for example typically specifies only the lower, radio layers. It is then left to other

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[44] With respect to the OSI seven layer reference model

bodies such as the Wi-Fi or ZigBee Alliances[45] to specify the higher layers to add to relevant IEEE standards such as 802.11 and 802.15. It is in manufacturers' interests to form such industry alliances in order to promote inter-operability and a hence larger total market.

In this chapter, we first look at a range of communications technologies used in licence exempt device bands, beginning with Wi-Fi. We then examine technologies and approaches to band sharing. Following this we map specific technologies and their sharing potentials to our key applications groups. Finally we summarise key implications of the technologies discussed.

2.2 Communications technologies

A number of technologies are used in common across various applications; hence we provide an overview of the common technologies here.

2.2.1 Wi-Fi and IEEE 802.11

As stated above, IEEE 802.11 specifications typically cover only the lower layers. In these layers, modulation, power and media access are defined. On top of these must be added networking and higher layers in order to produce a fully functional communications system. In the case of IEEE 802, the higher layer specifications are produced by trade bodies, such as the Wi-Fi Alliance.

802.11 specifications

Regular speed increases have been seen in IEEE 802.11, over the years. Early increases were due to modulation improvements, notably the move to OFDM, whereas later increases have also had a contribution from antenna techniques, specifically MIMO and from expansion of the RF bandwidth used, initially doubling channel bandwidth but now looking at four times and eight times the original 20 MHz channel width. This latter approach clearly puts more pressure on available spectrum and may thus increase congestion.

In terms of frequency of operation, 2.4 GHz has historically seen the most products, but more recently 5 GHz devices have been able to be produced at a more attractive price point in order to use the higher bandwidth available[46] and to take advantage of what is a relatively quiet band at the present time[47]. Where a very large bandwidth is required, such as for uncompressed HD video transmission, IEEE 802.11 specifies Wi-Fi operation at 60 GHz. There have also been other 802 standards to suit available frequencies, notably to address light-licensed operation in Japan and the USA and the recent formation of working group 11aj to address 45 and 60 GHz operation in China[48].

In Table 2-1, we summarise 802.11 standards which have been key to the ever increasing speed of Wi-Fi.

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[45] http://www.wi-fi.org/, http://www.zigbee.org/

[46] See Chapter 4 for a description of the bands available at 5GHz.

[47] Ofcom conducts measurement campaigns from time to time.

[48] 802.11aj is also referred to as CMMW, China Millimetre Wave.

Standard	***Frequency***	***Max Speed***	***Max Bandwidth***	***MIMO***
802.11a	5 GHz	54 Mb/s	20 MHz	N
802.11b	2.4 GHz	11 Mb/s	20 MHz	N
802.11g	2.4 GHz	54 Mb/s	20 MHz	N
802.11n	2.4 GHz, 5 GHz	600 Mb/s[49]	40 MHz	Y
802.11ac[50]	5 GHz	>800 Mb/s[51]	160 MHz	Y
802.11ad[52]	60 GHz	7 Gb/s	4 channels of 2.16 GHz[53]	Beam-forming

Table 2-1 Wi-Fi speeds[54], bandwidth and operating frequencies

At the time of writing 802.11n represents the latest mature generation of Wi-Fi, with 11ac beginning to arrive now and 11ad a little further out in terms of mass market products. While both offer higher speeds, 11ac is specifically intended for use at 5 GHz in similar manner to applications presently served by 11n, for example for whole house coverage. IEEE802.11ad is for single room applications such as uncompressed video transmission (an HD stream is around 3 Gb/s) or for wireless docking of laptops, including the display connection and 'instant' data backups.

IEEE 802 is not presently studying Wi-Fi variants any faster than 11ac, as this can already reach gigabit speeds. We examine the relevance of this in Chapter 5, where we look at balancing the supply and demand of spectrum.

Effect of frequency

In general, as the frequency of operation is increased, range reduces. When moving between 2.4 GHz and 5 GHz, the reduction in in-building coverage reduction is modest. However measurements have shown that a UK house which has full coverage at 2.4 GHz may have only 90% coverage at 5GHz[55]. This can be very important as a key application is a wireless access point for whole house Internet access.

Coverage at 60 GHz is much smaller, of the order of ten metres and may consist of directional beams. This restricted coverage is a bonus for the intended application of HD video distribution, where the range is sufficient for a single room and the directionality enables a high frequency reuse, bringing the user benefit of many links in the same house while avoiding congestion. Multiple antennas are highly feasible at 60GHz[56], but steerable beams (rather than MIMO) will be a more appropriate use of multiple antennas for the target applications.

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[49] For four spatial streams in a 40 MHz channel, using the lowest coding rate and highest order modulation. It is common in today's products to have only two or three spatial streams, leading to proportionally lower throughput. For example, two streams leads to a maximum speed of 300 Mbps.

[50] This is occasionally referred to as '5th generation Wi-Fi'.

[51] Rate per spatial stream in 160 MHz bandwidth; three streams would result in excess of 2.5 Gbps.

[52] Also commonly called WiGig, see http://wirelessgigabitalliance.org/

[53] Not all channels are available in all countries.

[54] Peak theoretical speeds. may be lower in practice due to distance from AP etc.

[55] "In home propagation", Aegis et al for Ofcom, 2011.

[56] Antenna size is inversely proportional to frequency.

Effect of bandwidth

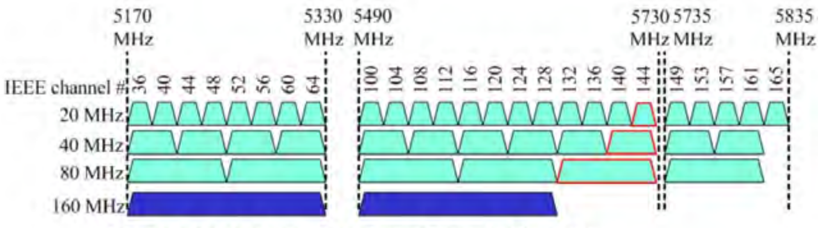
One way to increase bandwidth is by using multiples of the basic channel bandwidth, or by using much larger channels in the 60GHz band where 7 GHz is available[57]. However at 2.4 GHz and 5 GHz, wider channels can quickly consume the majority of the available spectrum, leading to an increased risk of congestion. This is especially true at 2.4 GHz which has only three independent 20 MHz channels. Therefore using 40 MHz channels via 802.11n at 2.4 GHz is not recommended by the Wi-Fi Alliance.

Tri-band Wi-Fi networks

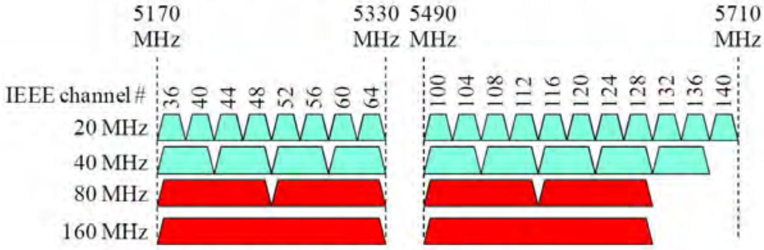
We can expect tri-band Wi-Fi networks in future[58]. This is influenced by the fact that 802.11ac, the upcoming Wi-Fi flagship is 5 GHz only and 802.11ad, with its huge bandwidth of shorter range connectivity for docking and displays, will work at 60 GHz only. In addition, 2.4 GHz (802.11g, n) will still be needed for legacy Wi-Fi devices.

Very wide channels

It might be thought that with a greater diversity of application bands, then congestion would be reduced. As already mentioned this must be balanced by the fact that wider channels will be available. This is illustrated in Figure 2-2 for 11ac's target band of 5GHz.



US and Global Operating Class Channel Allocation



Europe and Japan Class Channel Allocation

Figure 2-2 Effect of wider channels at 5 GHz[59]

It can be seen that, although in Europe we have 19 channels of 20 MHz in 5 GHz, that falls markedly when 40, 80 and even 160 MHz channels are used. At 80 MHz, there are only four independent channels, not too different from the three independent 20 MHz channels in 2.4 GHz today. Thus similar congestion issues might be expected at 5 GHz. If 160 MHz channels become popular in the market, then the situation at 5 GHz will be worse than today's situation at 2.4 GHz. By the same token a similar potential solution exists – that of

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[57] While 11ad present the same MAC interface, the MAC detail differs from all earlier versions.

[58] Chip makers have announced partnerships to achieve this, see e.g. http://arstechnica.com/information-technology/2012/07/tri-band-wifi-chips-for-7gbps-speed-coming-from-marvell-wilocity/

[59] Broadcom White paper, "802.11ac Technology", www.broadcom.com.

re-distributing demand over both the 2.4 and 5 GHz bands more evenly, for example by reserving 5 GHz for higher bandwidth applications[60].

To counter the effect of wider channels causing congestion for legacy devices, 802.11ac includes a built-in fall back mechanism to narrower channels, as we describe in Chapter 5.

Mi-Fi

Mi-Fi refers to a personal Wi-Fi hotspot which is backhauled to the Internet via a cellular connection, typically 3G in the UK. The technology to do this already exists and Mi-Fi is available via standalone devices, or via Smartphones. By use of personal hotspot, the availability of Wi-Fi is extended beyond the typical locations of fixed installations in homes, offices and the high street. Mi-Fi performs the opposite of what cell offload seeks to achieve (in other words it is on-loading to the cellular network) but still represents another source of Wi-Fi congestion. But use of MiFi can be more convenient than finding and logging onto public Wi-Fi, at least at the present time.

Wi-Fi Alliance higher layer specifications

The Wi-Fi alliance adopts the 802.11 specifications and builds on them so that manufacturer interoperability is ensured across a range of applications. The Alliance owns the Wi-Fi trademark.

Two particular forward looking programs from the Wi-Fi Alliance are of interest.

- Hotspot 2.0, Passpoint
- Wi-Fi Direct, Miracast

Passpoint is the term used for devices certified to the Hotspot 2.0 standard. This builds upon work done in 802.11u and addresses automatic hotspot discovery and selection, a necessary part of Wi-Fi hotspot roaming. For successful roaming, authentication is also required. A complementary program from the Wireless Broadband Alliance[61] called Next Generation Hotspot (NGH) particularly addresses the need for authentication to work seamlessly across different operators. Passpoint/NGH is a key future technology combination for public Wi-Fi hotspots.

Wi-Fi Direct is a point to point connection method for devices; no traditional access point is required. In fact Wi-Fi Direct operates an embedded access point in one device so another device may connect. This is of great interest as Wi-Fi Direct thus offers a fast cable replacement function. This may replace Bluetooth in certain circumstances where it is especially convenient, for example a smartphone to printer link, although Bluetooth will still be a better match tor low power applications.

In future, Miracast will be the term used to describe devices certified to the Wi-Fi Display specification, which is based on Wi-Fi Direct connectivity and targeted specifically at screen sharing, also referred to as screencasting. The functionality offered to the user is similar to proprietary approaches such as Apple's Airplay and Intel's Wi-Di[62].

Wi-Fi Future Directions

There is currently no proposal to make Wi-Fi go any faster.

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[60] 2.4 and 5 GHz have a degree of substitutability, but 60 GHz is for very different applications.

[61] http://www.wballiance.com/

[62] Airplay works only with specific Apple products and Intel Wireless Display (Wi-Di) works only with the company's Centrino chipset. Source: company websites. Intel has indicated it will join the open Miracast platform in future releases.

However, two new application-directed working groups have begun recently which are of interest. These are

- **802.11af**, TV White Spaces, also called 'White-Fi'.
- **802.11ah**, sub-1GHz, ultra lower power for sensors;

11af is in its second working group draft and 11ah expects a first working group draft in mid 2013[63].

Targeted at white spaces, 11af has limited channel bandwidth relative to the bands at 2.4 and 5GHz, but the longer range provides the motivation. A prototype working with a white space database was demonstrated by NICT (Japan) in October 2012[64]. The approach follows the FCC WSD rules.

With applications in sensors and smart meters, 802.11ah aims for very low power operation. In fact 11ah is targeting the M2M market generally, aiming to be 'the next big thing' in communications and to emulate for M2M what cellular did for voice. In this sense it competes directly against proprietary specifications for M2M like Weightless from Neul[65]. Rather than targeting WSD like Neul, it is anticipated that 11ah will target the 915 MHz USA band and any suitable bands which may become available in the EU to augment the rather narrow 868 MHz band. Possibilities exist at 870-876 and 915-921 MHz, see Chapter 4. The precise direction of the standard is still to be confirmed, as 11ah is not yet in first draft.

WiGig Alliance specifications

The WiGig Alliance performs a similar function for WiGig as the Wi-Fi Alliance performs for Wi-Fi. Specifically, in addition to the customary IP adaptation interface, DisplayPort/HDMI and PCIe/USB interfaces are specified[66]. These specifications enable the low level 11ad functionality to address higher level connection and network applications.

Note that we consider the potential for additional spectrum for licence exempt devices separately in Chapter 4.

2.2.2 Wireless video technologies

In- home wireless video technologies fall into two broad camps.

- Firstly, there are relatively low bandwidth solutions; these are aimed either at transmitting small screen, low resolution video such as from phones to larger displays or transmitting standard video which has been compressed to a lower bandwidth.
- Secondly there are solutions which transmit high bandwidth video. This video may be uncompressed or lightly compressed. The most obvious desire to use uncompressed video may arise from considerations of movie quality, but gaming is equally important. No compression or low compression translates to low latency, which is essential for interactive gaming.

Several standards exist or have been proposed.

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[63] Source: IEEE 802.

[64] See http://www.nict.go.jp/en/press/2012/10/17-1.html

[65] www.neul.com

[66] WiGig Alliance white paper, from http://www.wigig.org/

Standards suitable for Lightly or uncompressed video include WiGig – this is based on 802.11ad as already discussed in the previous section. Wireless HD also targets 60 GHz; this is quite similar to WiGig, but aimed at consumer devices and promoted by a different industry alliance group. A key technical difference is the maximum data rate which is 28 Gbps for WirelessHD versus 7 Gbps for WiGig. This makes WirelessHD potentially more suitable for future potential ultra HD video formats.

Small screen or compressed solutions operate in the 2.4 or 5 GHz bands. The wireless home digital interface (WHDI) is focussed on how consumer devices connect to TVs. It promises uncompressed 3 Gbps HDMI over a 40 MHz channel at 5GHz. Details on how this proprietary solution works are difficult to establish, but it seems that range is shorter than other systems and that video re-encoding, if not actual compression, plays a significant role[67]. WHDI 1.0 did not capture the market in 2009 and now more competition has arrived for uncompressed transmission, notably in the shape of WiGig, albeit this is in the 60 GHz band. WHDI is 40 MHz wide and has no coexistence mechanism with Wi-Fi.

Legacy video senders may employ analog techniques (frequency modulation), where no coexistence aspect is present at all. However newer video senders being promoted in the market today use 802.11n; given the higher data rates now available, moderate compression is now sufficient for this application. This confers the potential to co-exist with other 802.11n systems for wireless data. However, video streaming solutions tend to stream continuously and thus hog resources. Thus, even when using 802.11n to stream video, it may be impractical for any other devices to use the channel, due to the congestion which is likely to occur.

Other proprietary solutions for video transmission such as WiDi and AirPlay were discussed in the previous section.

2.2.3 Bluetooth

Where Wi-Fi targets the LAN, with a typical range of the order of 100m, Bluetooth targets the PAN or Personal Area Network, with a typical range of the order of tens of metres. Bluetooth tends to be used in portable equipment and ranges and speeds achieved by Bluetooth include shorter and slower options, which help battery life.

In fact three classes of Bluetooth exist with powers between 100mW and 1mW and ranges between 100 and 5m. The usable application throughput is around 2Mb/s for Bluetooth 2.1.

Bluetooth is unusual in that the whole standard, from physical layer to application layer, is specified by a single body, the Bluetooth Special Interest Group. The Bluetooth standard specifies profiles in order to make the device designer’s task easier. There are many profiles, for example the hands free profile addresses the main use case of Bluetooth, although this is normally now employed as part of a more capable audio distribution profile.

In terms of co-existence, Bluetooth adopted adaptive frequency hopping, where busy channels (1MHz channels are used) may be omitted completely from the hopping sequence.

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[67] http://www.whdi.org/ is the official web site but has insufficient technical content. Instead see, for example, http://www.mathworks.co.uk/company/newsletters/articles/developing-wireless-high-definition-video-modems-for-consumer-electronics-devices.html?issue=nn2011

A perhaps unusual avenue was taken for Bluetooth 3.0. Since Bluetooth itself was unable to reach higher speeds, a method was specified to negotiate a link over Bluetooth, but then to use Wi-Fi for the actual data pipe. This 'High Speed' option gave access to Wi-Fi type speeds, but of course with Wi-Fi power consumption. The attractive feature was that the link negotiation still appeared as Bluetooth to the application. Now the situation has been somewhat reversed with Wi-Fi Direct (see previous section) making peer to peer Wi-Fi very accessible, and so encroaching on Bluetooth's core application space.

Bluetooth Low Energy (BLE), which is part of Bluetooth 4.0, represented a fork in the development of Bluetooth. BLE is not backward compatible with previous versions. The advantage of the new approach is, as the name suggests, low energy - in fact much lower than the original standard could manage. This enables BLE to connect to sensors such as body worn sensors for sporting activities, such as step counters or heart rate monitors. Such sensors have very limited power sources, such as button cells whose characteristics are not well suited to high current delivery.

However, the intention is not that BLE should necessarily stand alone. Chipsets are expected to have dual mode Bluetooth/BLE functionality, using whichever radio is required in a given application. The two radios have many hardware modules in common, thus reducing complexity (hence cost) and size. The marketing objective of changing the standard, yet retaining the brand was successfully achieved before when Ethernet lost its traditional collision domain in the move to higher speeds.

Bluetooth low energy uses FSK modulation in 2 MHz channels in the 2.4 GHz band. To enhance co-existence, hopping is used. However there are three fixed frequency beacon channels, which are chosen specifically to avoid the spectrum used by 20MHz Wi-Fi channels 1, 6 and 11. These are the non-overlapping channels commonly used by Wi-Fi. Although such channel usage has been seen as best practice it is not mandated, so the BLE beacons may or may not be avoided in practice, now or in the future.

As might be expected BLE achieves a much lower data rate, around 200kb/s, although the range was designed to be longer than Bluetooth at around 50m, with the aim of covering a good proportion of a home environment.

2.2.4 ZigBee and IEEE 802.15.4

As the Wi-Fi Alliance is to 802.11, so the Zigbee Alliance is to 802.15.4, and colloquially ZigBee and the IEEE standard are often used synonymously. IEEE 802.15.4 targets very low power and very long battery life networks. It is specifically aimed at sensor networks, interactive toys, smart badges, remote controls and home automation, operating in license-exempt device bands. However, ZigBee is not the only low power wireless sensor network based on 802.15.4. Others include 6LowPAN and more loosely ISA-SP100 and wireless HART.

Like the Wi-Fi Alliance and the Bluetooth Special Interest Group, the ZigBee Alliance seeks to identify the common applications and to make them particularly easy to implement and to ensure interoperability between compliant devices. ZigBee provides various profiles including the following groups, for example:

- A general group including simple on/off and RSSI applications;
- An HVAC group (heating, ventilation and air conditioning);
- A lighting group;

- A security group;
- A measurement and sensors group.

In terms of spectrum, we expect European interest will continue to be highest in the 2.4GHz band for 802.15.4. This is firstly since this band is globally available, secondly since it supports more channels than at 868/915MHz, and thirdly since the throughput per channel is higher. We summarise these differences in Table 2-2

Frequency	*Region*	*Data rate*	*ZigBee channel number*[68]
868MHz	Europe	20kb/s	0
915MHz	USA	40kb/s	1 to 10
2.4GHz	Global	250kb/s	11 to 26

Table 2-2 ZigBee frequencies and properties

It is noteworthy that more spectrum and hence ZigBee channels are available in the US 915 MHz band than in the nearest equivalent European band at 868 MHz, where only a single channel is available. Smart meters have taken off in the US at 915 MHz using mesh technology[69], but the same opportunity clearly does not present itself in European spectrum. However spectrum may be made available in the EU at 870-876 MHz for smart meters, plus WSD spectrum could be used.

The co-existence properties of ZigBee are perhaps not quite as good as might be expected given that like 802.11, 802.15.4 is an IEEE standard. We showed this in earlier work performed for Ofcom[70]. In brief summary, avoiding interference is not as easy as might be expected since if all three non-overlapping Wi-Fi channels are in use, then only 4 (from a possible 16) 802.15.4 channels remain available. But even if these channels are used, then interference is still possible if the physical separation is not large enough. Moreover, problems can still occur for quite large frequency separations, for example even with a frequency difference of 22MHz (1/4 of the band). IEEE simulations show that a minimum separation of 7m is still required if ZigBee is not to be a victim of Wi-Fi. Conversely if we consider Wi-Fi is a victim of ZigBee, then a separation down to 3m can be tolerated. The clear conclusion is that ZigBee is less able to tolerate Wi-Fi than vice versa.

2.2.5 **White space devices**

White space devices (WSD) will likely operate first in the TV bands and have been referred to as 'super Wi-Fi' devices, which have longer range than Wi-Fi, since the lower frequency of the TV bands means better propagation. WSDs are cognitive wireless devices, which seek to use white space spectrum, i.e. that spectrum which, due to the TV frequency reuse plan, is free at a particular point in frequency and location. Such devices may operate in several ways, including that they may be enabled via a geo-location database which must assign one or more 'free' channels to the device before it can transmit. A key step is that the WSD must report its position to the geo-location database and receive permission to transmit.

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[68] Neither the same as 802.11 Wi-Fi channel number, nor the same set of centre frequencies, although the channel spacing of 5MHz is identical.

[69] See, e.g., www.silverspringnet.com

[70] "Wireless Sensor Networks", led by Steve Methley now with Quotient, 2008, www.ofcom.org.uk

The geolocation method of permitting the operation of WSDs has been adopted by the FCC and is expected to be adopted by Ofcom, subject to an ongoing consultation on details such as the appropriate power levels, for example. Trials, for example by British Telecom, have shown that WSDs are capable of providing service to broadband not-spots[71]. The speeds reported have been modest however and more efficient modulation scheme, perhaps using filter bank multicarrier (FBMC) have been suggested.

Filter Bank Multicarrier for TV WSDs

Looking ahead to future technologies which improve spectrum efficiently and sharing beyond today's OFDM (as used in 4G, Wi-Fi etc), filter bank multicarrier (FMBC) has been shown to be an attractive candidate. Like OFDM, FBMC is based on FFT[72] techniques. The FP7 PHYDAS project[73] showed that FBMC has particular advantages which will enable more spectrally efficient cognitive sharing networks:

- A higher density of users may be supported, who need not be synchronised;
- The lack of a cyclic prefix (as in OFDM) leads to greater spectral, efficiency especially in sharing schemes;
- As FBMC is an extension of the principles of OFDM, the potential for compatibility with joint sharing protocols is present.

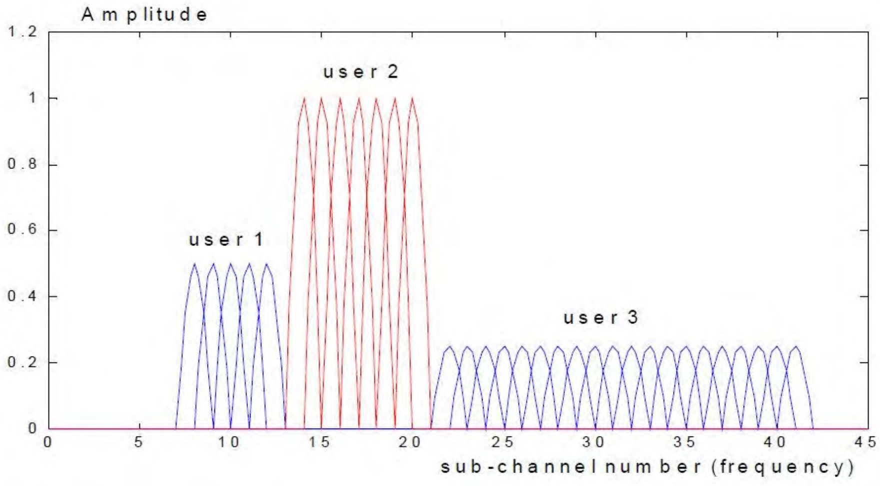

Figure 2-3 Multiuser FMBC: one channel separation is required for independent user operation.

Figure 2-3 shows FMBC spectra for three users. Where one channel of separation is used, there is no requirement to maintain inter-user synchronisation. This is a great advantage over OFDM and leads directly to greater spectral efficiency in shared systems. The associated cost is that the technology requirements for FBMC are approximately 4 times those of OFDM. However, given the normal rate on progress in integration techniques, FBMC systems are likely to be available with in the proposed study's 10 year time horizon.

In terms of co-existence, this is at the heart of the WSD approach and devices are under the ultimate control of the database. In this way individual or groups of WSDs may be turned off at will, or their power levels reduced, all under centralised control. WSDs must

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[71] "Spectrum sharing issues for small cells ", Michael Fitch, British Telecom, presented at Cambridge Wireless, March 2012,
[72] Fast Fourier Transform, a key cornerstone of digital signal processing.
[73] http://www.ict-phydyas.org/

coexist with the TV band's primary users and this is the main function of the database. In terms of co-existing with each other, WSDs could still be controlled by the database, but it is not sufficiently clear how priorities (such as first come first served) might be implemented by the database administrator and under what commercial imperatives. We revisit this in Chapter 4.

WSDs may represent a partial substitute for the 915 MHz band in the USA, although WSDs are significantly more complex than some of the most basic SRDs. WSDs may thus be better suited to higher value applications and those where power consumption is not the major issue. Finally we note that any further reduction in TV spectrum over time will also reduce WSD spectrum.

2.2.6 **Mesh networks**

Perhaps the largest initial attraction of mobile meshes is that they can be entirely unplanned in pure form. Historically this was useful to the military and to disaster recovery teams who neither needed infrastructure access for content nor wanted to rely on its presence for operation. Today, to a service provider, the lure of a network which promises no planning phase is high. Such an example is the deployment of smart meters. Thus smart meter mesh networking has seen a surge in popularity, where suitable unlicensed spectrum is available, such as the USA 915 MHz band. Unfortunately no comparable band exists with sufficient bandwidth in Europe, although re-purposing on 870-876 MHz is now being considered and white spaces may have a role. A further example of meshing is the backhaul of Wi-Fi hotspots.

It had often been said, as if it were a truism, that meshes increase capacity. The reasoning was usually along the lines of each new user brings additional capacity to the mesh, or each new user effectively becomes a base station. Unfortunately this has been proven to be a 'something for nothing' type of mythology[74]. Nonetheless, meshes do retain some strongly attractive features, notably in the area of coverage, where they offer complementary performance to that of cellular systems. It is for this reason that meshes find application in smart meters and Wi-Fi backhaul, although the use of a mesh can blur the backhaul/access boundary to some extent, since meshes are self backhauling. This blurring is often avoided by meshing for backhaul in the 5GHz band with access in the 2.4 GHz band[75].

Meshes do not offer an improved spectrum efficiency over traditional approaches. They benefit similarly from a small cell approach[74].

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[74] For an in-depth explanation, see "Essentials of Wireless Mesh Networking", Steve Methley, Cambridge University Press, 2009.
[75] e.g. as done in parts of O2's UK Wi-Fi network using Ruckus equipment.

2.2.7 Technology advances summary

In summary the likely advances over the time horizon of the study are shown in Table 2-3.

Technology advance	*Benefit to consumer*	*How far away are products?*
802.11ac, "5th generation" Wi-Fi (5 GHz)[76]	A range of greater speeds for existing Wi-Fi use cases; including better quality video streaming.	Products announced at CES 2012 , to meet *draft* 11ac specifications[77].
802.11ad, WiGig (60 GHz)	Ultimate Wi-Fi speed within the intended coverage area of a single room. Suitable for uncompressed HD video. However main application may be wireless docking, with backups possible in very short times.	Products also announced at CES 2012 and standard has been technically ready for some time. Business case now being made around tri-band Wi-Fi for cable replacement in office environments[78]. Expected to see a rise in growth when incorporated into tablets in two years' time[79].
802.11af, TV white spaces	Longer range using white spaces. Could partially substitute for 2.4 GHz when congested.	Final standard release expected in 2014. Prototypes now.
802.11ah, sub 1GHz	Very low power operation, targeting the IoT / M2M market.	Final standard release expected in 2016. First draft is still work in progress.
Hotspot 2.0 (Passpoint), Next Generation Hotspot	Automatic Wi-Fi roaming. Consumers will begin to receive a contiguous Wi-Fi experience when using Wi-Fi networks in urban areas, for example. Will not offer seamless operation at the session level.	NGH technology presently at live trials stage, HS 2.0 certification underway. There are several degrees of 'seamless' roaming and the scope will increase over time[80]. Estimate first products in Europe within two years.
W-Fi Direct (Miracast)	Quick and easy, direct device-to-device links for screencasting, printing etc. Faster then Bluetooth, but higher power	The Wi-Fi Direct specification is in place and the Wi-Fi Alliance has recently begun operating the Miracast video session certification

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[76] Most likely dual band with 2.4 GHz 802.11n. Buffalo and TRENDNet, for example, announced dual band '11acn' routers at CES 2012. Also tri-band with .11ad, see footnote 78.

[77] IEEE 802.11ac Sponsor Ballot is expected May 2013. This represents the final technical approval stage, although the formal approvals process may take a further year. Source: IEEE802.

[78] As demonstrated, for example, at the Intel Developer Forum, San Francisco, September 2012.

[79] "60GHz Technology, 11ad Driving Market Growth", ABI Research, www.abiresearch.com

[80] For example, seamless logon would be a first advance over today's manual system, with seamless mobility when using demanding applications such as VoIP being a 'holy grail'.

Technology advance	*Benefit to consumer*	*How far away are products?*
	consumption. Video links of low to medium quality – attraction is that they are delivered over regular Wi-Fi networks. Expected to replace analog video senders.	program. Presently only a limited number of devices are certified[81], but certifications re predicted to exceed 1.5 billion by 2016[82].
WirelessHD	Similar to WiGig, but larger maximum data rate which might prove important for future super HD displays.	Specification predates WiGig. Little apparent penetration. May face stiff competition from WiGig, which does more than video.
WHDI	Promise of HD video over regular Wi-Fi channels. Shortage of adequate evidence with respect to how effective this is.	Products for some time, little penetration apparent, and now strong competition from other standards; insufficiently clear how WHDI business case is differentiated.
Bluetooth 3.0	Wi-Fi data, Bluetooth negotiation. Faster, but still looks like using Bluetooth.	Now, but competition likely from Wi-Fi Direct.
Bluetooth low energy (BLE)	Connectivity for new personal devices, e.g. watches, heart rate monitors. New channel plan in 2.4 GHz.	Now. Already in some smartphones and watches/sensors.
ZigBee at 2.4 GHz in EU	Sensor networks for smart homes and cities.	Now. Issue is limited range in the built environment.
ZigBee sub-1GHz in EU	Longer range to enable smart meters in the home propagation environment and enabling smart homes and cities to be more economic.	Insufficient spectrum available, compared to the 915 MHZ band in US. Potential new spectrum at 870-876 MHz or white spaces.
White space device (WSD)	Longer range, 'super Wi-Fi'. Broadband not-spot infill. Machine to machine, potentially including smart meters.	Awaiting UK regulation; expected 2013.
Mesh	Quick network roll-out, Flexible response to changing coverage	USA- now for smart meters and Wi-Fi backhaul

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[81] Such as the Samsung Galaxy III smartphone, but not the iPhone 5.

[82] See. e.g. http://techcrunch.com/2012/09/19/wi-fi-alliance-simplifies-streaming-with-miracast-certification-just-dont-expect-apple-to-play/

Technology advance	*Benefit to consumer*	*How far away are products?*
	needs.	UK – now for Wi-Fi backhaul, but insufficient spectrum available for sub-1GHz smart meter meshes. Potential new spectrum at 870-876 MHz or white spaces.

Table 2-3 Anticipated technology advances over study time horizon.

2.3 Sharing technologies

Having evaluated communications technologies, we now turn to look at the technologies and techniques for band sharing.

2.3.1 Co-existence approaches

On the whole, communications technologies intended for use in shared spectrum implement some sort of co-existence mechanism, in order to

1. co-exist with other devices in the same and/or different systems[83] on an equal rights basis;
2. avoid interfering with other band users from different systems on an unequal rights basis, e.g. with any primary systems

A device may be required to use both methods in certain circumstances, see 2.3.3.

An example of the first mechanism is the back-off algorithm used for co-existence by Wi-Fi. This method is intended to work in a single shared channel. It works by detecting energy in the channel, so will detect both Wi-Fi and other users. The Wi-Fi device will delay transmission for a time, but will not change channel[84]. An example of the second is dynamic frequency selection (DFS), where a device has to listen and avoid other users, such as is mandated for WLANs avoiding radars in the 5GHz band. This method will automatically change channel and hence it is anticipated that more than one channel is available in the band. However, where no free channel is available, transmission must cease.

A further example of the first approach is frequency hopping, which causes the transmission frequency to move rapidly around the band. In this way the likelihood of interference is reduced, although not necessarily removed, so it cannot guarantee non-interference with any other band users.

Unfortunately for the wireless communications devices, there is a further problem in that some other band users do not offer anything in the way of co-existence mechanisms at all. Examples are microwave ovens, video senders and more recently wired USB3.0 ports, which have been found to be unintentional radiators into the 2.4 GHz band unless specific extra precautions are taken when designing products[85].

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[83] Examples of systems include WLANs, video senders, TV broadcast etc.
[84] There are proprietary extensions to Wi-Fi which will find a free channel, but this is not the back-off algorithm discussed here.
[85] “USB 3.0 Radio Frequency Interference Impact on 2.4 GHz Wireless Devices” Intel White paper, April 2012.

Polite protocols

Systems which exhibit some sort of co-existence behaviour are often said to be employing polite protocols. These systems will employ a listening function first and will not transmit immediately if existing band use is detected. This contrasts strongly with non-polite systems which simply transmit on channel without regard for what may already be present.

It should be apparent that an immediate conclusion can be drawn which is that

- polite protocol systems will always lose out to impolite systems.

This is simply a case of 'who shouts loudest wins'.

It is instructive to further consider what happens in the case where a band is becoming congested. There are clearly limits to how many users can share a band. In other words at some point the band will be full. It is at this point that reference must be made to any provisions for admission control. In a managed access system such as the cellular radio network, when the band is full, further users who attempt to join will simply be rejected. In other words access control is in operation and it is centrally managed. This is inappropriate for a shared resource like the spectrum used by license exempt devices.

There is no centralised control over the number of users of licences exempt device spectrum. A direct consequence of this is that at some point congestion must be expected to occur; it is a property of the system. It is this congestion that polite protocols are expected to manage gracefully. Cleary the amount of spectrum remains the same as the number of users increases, so each user must be given less access, in times of congestion. This sharing of spectrum must often be enabled by a distributed sharing protocol, i.e. one that has no centralised knowledge of the users. The challenge is to make this protocol fair in operation, but to accept that the meaning of congestion is that each user's performance level will deteriorate.

Therefore in times of congestion under a licence exempt regime with polite protocols, each user must accept a degradation in performance. Polite protocols simply attempt to distribute this degradation fairly across participating users.

However, to be fully effective, sharing systems need to operate the same polite protocol, but this is not always the case. In the event of dissimilar (or an absence of) polite protocols, then end result is imperfect co-existence, as we can see tin the following example of Wi-Fi and ZigBee, which are both based on IEEE802 standards, but differ in their specific choice of coexistence protocol. In particular ZigBee does not operate a back-off protocol like Wi-Fi. For full co-existence, a minimum inter-system range is also required to be established and maintained.

Polite protocols mismatch –example

ZigBee and Wi-Fi are both deployed in the in the 2.4 GHz band. This is the preferred European ZigBee band as the 915 MHz USA band which supports 10 channels is not available in Europe. In our earlier wireless sensor network study for Ofcom[86], we looked at the compatibility of ZigBee (802.15.4) and Wi-Fi (802.11). In normal operation ZigBee may select a free channel at start-up, but it is instructive to look at what happens when this is not the case, perhaps for reasons of subsequent crowding by other band users and/or because an 802.15.4 implementation's clear channel assessment is not set to utilise energy detection. If a free channel is not selected than the mutual interference effect will depend on the relative carrier offset between 802.11 and 802.15.4, i.e. how

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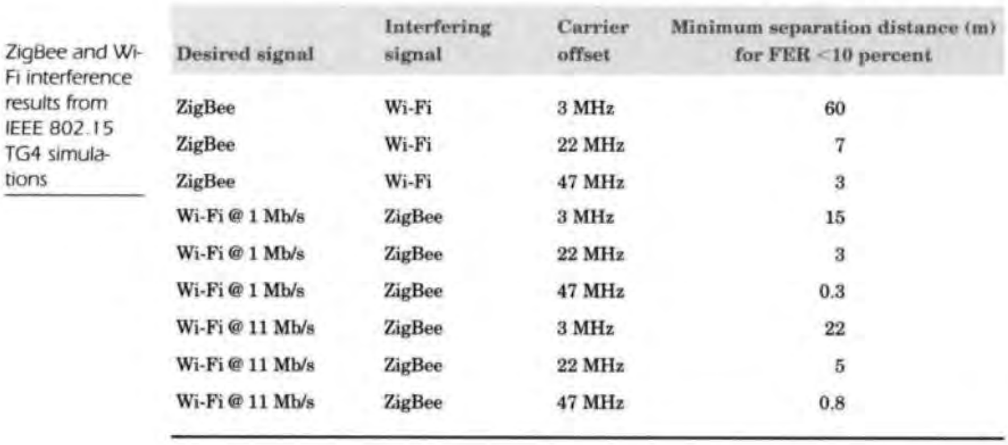
[86] "Wireless Sensor Networks, led by Steve Methley now with Quotient, 2008, www.ofcom.org.uk

close they are attempting to operate in frequency. The results of such mutual interference can be seen in Table 2-4[87], which is compiled from results presented during the 802.15.4 standardisation process.



ZigBee and Wi-Fi interference results from IEEE 802.15 TG4 simulations

Desired signal	Interfering signal	Carrier offset	Minimum separation distance (m) for FER <10 percent
ZigBee	Wi-Fi	3 MHz	60
ZigBee	Wi-Fi	22 MHz	7
ZigBee	Wi-Fi	47 MHz	3
Wi-Fi @ 1 Mb/s	ZigBee	3 MHz	15
Wi-Fi @ 1 Mb/s	ZigBee	22 MHz	3
Wi-Fi @ 1 Mb/s	ZigBee	47 MHz	0.3
Wi-Fi @ 11 Mb/s	ZigBee	3 MHz	22
Wi-Fi @ 11 Mb/s	ZigBee	22 MHz	5
Wi-Fi @ 11 Mb/s	ZigBee	47 MHz	0.8

Table 2-4 802.15.4 and 802.11 mutual interference versus frequency offset.

The table shows both cases where firstly 802.15.4 is the victim and secondly where 802.11 is the victim, for similar operating frequency differences. For each combination, a minimum spatial separation for acceptable operation has been found, by simulation. The minimum acceptable quality has been judged by arbitrarily choosing a frame error rate (FER) of 0.1 as the threshold of acceptable operation.

The results show that 802.15.4 is more sensitive to interference from nearby 802.11 than vice versa, in the sense that a lower minimum spatial separation is tolerable by 802.11 than by 802.15.4. Yet interference can be caused in each case at some minimum value of spatial separation, so neither system is ever completely immune to the other at any of the carrier offsets shown. Some of these frequency offsets represent a significant proportion of the total width of the 2.4GHz band, which implies that there really may be no such thing as simply picking a completely free channel - a minimum spatial separation is always needed as well.

2.3.2 **Sharing rights**

Turing now to the case where primary users exist and unlicensed usage is secondary, such as WSDs, we can immediately conclude that

- Polite protocols are inappropriate for ‘sharing’ a resource with a primary user.

This is because the primary user must take complete precedence. The secondary user can work only within that which is left after ceding to the primary; it is quite conceivable that in some cases nothing will be left. This is therefore much less a case of sharing and more one of exclusion.

For completeness, it should also be pointed out that impolite protocols are also inappropriate for sharing with a primary user. As we have already stated, the effect of an impolite protocol is to dominate polite protocols – but also to ignore all other band users. Impolite protocols are thus neither suitable for equal rights sharing nor unequal rights

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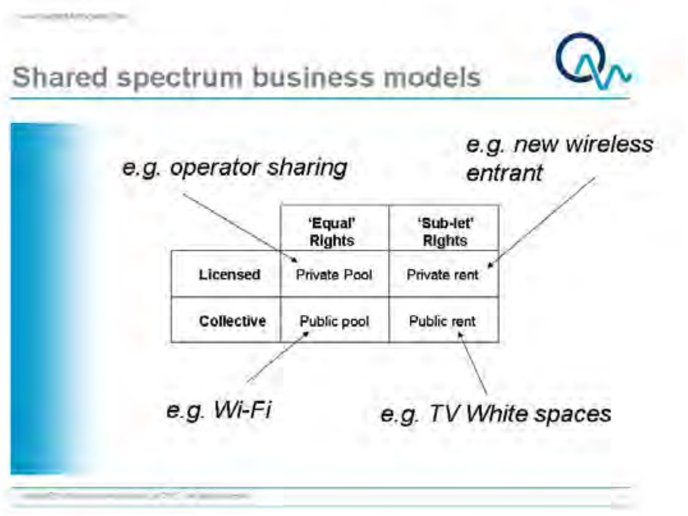
[87] “Wireless Network Coexistence”, Bob Morrow, McGraw Hill, 2004.

sharing, especially in times of congestion. An impolite protocol either requires that enough bandwidth is available for all users and that frequency co-ordination is provided in some external manner, or that the user is the sole user in the channel.

Since a secondary user must always give way to a primary user, there is a requirement that the secondary user must avoid transmitting when the primary user is active. This is very different from sharing since it is entirely inequitable. Methods to avoid primary users include dynamic frequency selection and more recently sensing or geolocation databases for white space devices. When a WSD operates in sensing mode, it is working in a similar manner to DFS and the avoidance decision is locally made. When the WSD uses a geolocation database, the decision is made centrally. The database approach is favoured today due to the technical challenges still to be overcome for successful sensing.

2.3.3 **Polite and impolite protocols, primary and secondary users**

We can summarise the foregoing discussions on sharing and coexistence via Figure 2-4.



Shared spectrum business models

e.g. operator sharing

e.g. new wireless entrant

	'Equal' Rights	'Sub-let' Rights
Licensed	Private Pool	Private rent
Collective	Public pool	Public rent

e.g. Wi-Fi

e.g. TV White spaces

Figure 2-4 Shared spectrum business cases - taxonomy of opportunities[88]

In terms of types of rights, we have equal rights such as in the 2.4 GHz band. Equal rights can also apply where operators agree to share their licensed spectrum. However, the newer forms of sharing, such as that used by white space devices involves unequal sharing, i.e. secondary level rights. In equal rights systems, co-existence approaches are appropriate, such as Wi-Fi back-off. In unequal rights systems, avoidance techniques are appropriate, e.g. dynamic frequency selection (DFS), as mandated in the 5 GHz band. It is also possible to envisage both equal and unequal rights approaches both being needed, e.g. in a situation where a license exempt sub-band band exists as a shared secondary resource in the same band as a primary user. In fact this occurs for Wi-Fi users who must also submit to DFS. This would appear to be an open issue for white space users, who must presently adopt avoidance techniques, but who coexistence approaches to other WSDs is not well defined and is presently under the control of the WSDB[89]. Rather than being

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[88] Steve Methley, "The Role of Shared Use in Solving the (projected) Spectrum Crunch – Business Cases", IEEE Wireless Communications and Networking Conference (WCNC), Paris, April 2012.

[89] White Space Database.

centrally controlled by the WSBD, local sharing could be controlled in a distributed manner by each device, like Wi-Fi.

It is also possible to envisage unequal rights sharing in licensed spectrum in an analogous way, such as the sub-letting of an operator's spectrum to a new entrant[90]. However this case quickly brings in issues of co-operation versus competition. Clearly these issues may strongly affect the market take up of such a service.

It is useful to summarise the properties of the sharing technologies discussed, Table 2-5.

Technology	*For equal or unequal rights*	*Politeness*
Back-off (e.g. Wi-Fi)	equal	yes
Hopping	equal	yes, if intelligent
Transmit only (e.g. analog video sender)	Unequal (or single user)	no
WSD	unequal	yes
DFS	unequal	yes

Table 2-5 Technologies versus sharing properties.

It is very noteworthy that transmit-only systems, since by definition they have no listening function, have total disregard for any other band users. Given this, it remains surprising to see their widespread use in shared bands alongside devices using co-existence protocols.

We examine practical ways of sharing spectrum in Chapter 4, including tiered sharing which offers a middle ground between licensed and licence exempt use.

2.4 Applications and key sharing technologies

For convenience, in Table 2-6 we bring together our key applications, with the technologies they use and the sharing and efficiency issues that are relevant.

Application	*Relevant technologies*	*Sharing and efficiency*
Wireless Data - indoor	Wi-Fi; AP mode and peering/screencasting modes at 2.4, 5 GHz. HD, docking and instant backups via WiGig at 60 GHz. Tri-band chipsets (11n, ac, ad). Video senders; simple transmit only methods dominate channels.	Wi-Fi; back-off protocol; polite, suitable for equal rights systems. Simple video senders are impolite, have no receiver therefore no sharing unless manual choice of channel. Interference from USB 3.0 (impolite).

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[90] i.e. Licensed Shared Access.

Application	*Relevant technologies*	*Sharing and efficiency*
Wireless Data - outdoor	Hotspot 2.0 and Next Generation Hotspot extensions enable roaming with authentication. Standalone Wi-Fi broadband operators will also be possible.	Similar issues to indoor Wi-Fi – but worse since without the helpful attenuation of walls between buildings to isolate hotspots. Wi-Fi throughput higher relative to cellular. User managed Wi-Fi distribution around digital fibre hubs could be very quick to set up.
Wireless Data – not-spot and rural	Need new modulation technology to increase bit rate for broadband over WSD – one possibility is a development of OFDM – Filter Bank Multicarrier (FBMC).	Efficient use of TV white spaces.
Wireless Data - backhaul	Backhaul by mesh at 5GHz. Fixed links backhaul at 5 GHz and 60/70/80 GHz.	Mesh architecture easy to roll-out; fixed links at 60/70/80 GHz are pencil beams with high re-use.
Internet of Things – Smart Meters and Smart Cities	Smart meter home area networks require low power networking such as ZigBee or proprietary solutions. Smart Cities need good range in order to keep down system cost, so need suitable spectrum, such as is used in the USA in Silver Spring's proprietary 915 MHz mesh system. Alternative may be to use WSDs.	Sharing needed on equal rights basis in SRD bands and as secondary user for WSD. EU may extend SRD bands.
Internet of Things – WPANs	Small devices require low power, low duty and long sleep modes as provided by Bluetooth low energy.	Bluetooth is polite, but with different mechanism to Wi-Fi; interference is possible. Bluetooth Low Energy is different again.
Internet of Things – RFID	High power RFID readers required to energise passive tags.	High power readers do not share well with lower power SRDs. EU may extend and harmonise RFID bands around 915 MHz.
Internet of Things –	Can be simple transmitter systems, without acknowledgement or sensing since no receiver.	Absence of receiver results in no sharing

Application	*Relevant technologies*	*Sharing and efficiency*
Alarms and Social alarms		mechanism. Relies on low duty cycle application.
Connected Health	Low Power Active Medical Implants (LP-AMI) using proprietary technology. Medical Body Area networks (MBAN) for professional use in hospital sites, based on modified 2.4 GHz Wi-Fi for economics of scale.	Sharing studies identified suitable bands in US; light licensing is part of the solution. Europe is undecided.
Intelligent Mobility	Based on 802.11 but at 5.9 GHz. Safety related, co-existence verified by sharing studies.	Sharing following the Wi-Fi model.
	Beam forming at 63G for vehicle to vehicle links.	Pencil beams with high re-use.
	2.4 GHz spread spectrum approach though to be favoured by London Underground is proprietary; LHR baggage system is Wi-Fi, but was moved to 5GHz to avoid possibility of issues at 2.4 GHz due to perceived congestion.	London Underground system specification is not known.

Table 2-6 Summary of key application areas with relevant technologies and sharing aspects.

2.5 Summary and implications of technologies

We summarise the key points made in this Chapter.

Wi-Fi specific points

- At 5GHz there are nineteen 20 MHz channels, but only four 80 MHz channels, giving rise a potential congestion situation not so different to 2.4 GHz today, which has three channels[91];
- The rise of Wi-Fi peer-to-peer usage could double bandwidth consumption requirements in the home. This could occur when a user streams from the Internet to a device and then screencasts the device to a large display. Video applications are resource hogs, as streaming is a constant, high demand activity;
- The rise of in-band/mesh backhaul for outdoor Wi-Fi could double the bandwidth demand on the wireless network;
- There is currently no proposal to make Wi-Fi go any faster. Instead Wi-Fi is targeting other application areas;
- Future Wi-Fi may compete with Bluetooth (Wi-Fi Direct), with WSDs (White-Fi, 802.11af) and with ZigBee (802.11ah, sub-1GHz; ultra lower power for sensors);
- Wi-Fi has been flexible in adapting to specific markets and bands, e.g. the 3.5 GHz light licensed band in USA and the current working group to address China millimetre wave

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[91] However we further examine wider Wi-Fi channel behaviour with respect to legacy devices in Chapter 4.

at 45 and 60 GHz. This flexibility may present an opportunity for Europe to target a specific Wi-Fi band, although economies of scale considerations may detract from this ;

Coexistence specific points

- Coexistence approaches are fragmented or absent. For example, Wi-Fi, BT 2.1, BTLE, and WHDI all operate in the 2.4 GHz band but do not follow that same politeness protocols. WHDI appears to have no politeness and in any case is expected to occupy a channel intensively since it is a streaming application. BTLE has made fixed assumptions about which Wi-Fi channels will be commonly deployed and has put fixed beacons in the assumed spaces;
- Technologies which share well always fall victim to non-sharing technologies. Wi-Fi shares well and is increasingly relied upon to provide Internet access, yet it is used in a band where impolite devices are also allowed. Therefore we have a perverse situation where the valuable Wi-Fi service is effectively de-prioritised;
- There is little that can be done to help polite users attain fair access with respect to impolite users in same band. Receiver standards will not help for example, nor will any politeness protocol improvements;
- New spectrum offers the opportunity to introduce new, fair-access rules.

Sub-1GHz specific points

- The EU presently has a dearth of sub-1GHz spectrum relative to USA. WSDs may substitute for this in part, but are unlikely to address very low cost solutions due to the additional complexity required;
- The use of a database approach to control lower frequency license exempt is appropriate, since propagation and hence the interference footprint is enhanced. A database could be made to avoid primary users, but also to control self interference and thus spectrum efficiency. Database control could be extended to be international, which would deal with anomalous propagation at VHF/UHF such as ducting.

3 DEMAND BY BAND

3.1 Introduction

In this Section we

- group applications with respect to the band they will use;
- introduce trigger event analysis;
- identify trigger events, per band;
- summarise demand hotspots.

3.2 Application demand by band

We characterise market demand in order to establish which applications will be important over the study time horizon, so that subsequently in Chapter 5, we can evaluate spectrum demand. We perform these steps separately since a high market demand does not necessarily translate to a high spectrum demand. We consider the following five regions of licence exempt device spectrum

- 2.4 GHz and immediately adjacent bands;
- 5 GHz and immediately adjacent bands;
- 60 GHz band;
- TV bands;
- 868 MHz / sub-1 GHz bands.

Table 3-1 lists the applications we described in Chapter 1 against the appropriate spectrum band. The table also includes a relative ranking of the importance of an application within a band and an indication of when the application may reach the mass market[92].

Band	*Application*	*Technology*	*Application Group*	*Rank*[93]	*Time-scale*[94]
2.4 GHz	Peer to peer[95] (indoor)	Wi-Fi	Wireless data	H	1-2 years
	Internet (indoor)	Wi-Fi	Wireless data	H	Now
	Outdoor hotspots	Wi-Fi	Wireless data	H	1-5 years
	Video senders	Transmit only	Wireless data	L[96]	Legacy
	Connected consumer goods	Wi-Fi; BT; ZigBee	IoT	H	1-5 years

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[92] Where significant uncertainty exists in the timing of mass market adoption, we give a wider time range.
[93] Rank has categories of High, Medium and Low.
[94] Timescale to mass market adoption, not first products.
[95] e.g. screencasting
[96] We expect these devices will fall out of use within this band over the study timescale. Video senders using polite technology are already available.
[97] Limited number of deployment sites.

Band	Application	Technology	Application Group	Rank[93]	Time-scale[94]
	WPANs	Wi-Fi; BT; ZigBee	IoT	H	1-2 years
	Driverless transit	Wi-Fi; bespoke	Intelligent Mobility	L[97]	1-10 years
Adjacent to 2.4 GHz	Medical body area networks (below), low power implants (above)	Wi-Fi based; low power bespoke	Connected Health	H	1-5 years
5 GHz[98]	Higher Speed data	Wi-Fi 802.11acn dual band[99]	Wireless data	H	1-2 years
	Outdoor hotspot backhaul	Wi-Fi	Wireless data	H	Now
	PtP links	Wi-Fi	Wireless data	L[100]	Now
	Driverless transit	Wi-Fi	Wireless data	L[97]	1-10 years
Adjacent to 5 GHz	Intelligent Transport band at 5.9 GHz.	Wi-Fi based	Intelligent Mobility	M[101]	1-10 years
60 GHz and above	In-room docking; HD video	Wi-Fi	Wireless data	H	3-5 years
	Backhaul	Wireless fibre	Wireless data	H	1-5 years
	Intelligent Transport vehicle to vehicle and roadside to vehicle at 63 GHz	Wideband, simple modulation	Intelligent Mobility	M[101]	3-10 years
TV bands	Rural access	WSD; White-Fi 802.11.af	Wireless data	M[102]	1-5 years
	M2M; smart meters	WSD; White-Fi 802.11.af	Wireless data	H (EU)[103]	1-2 years (EU)

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[98] In principle, applications listed under 2.4 GHz can also work at 5 GHz (although this is not the current practice) but we do not repeat them here. Instead we concentrate on those applications which target 5 GHz explicitly.

[99] IEEE 802.11ac runs in 5 GHz only; in order to accommodate 2.4 GHz devices in the same WLAN, dual band routers will be required. Theses are likely to be 11acn, i.e. both 11ac and 11n compatible (with fallback to 11g/b where needed).

[100] This remains a relatively low volume application. It excludes backhaul, which is a separate category.

[101] Uncertainty in take-up for ITS.

[102] Uncertainty in suitability of transmission speed and QoS mechanism when congested.

[103] The UK government has already put out tenders for smart meters, which pre-empts WSD technology availability.

Band	*Application*	*Technology*	*Application Group*	*Rank*[93]	*Time-scale*[94]
868/ sub-1GHz	Smart meters; RFID; other SRD	Proprietary; ZigBee; Low power Wi-Fi 802.11ah	IoT	H	2-10 years

Table 3-1 Applications and technologies by spectrum band.

3.3 Introduction to trigger event analysis

It is common in forecasting work to produce quite generic roadmaps of increasing technology progress, as shown in Figure 3-1. However in our experience such graphs lack sufficient specifics to enable meaningful discussion of likely future events.

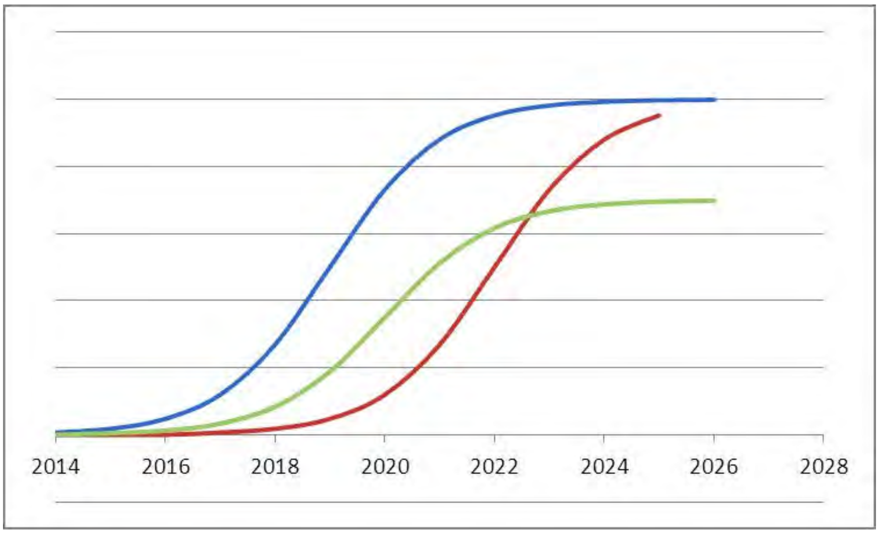

Figure 3-1 Generic technology roadmap.

In our experience of discussing future trends and demands, we have found two aspects are very important

- Firstly, there is a need to be specific about future events when discussing technology or service evolution. This can be achieved by adopting a cause-and-effect approach, using anticipated future 'trigger events' which familiar to the industry;
- Secondly, an industry is often more comfortable discussing uptake of a service or evolution of technology capability rather than directly how much spectrum is required. We therefore decouple technology/service demand from spectrum demand.

These two aspects taken together provide a sound basis upon which to generate discussion of underlying assumptions and growth scenarios.

A previous example of a roadmap shown to stakeholders during our Transport Sector Study[104] for Ofcom T is shown in Figure 3-2. This graph may appear complex, but in fact it

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[104] Transport Sector Study, http://stakeholders.ofcom.org.uk/market-data-research/technology-research/research/sector-studies/transport/, June 2008.

proved to have no more than the complexity necessary for expert stakeholders (in this case experts in road transport) to fully appreciate the context of the discussion.

In the demand graph, three applications are shown. The blue line represents eCall, where a car in distress may place a GSM call for assistance, potentially automatically. The white line is for car to car (C2C) communications, for example safety features or potentially road user charging. The red line is for roadside to vehicle (R2V) communications, potential for safety or perhaps entertainment links to cars.

Examples of trigger points and flip-flops on the graph include:

- The cost of in-car C2C units falling below £50. This is a trigger event with a flip-flop implication. If the cost does fall to this level, then the market will be higher and may also include a considerable after-market fitment component ('flip'). If the cost does not fall to this level then market take-up will be restricted to only premium vehicles, where the cost is more easily absorbed ('flop').
- Roadside to vehicle communications used for entertainment delivery. If entertainment were to be a successful driver, then the R2V market would grow, otherwise the application delivery mechanism would be substituted, in this case most likely by cellular devices. This is a trigger event with a flip-flop implication.

One of the key aspects of this demand forecast and all the others produced in the transport study was that they were widely agreed in a series of industry stakeholder feedback events organised by Quotient Associates. The transport sector study went on to predict spectrum demand from this market demand.

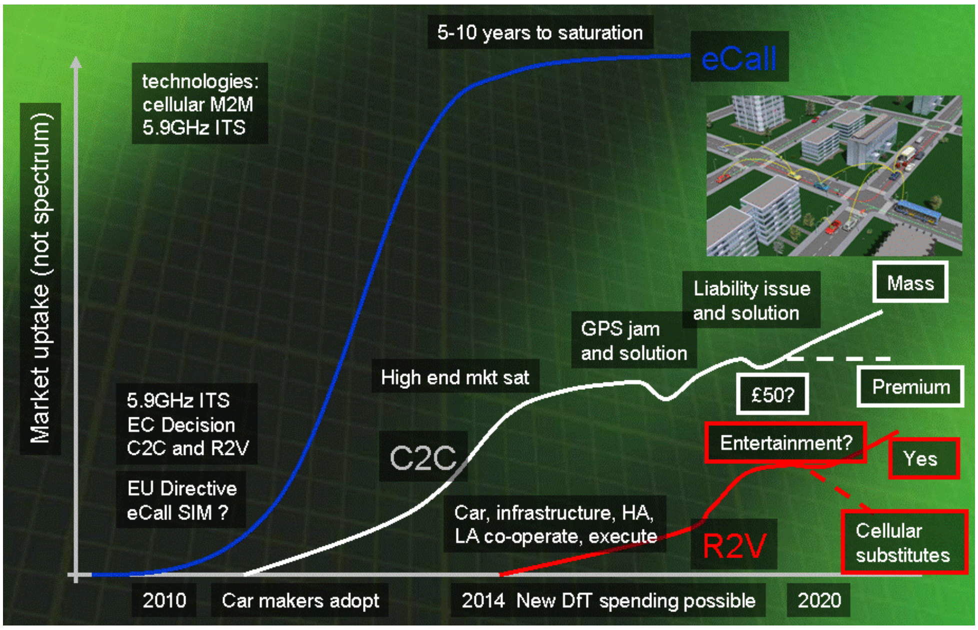

Figure 3-2 Graphical representation of demand for safety services take-up in the road transport area (previous work example)

Relying on actual trigger events (which can be observed) rather than fixed dates (which may be uncertain) provides the ability for Ofcom to monitor the changing environment for trigger events even after project end and to continue to be able to predict how licence exempt usage will most likely to change for a given application.

3.4 Demand triggers per band

Our key bands of interest are the Wi-Fi bands 2.4, 5 and 60 GHz, but we also review 868 MHz, and TV white spaces. We identify the key triggers for demand in each band.

3.4.1 2.4 GHz

The main triggers of demand in this band will be due to increased Wi-Fi use for Internet access and screencasting, plus Wi-Fi, Bluetooth and ZigBee for connecting devices in the personal Internet of Things.

Demand may be reduced if other bands prove to be substitutes. In particular, increased use of the 5GHz band could reduce Wi-Fi demand in 2.4 GHz. This will create a situation where 5 GHz becomes the preferred Wi-Fi band, since it brings the added benefit of being free from Bluetooth, ZigBee and other SRDs; and the only band where 5th generation Wi-Fi, 802.11ac, is specified to operate. Such a situation would be beneficial to both Wi-Fi and SRD users. However it would be unreasonable to expect all Wi-Fi use to move to 5 GHz, legacy devices and the lowest cost Wi-Fi enabled devices would still see 2.4 GHz as attractive.

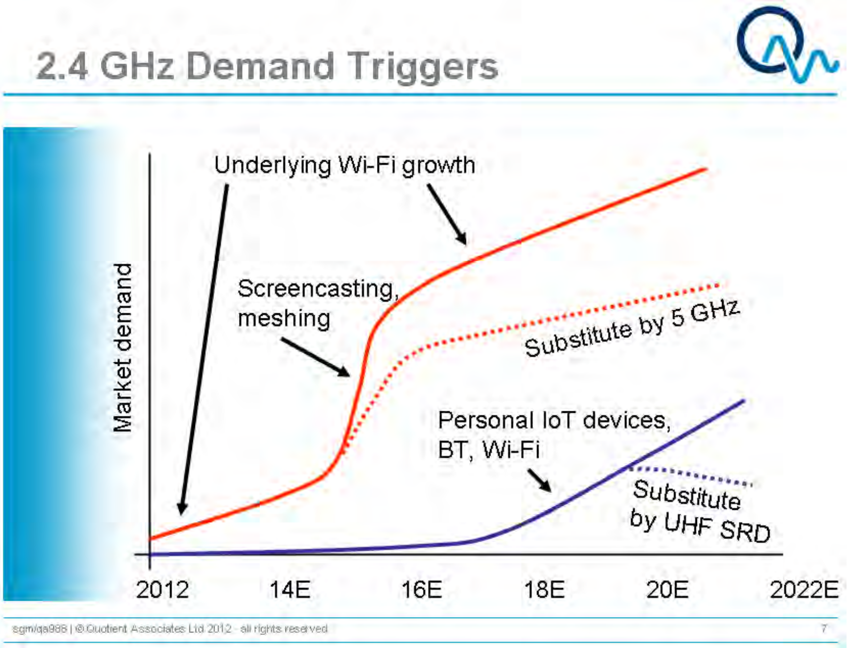

Figure 3-3 Triggers for changes in demand for 2.4 GHz

Figure 3-3 illustrates key triggers and their effects. There is flip-flop event with respect to Wi-Fi; demand for 2.4 GHz may be reduced if and when 5 GHz is adopted as an effective substitute. There is a second flip-flop since the demand for personal Internet of Things devices at 2.4 GHz may be substituted by future short range devices operating in future extended 868 MHz bands (see below). We have assumed that analog video senders will become legacy devices over the study time horizon and their functionality will be replaced by 802.11 compliant units[105].

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[105] Ofcom could encourage this by arranging to 'age-out' such devices.

3.4.2 **5 GHz**

The main triggers of demand in this band will be due to increased Wi-Fi use, both indoors and out doors; we expect 5 GHz will become the main Wi-Fi band for the reasons outlined above. As at 2.4 GHz, concurrent Internet streaming and screencasting has the potential to double bandwidth consumption indoors. Outdoors, a comparable situation exists where in-band hotspot backhaul (such as via the mesh systems presently popular in the UK) also has the potential to double bandwidth consumption. Wider channels will be used to achieve higher data rates. It is important to note that the future demand will be characterised by coarser granularity, in other words spectrum will be required in larger contiguous 'chunks' equal to the wider Wi-Fi channel widths, such as 80 or 160 MHz. However, fallback to narrow channels is automatic[106], so a problem may arise only once users are in a position to realise they are not attaining top speeds, such as when

- fixed home broadband speed rises sufficiently that Wi-Fi becomes the bottleneck for the first time;
- an application must have top speed and/or lowest latency and fails without this. Examples include streaming high end video or screeencasting high end games, which are normally uncompressed to reduce latency.

This will put additional strain on spectrum resources, which we address in Chapter 5.

A likely substitute for video distribution applications in this band is 60 GHz. However this will substitute best only for point to point high quality video within the same room.

Use of 5 GHz depends on the deployment of concurrent dual band routers, since single radio routers will use 2.4 GHz for all network devices if any network device is 2.4 GHz only.

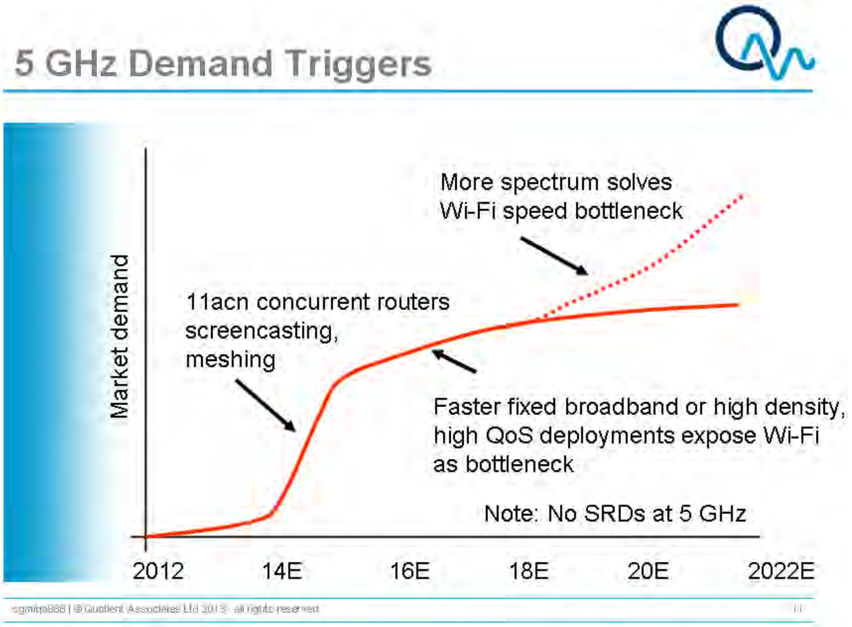

Figure 3-4 Triggers for changes in demand for 5 GHz

Figure 3-4 illustrates key triggers and their effects. There is a flip-flop event; demand for 5 GHz will require more spectrum to be allocated

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[106] See Chapter 5.

3.4.3 **60 GHz**

The key triggers for 60 GHz use are

- In room docking applications;
- In room video application;
- The wide adoption of tri-band chipsets to create concurrent 2.4/5/60 GHz devices running 802.11acn and 11ad;
- At 60 GHz and the lightly licensed bands above, growth in line of sight backhaul for smalls cells and Wi-Fi hotspots.

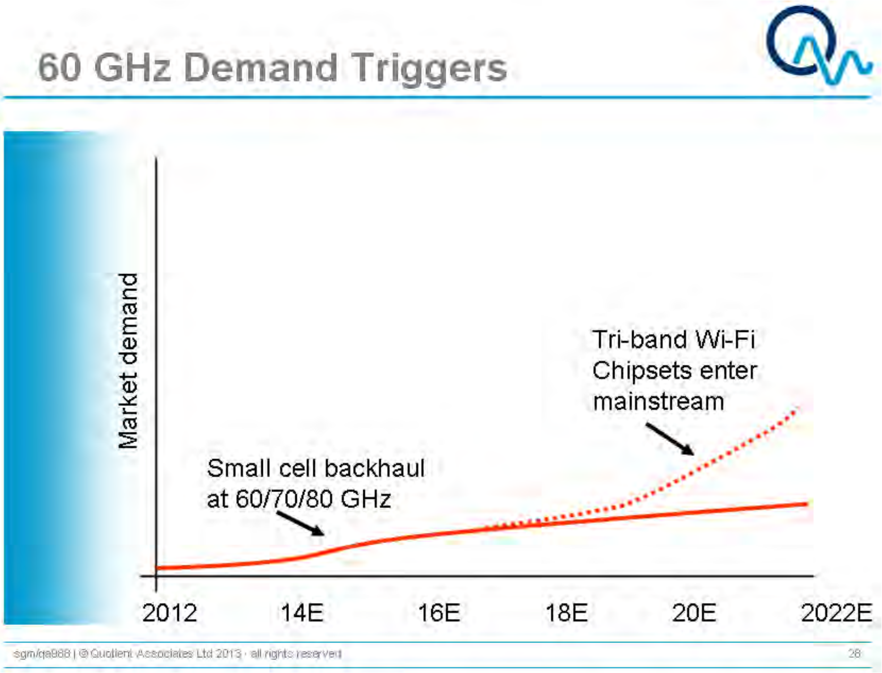

Figure 3-5 Triggers for changes in demand for 60 GHz

Figure 3-5 illustrates key triggers and their effects. There is flip-flop event; adoption of 60 GHz may stall if 60 GHz tri-band chipsets are not adopted in the wider market.

3.4.4 **868 MHz**

The main triggers for 868 MHz use are

- Smart meters;
- RFID.

In fact, this demand is already well appreciated and ESTI have already begun plans to increase spectrum in this area. We concur that ETSI's plans are likely satisfy demand over the next 10-15 years. A major re-organisation and expansion of 868 MHz is intended and we review this in Chapter 4.

3.4.5 **WSDs**

The main triggers for WSD use are

- rural broadband;
- M2M.

TV WSDs may substitute for 868 MHz devices to an extent, but the 868 MHz band expansion plans referred to above are likely to dampen this effect. The main threats arise firstly from the lack of bandwidth available for rural broadband applications, although FBMC modulation technology may help, and secondly from the shrinking TV spectrum bands, which are likely to shrink further and thus reduce TV white space. TV WSDs which suit moderate bandwidth applications over relatively long ranges are thus expected to be most successful, but not where lower cost 868 MHz devices can substitute.

3.4.6 Bands adjacent to 2.4 and 5 GHz

We deal with these special cases, which are already well advanced, in Chapter 4.

3.5 Summary

We made the following key points in this Chapter

2.4GHz and 5GHz bands

- The paucity of channels[107] and the interference from SRDs in 2.4 GHz, plus the exclusivity of latest generation Wi-Fi to 5GHz all favour the advent of 5 GHz as the main Wi-Fi band in future. This would benefit both Wi-Fi and SRD users;
- Demand at 5GHz will be for more and wider channels;
- The effect of ultrafast broadband into the home may cause Wi-Fi to become a bottleneck for first time. This may occur either with lower speed Wi-Fi variants or when gigabit speed 802.11ac is forced to fall back to narrower channels due to spectrum congestion[108].
- It would be most helpful to identify a plan to release additional spectrum in the 5GHz band for future W-Fi;

60 GHz and above

- Use of 60 GHz could reduce demand at 5 GHz for video, although not in the short term;
- Wide adoption of tri-band chipsets may be critical in kick-starting 802.11ad in the 60 GHz band, in order to benefit from economies of scale;
- The 60 GHz licence exempt band and the lightly licensed bands above have abundant spectrum and will employ directed beams, so there is a lower chance of excess demand.

Other bands

- Demand at 868 MHz will be catered for by the ETSI planned 870/915 extensions and reorganisation[109];
- WSD demand in the TV bands may be substituted by the extension bands at 870/915 MHz. Spectrum appears to be shrinking for TV broadcast and hence WSDs.

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[107] We explain why a higher number of channels is preferable in Chapter 5.
[108] We explain channel fallback in Chapter 5.
[109] See Chapter 4.

4 POTENTIAL 'NEW' LICENCE EXEMPT SPECTRUM

There is little if any truly new or unallocated spectrum available except at very high frequencies, so we concentrate on the potential for new licence exempt spectrum either by sharing, or by release from non-Ofcom sources, such as the MoD.

In this chapter we first benchmark existing bands of interest together with bands which are already in the planning or proposal stage. We also evaluate new options to increase licence exempt spectrum in the UK. In particular, given that we have already shown that the 5GHz band will be the major focus for high speed Wi-Fi, we examine what opportunities and constraints there are in extending the 5 GHz band for Wi-Fi use. Finally we review the varied processes adopted by recent proposals for new licence exempt spectrum allocations.

Specifically, in this chapter we

- Benchmark existing and planned bands;
- Suggest specific candidates for extensions of Wi-Fi spectrum;
- Review options for bands below 1GHz;
- Review options for bands above 6GHz;
- Review a range of processes for new allocations;
- Summarise key findings.

4.1 Benchmarking existing bands

In Figure 4-1 we have split spectrum into a range below 1 GHz, a range above 6 GHz and the range 1-6 GHz. Propagation and building loss characteristics are distinct between these ranges and hence the types of applications using the spectrum also tend to follow a similar split. While this is not an exact split, it is convenient for discussion purposes. We first introduce the key aspects of each frequency range in turn.

4.1.1 Sub 1 GHz

This spectrum range is best for supporting applications which require larger distances and/or good building penetration, although not the highest data rates[110]. The top of the range is considered to be within a valuable sweet spot where the balance of distance and data rate (bandwidth) is especially suitable to serve broadcast and mobile communications.

If we consider the licence exempt (LE) and ISM bands in Region 1 represented in Figure 4-1, then it may initially appear that Region 1 (Europe, Middle East and Africa) and Region 2 (the Americas) are similarly served, in that each Region benefits from licence exempt spectrum below 1 GHz. However the situation is not equitable in terms of the bandwidth available. The Region 2 ISM band at 915 MHz is much wider (26 MHz) than the SRD band around 868 MHz (7 MHz) in Region 1. This gives the UK and the rest of Region 1 a relative paucity of licence exempt, sub 1 GHz spectrum, especially near the sweet spot at the upper end of the frequency range. This relative lack of spectrum puts Region 1 at a comparative disadvantage. Steps are being taken to circumvent this, as we discuss in Section 4.3. This

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[110] It follows that a given distance may be achieved at a lower power than in higher bands.

includes the 870 and 915 MHz bands shown which may, for example, serve Smart Meter Home Area Networks (SMHAN) and RFID applications.

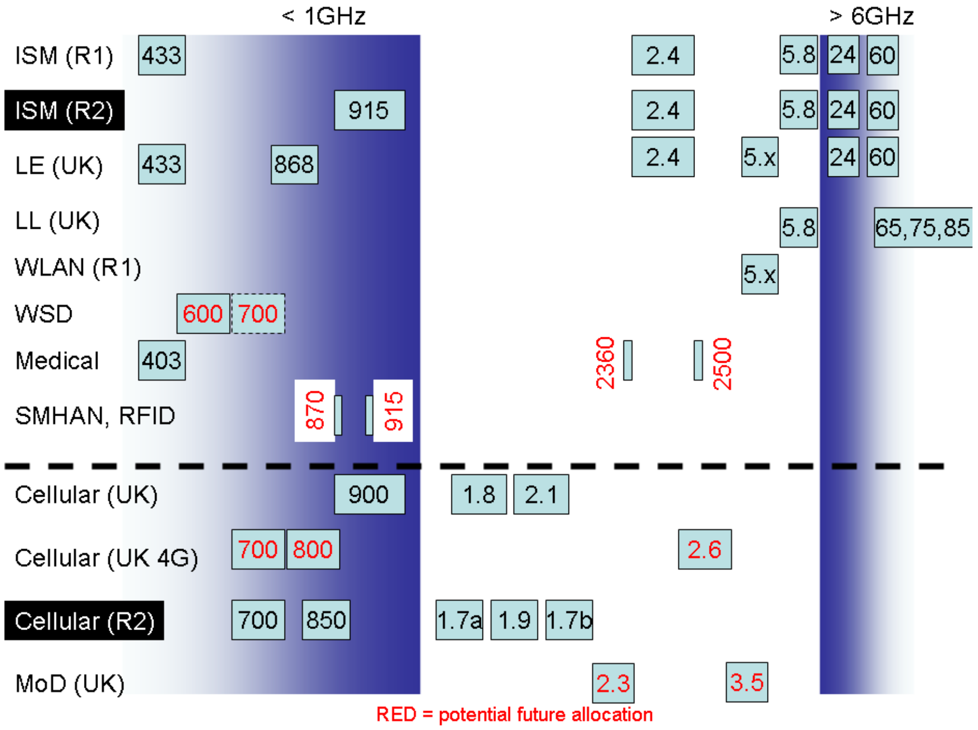

Figure 4-1 Selected key bands shown in relation to each other[111].

Further opportunities for increasing the amount of sub 1 GHz spectrum also include the use of TV white space devices (WSD). TV WSDs are secondary users in the TV bands. They operate on an opportunistic basis, controlled via a database of valid channels for a given location, i.e. those channels which will not impact the primary TV and PMSE[112] users. TV WSDs are permitted by the FCC in the USA and have been trialled in the UK. Ofcom is expected to enable UK operation later in 2013. We discuss WSDs further in Section 4.3

Demand for sub 1 GHz spectrum for cellular applications is very high. LTE in particular has been aggressively seeking suitable bands for both FDD and TDD variants across the globe. The 700 MHz 'second digital dividend' band is already a target for LTE. It may thus already be too late to consider this band for licence exempt use.

There is a medical band around 400 MHz which is used for implants and which is well harmonised. There is pressure for more spectrum for medical applications as we discuss below.

4.1.2 **1-6 GHz**

In the UK, the MoD has signalled its intention to release by auction a number of bands on varying timescales. The first two bands will be around 2300 and 3500 MHz. Competition in the lower portion of this space, being part of the sweet spot, is high for cellular

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[111] The figure is intended to represent the bands at a high level and is not drawn to scale.
[112] Program making and special events

applications and the 2300 band was first targeted for LTE TDD use in China. Interest in this band is increasing in other areas and it has recently been proposed for mobile use in Europe[113].

This frequency range also contains the main Wi-Fi bands at 2.4 and 5 GHz. These are of great interest to this study and we examine them in more detail in Section 4.2. It is generally considered that the 2.4 GHz band is the more highly used band and is subject to congestion from time to time in certain locations. Congestion may arise from other Wi-Fi users, or more likely other band users which do not operate Wi-Fi's polite sharing protocol[114]. It is noteworthy that the 5 GHz band is less well used at the moment, as 2.4 GHz technology has historically been lower cost. However, the wider bandwidth at 5 GHz and falling hardware costs have spurred renewed efforts to take advantage of the 5 GHz band. We have already shown that high speed Wi-Fi (802.11ac) will target only the 5 GHz band[115]. A final noteworthy point is that a significant part of the 5 GHz band (bands A and B[116]) is specifically allocated to WLANs and has no ISM/SRD allocation. Thus interference from non-Wi-Fi sources such as Bluetooth will be absent in 5 GHz bands A and B.

Given the existence in the market of low cost Wi-Fi, Bluetooth and ZigBee devices, there is a very good reason for new services to try to use spectrum adjacent to the bands where these are already used. Such new services will benefit from the economies of scale already created by Wi-Fi devices. This argument makes the 2300 MoD band attractive, for example, but less so the 3500 band. The economies of scale argument is further bolstered if any new bands themselves can be widely harmonised.

Medical device proponents have adopted the aim of using spectrum adjacent to Wi-Fi, for both Medical Body Are networks (MBAN) and Low Power Active Medical Implants (LP-AMI). Although MBANs will need a modified protocol stack, they should be able to re-use much of IEEE 802.15.4's PHY layer and hardware. LP-AMI will be more specialist, but may still be able to benefit from the cost effective antenna and RF technology already developed. Harmonisation is a strong objective for medical devices, especially implants which may well need to work globally as the user travels.

We discuss extensions to the 2.4 and 5 GHz bands in specific detail in Section 4.2.

4.1.3 **Above 6 GHz**

In this range, the band of greatest interest is 60 GHz (57.100-63.900 GHz), as this is where WiGig[117], IEEEE 802.11ad, will operate in almost 7 GHz bandwidth for applications within rooms or at even shorter distance, such as within device docking stations. There are also lightly licensed bands at 65 GHz (64000-66000), 75 GHz (71.125-75.875) and 85 GHz (81.125-85.875). We studied licence exemption in bands above 30 GHz in earlier work for Ofcom. Key conclusions of this work remain valid and we summarise these in Section 4.4.

The 24 GHz band is for vehicular radar rather than wireless data and thus outside the scope of this study.

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[113] "Enabling Europe's Radio Spectrum Policy Programme with the 2300MHz band for LTE" Huawei White paper, June 2012, from www.huawei.com

[114] Ofcom continues to conduct and publish measurement campaigns in this area.

[115] We discuss 802.11ad WiGig at 60 GHz below.

[116] See Section 4.2.

[117] It is planned in future to subsume the WiGig Alliance within the Wi-Fi Alliance.

4.2 Options to extend existing 'Wi-Fi bands'

4.2.1 2.4 GHz

Figure 4-2 has been constructed from the UK Frequency Allocation Table, plus other regulatory and industry sources. It shows key allocations in and around the 2.4 GHz bands which are of interest to this study.

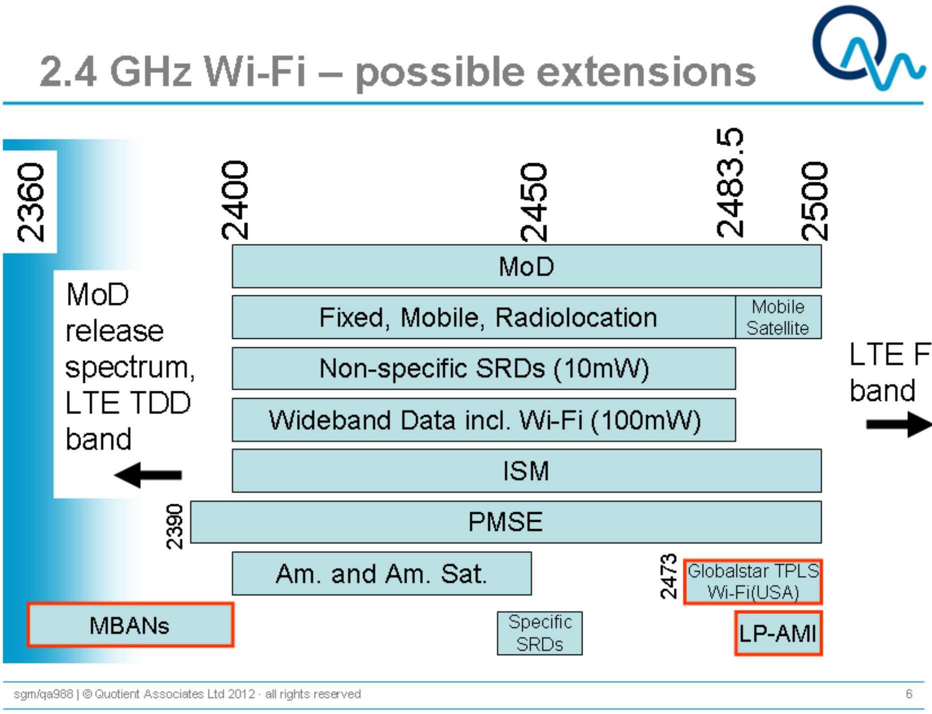

Figure 4-2 Key allocations in the 2.4 GHz band with possible extensions (shown in red)[118]

WLANs, including Wi-Fi, are permitted from 2400-2483.5 MHz. Non-specific SRDs, such as video senders, are allowed in the same range, but at lower power. The ISM band extends all the way from 2400-2500 MHz and PMSE all the way from 2390-2500 MHz. (It should be borne in mind that these allocations give no information on actual usage levels of the bands).

We note that previous congestion studies by Ofcom have found that interference with Wi-Fi at 2.4 GHz may often be from SRDs, notably video senders[119]. As we pointed out in Chapter 2, simple analog video senders do not adhere to polite protocols whereas Wi-Fi does. Therefore Wi-Fi will always give way to video senders in range, which is manifestly not a fair sharing of the spectral resource. It is noteworthy that this situation does not apply to WLANs in the 5 GHz band.

In Figure 4-2, we have highlighted, in red, three extensions to the 2.4 GHz band currently under consideration. Two are medical[120] and one is an unusual hybrid proposal from the

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[118] Collated from UK FAT and Annexes, Ofcom, FCC, 3GPP and industry publications

[119] "Estimating the Utilisation of Key Licence Exempt Spectrum Bands", Mass for Ofcom, 2009.

[120] In Region 1, there are no equivalent bands to the WMTS (Wireless Medical Telemetry Service) bands in Region 1, plus there is no wide 915 MHz band, so medical applications have to consider the 2.4 GHz band.

USA potentially creating a potential fourth, non-overlapping Wi-Fi channel at 2.4 GHz, which could be used for a Wi-Fi 'superhighway', in other words, premium cost Wi-Fi.

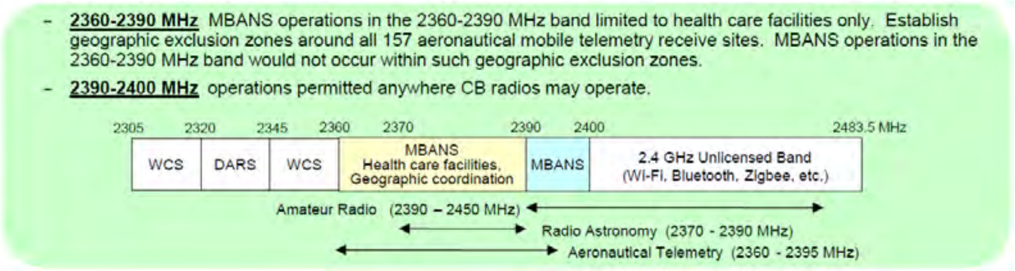
In this study we are particularly interested in establishing the various processes which have been used globally when seeking to achieve agreement on new spectrum allocations, so we next consider these three extension bands as mini-case studies.

Case study 1: Medical –Aeronautical joint proposal to regulator

This case study illustrates a process where independent industry sectors co-operated in a shared spectrum proposal to a regulator.

Sharing with the Aeronautical Service is very challenging. Simply put, a regulator cannot wait for interference to be discovered and then mitigated, as safety of life is involved.

Nonetheless, industry sectors co-operated in the US recently and submitted a joint proposal to the FCC for sharing aeronautical spectrum with a proposed medical band for medical body area networks, MBANs. The proposal met with success, but it should be noted that the process was far from smooth at times and that the aeronautical spectrum concerned was for flight testing telemetry, rather than operational communications or radio navigation.



- **2360-2390 MHz** MBANS operations in the 2360-2390 MHz band limited to health care facilities only. Establish geographic exclusion zones around all 157 aeronautical mobile telemetry receive sites. MBANS operations in the 2360-2390 MHz band would not occur within such geographic exclusion zones.
- **2390-2400 MHz** operations permitted anywhere CB radios may operate.

Figure 4-3 MBANs spectrum in relation to other allocations in USA[121]

Figure 4-3 shows the MBANs spectrum in relation to adjacent spectrum in the USA. WCS is the wireless communications service, providing fixed broadband. DARS is the satellite digital audio radio service. Together these existing services occupy the USA '2.3 GHz band' from 2305-2360 MHz. Of key interest is the aeronautical telemetry band from 2360-2395 MHz used for flight testing by companies such as Boeing and others in the aeronautical mobile telemetry (AMT) field.

The MBANs proposal was spearheaded by Philips and GE Healthcare, whose contention was that MBANs would be used in only a limited number of fixed locations. The response from the AMT incumbents was that, nonetheless, necessary protection zones would need to be so large as to preclude MBANs operation. Based on detailed analysis of projected MBANs interference levels versus existing ambient interference levels, the MBANs community sought to show that large exclusion zones were inappropriate. A series of claims and counterclaims ensued over a period of two years.

Eventually a joint proposal was worked out over the subsequent two years, with several conditions on the operation of MBANs including registration and co-ordination and a limitation to professional use only (hospitals etc), plus indoor use for most of the band,

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[121] "Status of 2360 to 2400 MHz MBANS Proposal to the FCC", GE Healthcare submission to IEEE 802.15.4, 2008.

although the top 10 MHz was available for home use. Geographical exclusions were stipulated around all 157 AMT sites[122].

Thus in 2011, the medical and aerospace industry submitted a joint proposal to the FCC. The FCC NPRM appeared in 2012, following a process which had begun in 2007.

A harmonised MBANs proposal is currently being considered in Europe by ETSI. However, aside from MBANs, there are other new interests in the same frequency space. In the UK, the 2300 band is expected to be auctioned by the MoD and the band has also been proposed for TDD-LTE in Europe[123].

Case study 2: ETSI/CEPT driven compatibility investigation

Active medical implants are already used in the 400 MHz band. The need for new spectrum arises not from a need to increase the number of users, rather it arises from a need to transmit more data in a shorter time. Short transmission times are critical for low power medical implants whose batteries must last ten years. Such devices may be pacemakers, or implantable infusion pumps for insulin plus their associated sensors, for example. Patient data is collected over days or weeks and stored by the implanted device, and subsequently this data is read out within a period lasting only tens of seconds by a professional medical worker using an interrogator unit.

The low power active medial implants (LP-AMI) proposed in 2483.5-2500 MHz are for indoor use only. Although future use may become more widespread, it is not proposed that this allocation should allow that use case. The restriction of usage to indoors is helpful in terms of compatibility with other band users. In addition, a globally harmonised band is very important for implantable devices, to cover situations when the patient travels. CEPT has carried out modelling using SEAMCAT to evaluate co-existence[124]. Modelling included interactions with the MSS service from GlobalStar, with adjacent mobile use in the 2600 MHz band and with possible future use by the Galileo global navigation satellite system.

Assumptions used in the CEPT analysis included that LP-AMI use would be indoors whereas Globalstar and Galileo are outdoors. This appears a reasonable assumption since LP-AMI will transmit only when instructed by an interrogator, and these are held only by professional medical staff within hospitals etc. In addition LP-AMI will be required to operate listen before talk and dynamic frequency selection (LBT/DFS). This is both for reasons of compatibility with other services which may be operating indoors (such as mobile or MSS ground components) and for sharing the available spectrum with other LP-AMI devices. The low duty cycle nature of LP-AMI was important for the analysis in terms of the likely effects of any interference.

Not known at the time of the CEPT analysis were Globalstar's plans to create a Wi-Fi 'superhighway', as we discuss below.

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[122] See, for example, http://www.fcc.gov/document/fcc-dedicates-spectrum-enabling-medical-body-area-networks

[123] "Enabling Europe's Radio Spectrum Policy Programme with the 2300MHz band for LTE" Huawei White paper, June 2012, from www.huawei.com

[124] ECC Report 149, 2010.

Case study 3: Satellite – Wi-Fi diversification proposal to regulator

This case study illustrates a process where an individual industry player made a unilateral petition to a regulator to amend the use of existing spectrum, on a hybrid licensing basis.

Globalstar's TLPS[125] Wi-Fi superhighway petition to the FCC promotes 'hybrid' spectrum. In this way GlobalStar proposes to combine some of its own licensed MSS[126] spectrum with some licence exempt spectrum at the top of the 2.4 GHz ISM band. In this way a useable fourth channel (Channel 14) may be created in the USA and added to the normal situation of three non-overlapping Wi-Fi channels at 2.4 GHz, albeit with no inter channel guard band.

The FCC has not responded to this petition at time of writing. Globalstar have indicated that they intend to promote this as a premium Wi-Fi service and have coined it a Wi-Fi superhighway[127]. Existing Wi-Fi client devices should be able to tune to the new channel, given a firmware upgrade (an example of economies of scale). However such a firmware upgrade would be distributed only to Globalstar 'Wi-Fi superhighway' customers. Globalstar's submission to the FCC implies that only this channel will be used to provide a single channel Wi-Fi system. The extent to which a single channel will limit a realistic widespread deployment was not addressed.

The MSS allocation is global, so it would be possible for similar petitions to be made to other regulators around the world. Globalstar report that they expect primarily Bluetooth interference as Wi-Fi channels 12 and 13 are not used in the USA. However this will not be true in other countries, such as in Europe. Other countries are not addressed in the FCC petition. It remains to be seen how the FCC will view hybrid use of licensed and licence exempt spectrum, and whether this raises competitive issues, for example.

4.2.2 **5 GHz**

As we discussed in Chapter 2, the 5 GHz band is of great interest as it will be the sole focus of 802.11ac, 5th generation Wi-Fi. This can achieve gigabit rates and IEEE 802.11 is not currently planning any faster versions; instead they are looking at white spaces and the Internet of Things. Given this and the application demand we discussed in Chapter 3, we concluded that the 5 GHz band would become a Wi-Fi demand hotspot in future.

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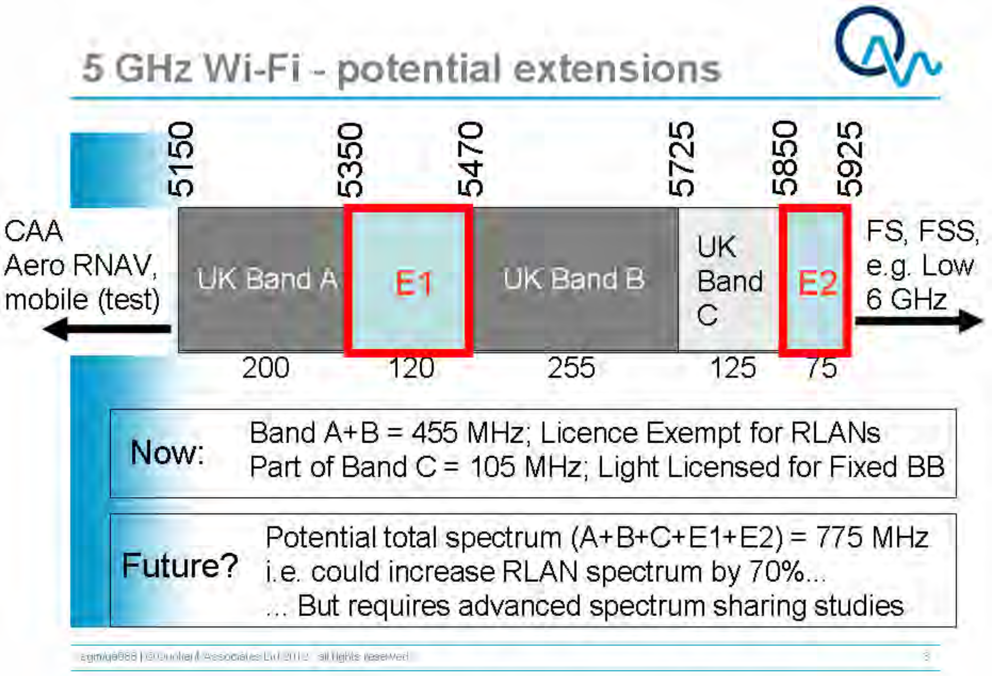
[125] Terrestrial Low Power Service

[126] Mobile satellite service

[127] "Globalstar, Inc. Petition for Rulemaking to Reform the[FCC] Commission's Regulatory Framework for Terrestrial Use of the Big LEO MSS Band", November 13, 2012.

We thus examine possibilities for extending the 5 GHz band.



5 GHz Wi-Fi - potential extensions

Now: Band A+B = 455 MHz; Licence Exempt for RLANs
Part of Band C = 105 MHz; Light Licensed for Fixed BB

Future? Potential total spectrum (A+B+C+E1+E2) = 775 MHz
i.e. could increase RLAN spectrum by 70%...
... But requires advanced spectrum sharing studies

Figure 4-4 Potential extensions for 5 GHz band

Figure 4-4 shows both existing bands and where extension bands might be possible. All potential extensions will require some form of sharing. In this section we seek to draw out the main issues and constraints which are likely to occur when considering such extensions to the 5 GHz band in future.

Firstly, we take a simple view, by establishing likely bounds on the maximum space which could available. Figure 4-4 shows existing bands A and B which are licence exempt for WLANs. Also shown is band C which is subject to light licensing for fixed broadband by Ofcom and has a notch mid-band for RTTT (Road traffic and transport telematics).

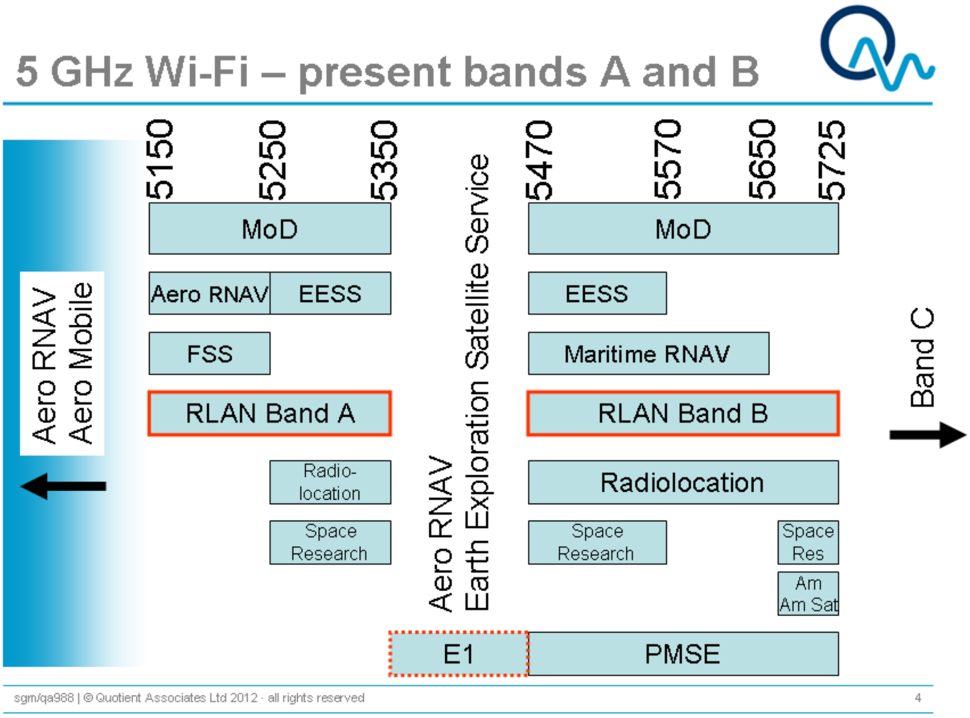
Extensions at the low end of the band, below 5150 MHz, would appear to be particularly challenging. This region of spectrum is controlled by the CAA and contains aeronautical radionavigation and aeronautical mobile test. By way of example, the microwave landing system (MLS) used around the world is in this region.

Extensions at the top of the band would appear to be limited by the fixed and fixed satellite services. Specifically the low 6 GHz band begins at 5925 MHz.

There would thus appear to be three areas where an investigation into extending the 5 GHz band for Wi-Fi use would be worth undertaking. These are the bands labelled E1 and E2 in Figure 4-4 plus a repurposing of Band C to allow licence exempt WLANs. As shown in Figure 4-4, this could increase the Wi-Fi spectrum available at 5GHz from 455 MHz to 775 MHz, an increase of 70%.

Such a move would not be without considerable issues and would require thorough investigation. The details of this are well beyond the scope of the present study, but we next present a preliminary analysis of the problems areas likely to be faced when seeking to create extension bands E1, between Bands A and B, and E2, above band C.

Extension band E1



5 GHz Wi-Fi – present bands A and B

5150
5250
5350
5470
5570
5650
5725

Aero RNAV
Aero Mobile

MoD
Aero RNAV
EESS
FSS
RLAN Band A
Radio-location
Space Research

Aero RNAV
Earth Exploration Satellite Service

MoD
EESS
Maritime RNAV
RLAN Band B
Radiolocation
Space Research
Space Res
Am Am Sat

E1
PMSE

Band C

sgm/qa988 | © Quotient Associates Ltd 2012 · all rights reserved

4

Figure 4-5 Key allocations in and around 5GHz bands A and B

5 GHz bands A and B are particularly attractive for RLANs as, unlike at 2.4 GHz, there is no ISM allocation here and thus one less source of potential interference. Figure 4-5 shows bands A and B in relation to other allocations in the same range. The potential extension band E1 lies in the gap between bands A and B. The allocation in this gap is for aeronautical radionavigation (RNAV) and the earth exploration satellite service (EESS). Sharing in this area is likely to be highly challenging. One use for aeronautical radionavigation in this region is for airborne weather radar, thus any exclusion zones required to avoid interference here are likely to be large. The present technique of DFS to avoid aeronautical weather radar is unlikely to be directly applicable as DFS was designed to avoid terminal (i.e. ground) based weather radar. Aeronautical spectrum is harmonised globally, so moving this allocation is also likely to be very difficult.

The US government has signalled its intention to promote this band at the World Radio Conference. It will be discussed under agenda item 1.1 at WRC-15. Objections have already been raised by the European Space Agency with respect to their GMES (Global Monitoring for Environment and Security) project, who have already had to modify their usage due to the introduction of Bands A and B and now have SAR (synthetic aperture radar) instruments on their Sentinel-1A, -1B and -1C satellites, specifically in 5350-5470 to avoid RLAN interference[128]. ICAO has also expressed concern at WLANs in a globally harmonised airborne weather radar band which is safety critical[129].

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[128] "Agenda item 1.1 - ESA concerns related to the band 5350-5470 MHz", ESA submission to ECCCPG-15 PTD #2, Marseille, 14-17 January 2013.

[129] "Draft ICAO Position on items of interest to aviation on the agenda of the International Telecommunication Union (ITU) World Radiocommunication Conference (2015) (WRC-15)", ICAO, Canada, 28 November 2012.

Extension band 2

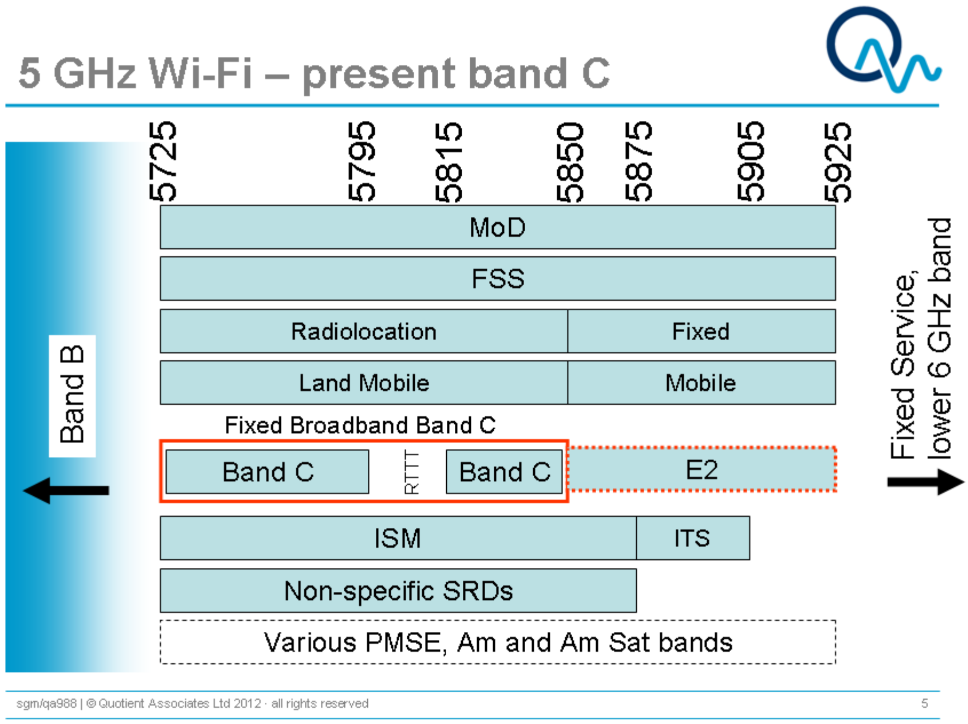

Figure 4-6 Key allocations in and around 5 GHz band C

Figure 4-6 shows Band C in relation to other allocations. There is a notch in band C to allow RTTT, where example applications include road transport tags. Possible extension band E2 lies above band C and below the low 6 GHz fixed service band which begins at 5925 MHz.

Although it can be seen that several other allocations exist in this range, none of them are for the aeronautical service as was the case for potential extension band E1. Also the 5.9 GHz ITS (Intelligent Transport Systems) band was permitted in this region within the last five years via a process which included compatibility studies. The 5.9 GHz ITS band is allocated car to car communications and is based on Wi-Fi principles[130], however it is little used. There would appear to be merit in considering this region for Wi-Fi expansion.

There does appear to be interest from elsewhere in examining the potential for creating an extension equivalent to the band we have termed E2. For example, in the US, “Spectrum Policy in the Age of Broadband: Issues for Congress”[131] carries a brief reference to 5850-5925 MHz for potential unlicensed use and the FCC has recently spoken of releasing more spectrum at 5 GHz. Although the FCC is yet to detail specific frequencies at the time of writing, it would seem logical that they will identify a similar opportunity at the top of the band for similar reasons to those we have given[132].

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[130] “Future Spectrum Requirements of the UK Transport Sector”, Quotient et al for Ofcom, 2008.

[131] Congressional Research Service, August 29 2012. See p7.

[132] i.e. above the US UNII bands

Band C

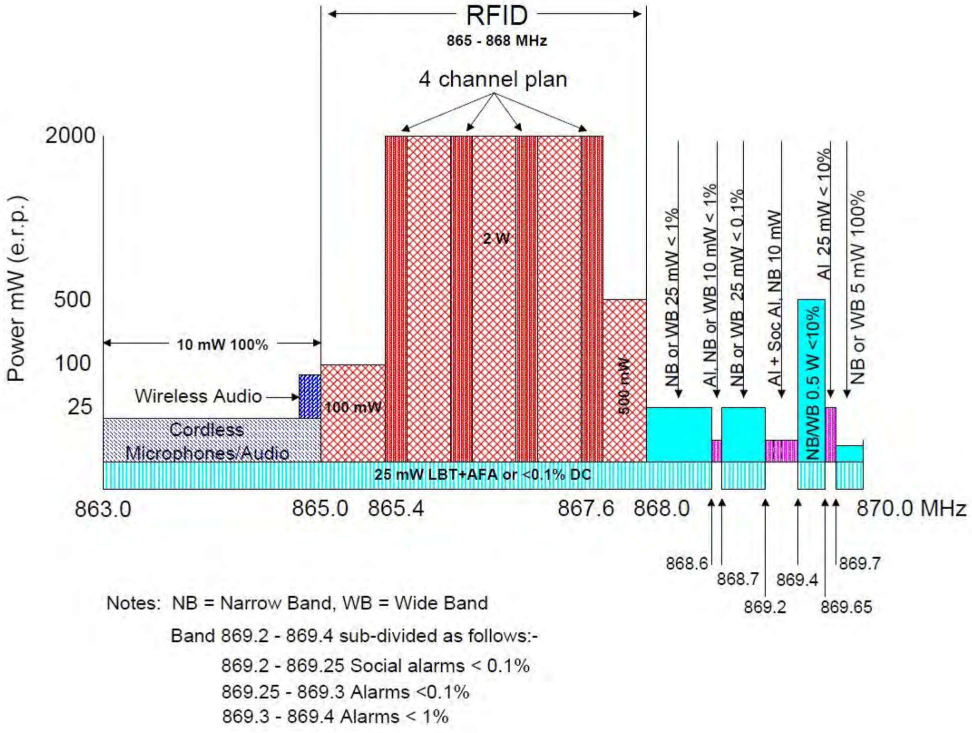
Band C is currently light licensed by Ofcom for fixed broadband. To become a general Wi-Fi extension band this would need a change in regulation to allow licence exempt Wi-Fi use and compatibility would have to be shown with other allocations. We note that this band is used already elsewhere, e.g. USA, in a license exempt regime as part of the UNII bands presently used for Wi-Fi. However, moving away from light licensed to license exempt would lose the ability for Ofcom to contact users of the band in future and would potentially reduce the quality of service available within the band.

All extension bands- sharing with primary services

We note that DFS has not always been successful in avoiding primary services, especially in its early days. There may be something to learn here from practical cognitive radio applications: In the white spaces, sensing approaches (the set to which DFS belongs) have been relegated in favour of geolocation approaches. It may be that geolocation approaches will prove to be more appropriate for sharing the extension bands we have described here, either stand alone, or in conjunction with other avoidance techniques.

4.3 **Options for new shared bands sub 1 GHz**

4.3.1 **Around 868 MHz**



Notes: NB = Narrow Band, WB = Wide Band

Band 869.2 - 869.4 sub-divided as follows:-

869.2 - 869.25 Social alarms < 0.1%
869.25 - 869.3 Alarms <0.1%
869.3 - 869.4 Alarms < 1%

Figure 4-7 Existing SRD allocations[133]

As shown in Figure 4-7, the 868 MHz SRD band is well used and has a diverse range of applications, leading to a rather fragmented band. This is well accepted and steps are

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[133] From ETSI TR 102 649-2

already under way in the ECC to both extend the band and to simplify allocations within it. For example 870-876 MHz is likely to be allocated to low power SRDs such as smart meters. This would go some way to match the amount of spectrum available within 902-928 MHz in Region 2 which has seen considerable usage in the US smart meters sector. A similar expansion is expected at 915-921 MHz in the EU, in order to accommodate high power SRDs such as RFID. This will allow better harmonisation with RFIDs around the world. The 870/915 MHz paired bands became available since they were not being used for their earlier allocation to private mobile radio.

A draft ECC report describing the new bands is available on the CEPT meetings document server and we show two figures from that draft below. These take into account systems reference documents (SRDocs) covering the following[134]

- Generic SRD, RFID, and Automotive SRD
- Smart Meters
- Metropolitan Mesh Machine Networks[135] (M3N) and Smart Metering (SM) applications.
- Alarm and Social Alarm systems
- Assistive Listening Devices

Figure 4-8 illustrates the drive to avoid future fragmentation in the allocation of SRDs by splitting the band into groups of similar applications, rather than allocating applications individually. In other words, applications will be harmonised into sub-bands. Figure 4-9 shows how high power RFIDs are largely kept away from lower power devices in a separate band.

We caution that Figure 4-8 and Figure 4-9 are taken from a draft document and may be subject to change.

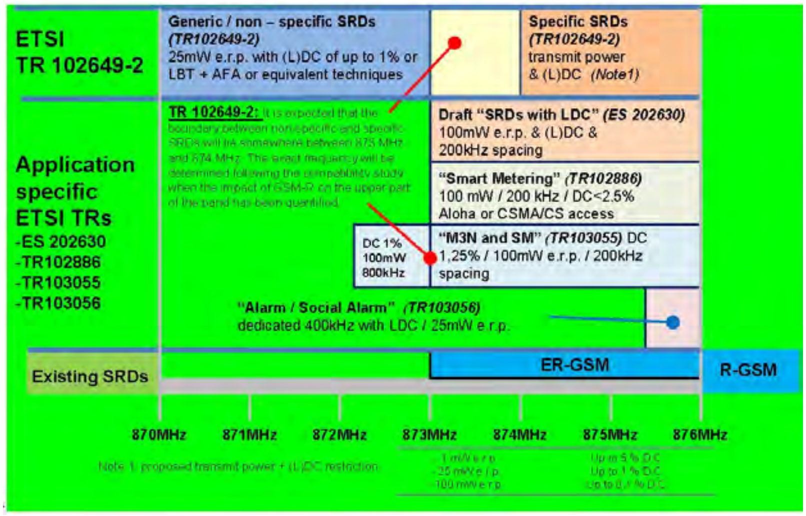

Figure 4-8 Draft summary requirements for 870-876 MHz[136]

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[134] Generic SRD, RFID, Automotive SRD and Assistive Listening Devices TR 102 649-2; Smart Meters TR 102 886; Metropolitan Mesh Machine Networks (M3N)TR 103 055; Alarms and Social Alarms TR 103 056.

[135] In this study we have included these within smart cities; they were also previously included within wireless sensor networks

[136] Based on TR 102 649-2, annotated by working draft of ECC Report "Future Spectrum Demand for Short Range Devices in the UHF Frequency Band"

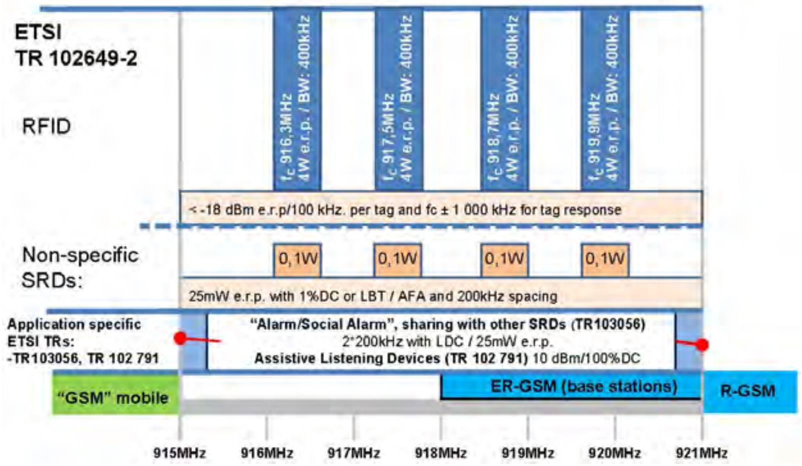

Figure 4-9 Draft summary requirements for 915-921 MHz[137]

The expansion bands shown above seem an entirely reasonable step given the demand forecasts we reviewed in Chapter 3. We concur with the view expressed in the draft ECC report that the proposed extension bands are likely to satisfy the market over the next 10-15 years.

One problem which does appear to exist however is the issue of interference from the new mobile allocation at 800 MHz. Ofcom have undertaken measurement work in this area and we are aware that other measurement work to characterise potential issues is ongoing in the industry.

4.3.2 **TV White Spaces**

In terms of usable spectrum, WSDs depend on the total amount of TV spectrum allocated less the amount actually used by TV and PMSE in a given location. With respect to future availability, an issue arises in that the total amount of spectrum allocated to TV has decreased and may decrease further, partly due to the transition to efficient digital technologies and partly due to growing competition from alternative delivery platforms. The first digital dividend has already resulted in the re-allocation of the 800 MHz band to mobile use, see Figure 4-10. A second digital dividend has been proposed in Region 1 which may re-allocate the 700 MHz band to data services. Given the amount of TV WSD spectrum is likely to decrease, it is uncertain how much sub 1 GHz licence exempt spectrum will ultimately be realised by the adoption of TV WSDs.

In addition, TV WSDs do not suit every sub-1GHz application. The bandwidth and hence data rate is limited for high end applications plus, at the lower end of the scale, a WSD is not likely to be produced at the same low price point as a much simpler 868 MHz band SRD.

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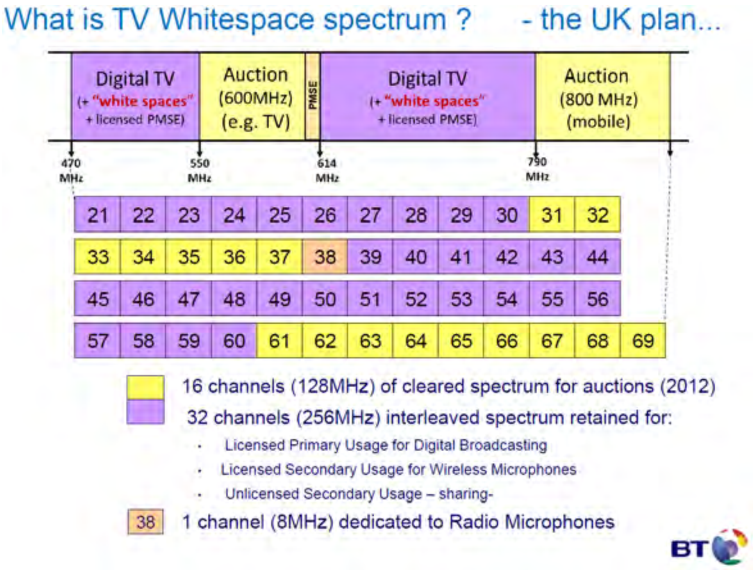
[137] Based on TR 102 649-2, annotated by working draft of ECC Report "Future Spectrum Demand for Short Range Devices in the UHF Frequency Band"



What is TV Whitespace spectrum ? - the UK plan...

🟪 21	🟪 22	🟪 23	🟪 24	🟪 25	🟪 26	🟪 27	🟪 28	🟪 29	🟪 30	🟨 31	🟨 32	
🟨 33	🟨 34	🟨 35	🟨 36	🟨 37	🟧 38	🟪 39	🟪 40	🟪 41	🟪 42	🟪 43	🟪 44	
🟪 45	🟪 46	🟪 47	🟪 48	🟪 49	🟪 50	🟪 51	🟪 52	🟪 53	🟪 54	🟪 55	🟪 56	
🟪 57	🟪 58	🟪 59	🟪 60	🟨 61	🟨 62	🟨 63	🟨 64	🟨 65	🟨 66	🟨 67	🟨 68	🟨 69

🟨 16 channels (128MHz) of cleared spectrum for auctions (2012)

🟪 32 channels (256MHz) interleaved spectrum retained for:

- Licensed Primary Usage for Digital Broadcasting
- Licensed Secondary Usage for Wireless Microphones
- Unlicensed Secondary Usage – sharing-

🟧 38 1 channel (8MHz) dedicated to Radio Microphones

Figure 4-10 TV white space spectrum summary - in March 2012[138]

Trials in Cambridge and by BT on the Isle of Bute have shown that a suitable range for rural broadband may be achieved. Specifically the Isle of Bute trial showed that TV WSDs can deliver over 30 Mbit/s and reach 8km with 2 Mbit/s with 4W eirp, with ten users connected[138]. In order to gain more speed a development of OFDM, called FBMC[139] has been proposed. We discussed FBMC in relation to OFDM in Chapter 2.

TV WSD use was also studied in the EC FP7 project QoSMOS. The business case presented at the final project presentation[140] assumed uncontended secondary access to spectrum. In other words no other white space users were expected in addition to the rural broadband users in the QoSMOS business case. This is an assumption which does not fit well with the present idea of collective spectrum. It thus seems likely that some sort of preferential licensing would be needed by the QoSMOS system, but specifics were not available at the project presentation. We discuss tiered sharing approaches in Section 4.5.4.

It is expected that a Voluntary National Standard and Interface Specification will be published this year by Ofcom for WSDs. Vendors are expected to self-certify against the VNS. As we mentioned in Chapter 2, the new initiative IEEE 802.11af is active in the white space area.

The possibility exists for white space use beyond the TV bands, which could be either a cognitive radio approach or a database approach. We expect that elements of cognitive approaches will play an increasing role as spectrum sharing becomes more advanced, although a fully cognitive approach may be some way off.

4.4 Options for bands above 6 GHz

The following key conclusions from our earlier Higher Frequency Licence Exempt (HFLE) work for Ofcom[141] remain valid today for the frequencies above 30 GHz considered in that

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[138] "Spectrum sharing issues for small cells", Michael Fitch, Cambridge Wireless Small Cells SIG, Cambridge, March 2012.

[139] Orthogonal Frequency Division Multiplexing and Filter Bank Multicarrier respectively.

[140] "QoSMOS Final Project Event", London 12th December 2012. See also http://www.ict-qosmos.eu/

[141] "Higher frequencies for license exempt applications", Quotient Associates Ltd, Final report to Ofcom, February 2007.

study. We also believe they remain relevant to the frequencies above 6 GHz considered in this study. Our earlier findings were as follows

- Over the coming decade, wireless technology and licence exempt techniques will advance with the result that there are likely to be growing opportunities for the beneficial allocation of higher frequency spectrum for licence exempt and lightly licensed uses. Although there is expected to be adequate spectrum to accommodate the growth in usage (provided that the uses are operated under an appropriate licensing regime) there is nevertheless value in delaying the allocation of spectrum when the uncertainties in the benefits from doing so are large. Making allocations today (and not at a future time) is most likely to be optimal only when the expected benefits are large and the associated uncertainties are low;
- Future developments in licence exempt technologies can be expected to encompass both longer range and wide area uses, expanding the range of applications that can be permitted to operate on a licence exempt basis. These advances will, in effect, automate the self coordination processes that feature in many current lightly licensed regimes. This opens the possibility that uses that can operate under a lightly licensed regime today could be migrated to a licence exempt regime once the technology is developed;
- We note, however, that the interference mitigation measures used in licence exempt protocols work best between systems operating over similar ranges. Licence exempt uses will therefore need to be grouped according to the distance over which they operate. Thus the expansion in the range of applications to which licence exemption can be applied will also lead to the need for a small number of different classes of licence exempt spectrum;
- To be commercially viable, some uses will need to operate to higher quality of service levels than can be guaranteed with today's licence exempt technologies. In these cases a light licensing regime can secure the necessary quality of service and provide investor's with the confidence to proceed;
- Where there are large uncertainties in the benefits to be had or to be forgone, it can be economically advantageous to wait rather than immediately allocate spectrum. Non-use of a band can be the highest value use at a particular time;
- When demand is uncertain and decisions are irreversible, the optimal allocation at a point in time is likely to be smaller than a conventional net present value calculation would suggest. Hence, smaller more frequent releases of spectrum may be more appropriate than a single large release.

With respect to mapping our earlier findings to the present study, we expect that the 7 GHz of spectrum available at 60 GHz for WiGig and other wireless data services is not likely to create a bottleneck over the ten year time horizon of our study. Promotion of the use of 60 GHz will face a challenge due to cost, but the approach of supplying tri-band chipsets may allow economies of scale to be created. These effects may delay uptake by the market. Nonetheless, usage of 60 GHz should be encouraged by the industry as it will lighten some of the load at 5 GHz.

The conclusion from our earlier work that license exempt operation will gravitate towards longer range and wider are uses has been borne out by the advent of WSDs and especially their application to rural broadband. One aspect of the co-ordination process we envisaged is presently exemplified by the geolocation approach.

With respect to light licensing, we continue to believe that more automation could lead to such bands becoming automatically assigned and thus potentially offering a convergence with licence exempt in some cases. However the dangers are losing track of users and thus the ability to re-purpose a band, plus light licensing offers a form of admission control and thus at least some notion of quality of service. Thus convergence with licence exempt may not suit all cases. Following our earlier conclusion, we recommend that changes are not made until uses are well understood.

4.5 **Further spectrum sharing options**

In this section we review a number of other sharing approaches being considered in the UK and beyond.

4.5.1 **MoD release**

For some time the MoD has been planning the release of around 500 MHz of its own spectrum which could be used for increasing public mobile broadband spectrum in the UK. Currently it is planned to release 160 MHz from the 2.3 -2.4 GHz and 3.4 -3.6 GHz bands by the end of 2016. Up to a total of 200 MHz from this range could be released by 2020. The 2300 band is a LTE TDD band and part of the 3500 band is already used in the UK for fixed broadband.

Over the longer term, the feasibility of releasing up to 150 MHz of spectrum from other bands is being examined. Key bands under consideration include portions of 2.7 -3.1 GHz and 4.4 -5.0 GHz. These bands have not yet been targeted by LTE, for example, which means they might be considered for licence exempt use. 2.7 GHz may be just close enough to 2.4 GHz to enable economies of scale with present 2.4 GHz Wi-Fi designs, similarly with respect to 4.4 GHz and present 5 GHz Wi-Fi designs. This conclusion is encouraging but tentative, and is based on the general engineering rule of thumb that RF circuits may often offer a tuning range of 10% of their centre frequency without major redesign.

4.5.2 **Small cells band in US**

Based on recommendations by PCAST (President's Council of Advisors on Science and Technology), the FCC/NTIA in the USA is proposing to release spectrum for small cell use in the range 3550-3650 MHz. Use of this spectrum will be controlled by an extension of the approach used in the USA for white spaces in the TV bands[142], i.e. one of management based on a geo-location database. PCAST's contention is that this approach is simpler and/or quicker to market than cognitive radio (sensing) techniques, smart/flexible antenna technologies and dynamic spectrum access.

The system will involve defining a hierarchy of users, see Figure 4-11. These are

1. Federal Primary Access, as the incumbent user;

2. Secondary Exclusive Access, to provide a level of quality of service, or cellular (which is based on admission control rather than sharing) ;

3. General Authorized Access.

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[142] "Realising the full potential of government-held spectrum to spur economic growth", PCASR presentation, July 2012.

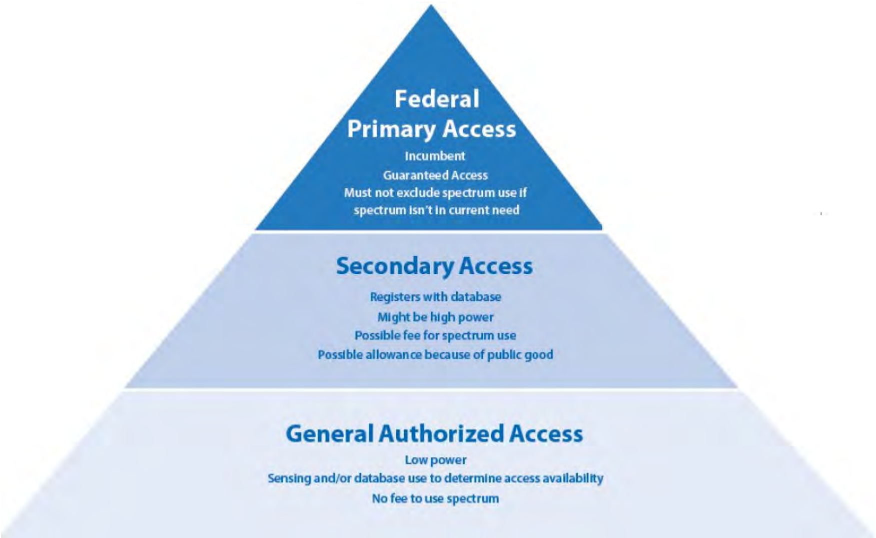

Figure 4-11 USA smalls cells proposed hierarchy

That such a scheme cold be implemented with today's technology is not really in doubt. Where criticism has been attracted is that the small cell users will be third class users, behind two other classes of user who will always take precedence. Moreover, it seems possible or even likely that all classes of user will require access at the same times of day. It is not yet fully clear how the business case for small cells will stand up to this apparent level of uncertainty of access.

Finally, since sharing is with naval radar spectrum, 40% of the US population, who live on the coast, will not be eligible to use this spectrum, see Figure 4-12.

Figure 4-12 USA small cells proposed exclusion zone due to naval radar sharing

Nonetheless, this is another step forward to examine how creative spectrum sharing techniques might the increase the availability of licence exempt device spectrum on short timescales.

4.5.3 Allocation of large blocks of license exempt

A recent report conducted on behalf of the European Commission highlighted anticipated future benefits of releasing more licence exempt spectrum, either as new bands or by sharing existing bands[143]. In particular two new bands of 50 MHz each were proposed at 500-600MHz and 1400 MHz. It was suggested that these could arise from a future Digital Dividend (535-585 MHz[144]) and L band (1452–1492 MHz[145]).

We expect the digital dividend suggestion is feasible and could happen if not secured for LTE first. We expect database control would be needed to avoid interference, with self and other systems due to long range. But L band has been auctioned in UK and taken by the military in USA. It had most recently been intended as a DAB band, but did not succeed in the market.

While we do not necessarily agree with the precise frequency ranges put forward in the report for the Commission, we do concur that more licence exempt spectrum above and below 1 GHz is needed.

We have already suggested that the key is to have both more spectrum below 1GHz for SRDs and WSDs and a greater amount above 1 GHz for short range and high data rate applications. We believe our suggestions for extending the 5GHz Wi-Fi band, plus the planned 870/915 MHz SRD band and the TV white spaces band will realise a great benefit. Rather than create new isolated bands as in the Commission study, we prefer the approach extending bands in order to re-use existing RF designs, antennas, chips and devices.

4.5.4 Tiered sharing rights

In addition to the USA proposed small cells band discussed in Section 4.5.2, there have been at least two other tiered sharing approached adopted or proposed

- IEEE 802.11y in the USA
- WSD tiered sharing in EU FP7 project QUASAR[146]

802.11y

Some time ago, IEEE 802.11y extended Wi-Fi operation to the 3650-3700 MHz licensed band in the USA[147]. It included mandating operation with respect to exclusion zones and the use of polite protocols. Higher power variants, which are light licensed and whose location is registered with the FCC, can reach over 5km. Low power stations must receive an enabling signal from high power stations via a method called Dependent Station Enablement (DSE) which allows the creation of exclusion zones, without requiring low power devices to include location technology. All devices must transmit their ID so any interference can be traced and so that the users themselves have the opportunity to directly resolve disputes. Where operation is permitted, many devices may share the spectrum and the FCC stipulated that this collective use must adhere to a contention based

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[143] "Perspectives on the value of shared spectrum access", S. Forge, R. Horovitz and R. Blackman, ,Final report for the European Commission, February 2012, http://ec.europa.eu/information_society/policy/ecomm/radio_spectrum/_document_storage/studies/shared_use_2012/scf_study_shared_spectrum_access_20120210.pdf

[144] The report does not detail how this range was chosen.

[145] The report actually cites 50 MHz between 1442 and 1492 MHz, but does not detail how this was chosen.

[146] See www.quasarspectrum.eu

[147] IEEE 802.11y-2008,

protocol. This is readily addressed by adopting normal Wi-Fi operating principles. Suitable applications in this band include fixed links, rural broadband, and backhaul.

The DSE approach is very similar to white space database approaches and the general principle of using geolocation may well be applicable in other bands. Given historic problems with DFS in the 5 GHz bands in order to avoid terminal weather radar (where some Wi-Fi manufacturers were fined by the FCC for not detecting radar), it may be that DSE has a future role to play here, perhaps in future band extensions.

QUASAR 'soft' licensing

Soft licensing, as suggested by the QUASAR project is an example of creating a class of license in between licensed and license exempt. Although this idea itself is not new, having been discussed in Ofcom's Licence Exempt Framework Review of 2007 and elsewhere, the QUASAR proposal applies specifically to a wireless data application; that of rural broadband in TV white spaces, which is of interest to the present study.

Soft licensing was developed not to address the issue of secondary users (rural broadband) coexisting with primary users (TV, PMSE), but rather the issue of secondary users co-existing with each other. It is predicated on the fact that where an application requires a defined QoS, use of equal sharing with an unrestricted number of other users is likely to prove problematic under conditions of high load. Soft licensing thus seeks to create a secondary super-user, who remains secondary with respect to the primary, but becomes superior to ordinary secondary users. In effect a tier of (partially) protected secondary users has been created. This is illustrated in Figure 4-13.

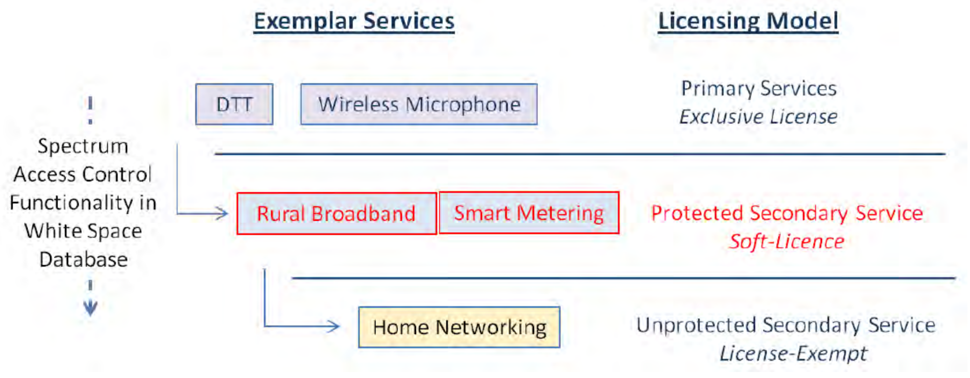

Figure 4-13 The QUASAR 'soft' licensing model[148]

Issues with this approach include the fact that protected secondary users are protected only from ordinary secondary users – they must still cede to the primary. There is clearly a need to consider how soft licensing would be introduced by a regulator; questions could include how to handle competition in cases where two protected secondary services are involved, for example. The protected category is also open to the question of the mechanism by which the protected secondary status might be attained by a user. If it were to involve a fee then it could be considered a form of light licensing in the same space as license exempt. Further issues of fair competition might be involved. Cleary there would be a number of issues to clarify before this approach could be adopted.

Nonetheless, such creative suggestions for future spectrum sharing are highly appropriate at the present time.

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[148] QUASAR deliverable 1.3, "Business Impact Assessment", www.quasarspectrum.eu

4.6 Summary

We summarise our findings in this Chapter under three headings

- New spectrum bands;
- New spectrum allocation processes;
- New spectrum sharing.

New spectrum bands

Mindful of the demand from 5th generation, gigabit rate Wi-Fi (802.11ac), we identified potential avenues to realise 70% more spectrum in the 5 GHz band. Moreover there is the potential for this to be contiguous spectrum and thus well suited to support a number of wide channels. However, such expansions would have to be subject to detailed scrutiny with respect to co-existence potential.

Expanding a band such as 5 GHz leads to economies of scale and we showed that this is also a driver at 2.4 GHz from the medical community and for a hybrid terrestrial low power service from a satellite operator.

We noted the demand for sub-1GHz spectrum and concurred that this is likely to be satisfied over the next 10-15 years by plans already under way in ETSI. Other sub-1 GHz spectrum opportunities such as TV white spaces will face challenges due to a reducing TV allocation in future. In terms of higher frequencies we believe the results of our previous work remain valid today, especially our conclusion that it is economically advantageous to wait until spectrum use is better understood before making or changing allocations.

Finally, we noted that the mobile industry has an aggressive program of spectrum acquisition or LTE 'land-grabs', with which future licence exempt plans have to contend.

New allocation processes

Timescales are long when seeking new allocations and there is a range of ways to approach the new allocation process. We reviewed three different processes by way of mini-case studies. These were

- Industry sector co-operation (aeronautical-medical joint proposal);
- CEPT study process (traditional co-existence study);
- Hybrid spectrum expansion by incumbent (satellite operator seeks premium Wi-Fi).

The approaches are very diverse. However, none removes the key requirement of needing to choose a complementary service with which to share at the outset.

Sharing

Our findings showed that future sharing will need to be highly case specific and will likely include several precise conditions at RF and protocol levels. The key finding at a generalised level was that the initial enthusiasm for sensing approaches is losing out to geolocation for sharing with primary users. This has implications for the 5 GHz band where DFS (based on sensing) is presently used despite initial problems. In future it may become more appropriate to use geolocation approaches such as in the TV while spaces, with as many additional constraints as necessary, as used for example in the new US small cells band. Additional constraints can include permanent geographic restrictions and dynamic station enablement (DSE) to create exclusion zones at will.

In terms of licensing, the notion of classes of use is now being examined with renewed interest. Tiered classed of use have been put forward by the FCC/NTIA for the US small cells band. Soft licensing has been suggested for protected secondary use of TV whiter spaces by EU project QUASAR. Licensing schemes which require registration enable users to solve issues themselves, including issues of QoS. The introduction of new, shared bands is a prime opportunity to introduce new rules which better enable fairer use of the spectrum.

Finally, although sharing with aeronautical, other safety of life and satellite services is often thought most challenging, sharing possibilities with these high reliability applications do exist. The key is that opportunities must be addressed case-by-case and in detail. For example, the aeronautical service actually consists of a number of different services; MBANs can share with aeronautical mobile telemetry, Wi-Fi already shares with terminal weather radar via DFS. We suggest a future possibility is increased Wi-Fi sharing with aeronautical navigation, for example airborne weather radar, via an approach which includes geolocation within its set of conditions.

5 FINDING A BALANCE - SPECTRUM DEMAND AND SUPPLY

In earlier Chapters we examined the details of applications, technology and spectrum. We now bring these together in a concise manner. In this Chapter we

- Review supply and demand per band;
- Confirm 5GHz and Wi-Fi as the band and application combination where excess demand is most likely in future, and for which no plan yet appears to be in place;
- Characterise 802.11ac operation more closely, with respect to wide channel behaviour ;
- Show that more contiguous spectrum would be appropriate to support a sufficient number of channels for efficient dense networking;
- Review MoD release spectrum;
- Show that a middle ground is required between license and license exempt spectrum and that this is also likely to require the combination of a number of sharing mechanisms at the physical, protocol and regulatory levels.

5.1 Demand and supply by band

In this Section we summarise our findings and expectations of application demand, technology and spectrum availability, over the study time horizon, for the following bands

- 2.4 GHz;
- 5 GHz;
- 60 GHz;
- 868 MHz;
- TV white spaces.

5.1.1 2.4 GHz

Over the study timescale, this band will cede to 5 GHz as the high speed Wi-Fi band. This will bring benefits to both those lower speed Wi-Fi users who remain in the band as well as users of short range devices such as Bluetooth and ZigBee. Immediately adjacent frequencies to this band are important for medical monitoring and medical implants. At the top of the band a hybrid satellite-licence exempt band has been proposed in the USA as a premium Wi-Fi channel under the control of one specific operator, although this may be unsuitable for Europe.

5.1.2 5 GHz

This band will become the main high speed Wi-Fi band. In addition to strong general growth, there are potentially specific doublings of resource requirements in this band. Firstly this will occur indoors due to concurrent Internet streaming/screeencasting; and secondly outdoors due to in-band backhaul of hotspots. In addition, the demand in this band will be for larger channels. Only a small number of such wide channels are available in the present spectrum. There is a need for more *contiguous* spectrum to support a larger number of wider channels, and this could be found as shared spectrum adjacent to the present bands, subject to coexistence investigations.

5.1.3 60 GHz

Demand will be driven by in-room video links and instant docking applications indoors, although take-up may prove to be reliant on the wide adoption of tri-band chipsets.. Outdoors 60 GHz is attractive for small cell / Wi-Fi backhaul, as are the lightly licensed 70/80 GHz bands. Congestion is not expected due to the use of directed beams and the large amount of spectrum available.

5.1.4 868 MHz

There is already a plan in place by ETSI to correct the fragmented nature of this band and to provide additional allocations for low power short range devices such as smart meters and high power short range devices such as RFID. We concur with this approach, but we also note that there may be an interference problem from the new LTE band at 800 MHz.

5.1.5 TV white spaces

TV white space devices offer good bandwidth and good range. There is however a question of whether the rate-range combination available will be adequate for rural broadband, which is a key application in this space. New modulation such as Filter Bank Multi Carrier may help. Broadcast spectrum allocations are in decline, and so TV white space device spectrum as well. Furthermore there is a threat of substitution from devices in the proposed new short range device bands above 868 MHz.

5.2 Likely excess demand: Wi-Fi at 5GHz

Our conclusion is that, over the study time horizon, an excess of spectrum demand is likely to be seen in the 5GHz band, for the application area of WLANs, i.e. Wi-Fi.

With respect to the other licence exempt bands listed above, we do not anticipate the development of such a clear excess demand situation. This is either because there is already a large amount of spectrum available with respect to applications, e.g., 60 GHz; or new bands are already being planned e.g. short range devices at 868 MHz; or other bands may substitute, e.g. 5GHz for 2.4 GHz and 868 MHz expansion bands for TV white spaces.

We thus evaluate more closely the need for more 5 GHz spectrum.

5.2.1 Channel fallback behaviour of 802.11ac

As we described in Chapter 4, in order to achieve the higher speeds required by applications, 802.11ac has created wider channels compared to previous versions. These channels are 80 MHz and 160 MHz wide, compared to the 20 MHz and 40 MHz channels of 802.11n. We also showed that only a limited number of such channels can be created in the available spectrum. For example, while nineteen 20 MHz channels are available, no more than four 80 MHz channels would be available, see Figure 5-1.

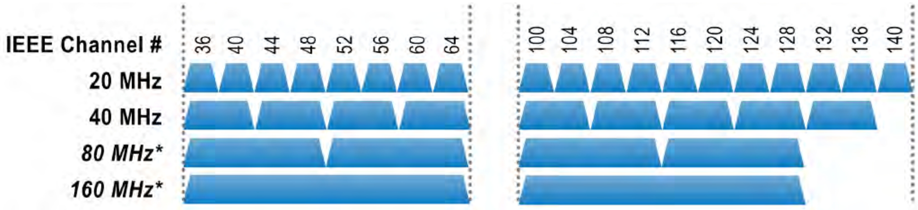

Figure 5-1 Number of channels of various widths[149]

At first sight it might be thought that when all possible 80 MHz channels have been created in the presently available 5GHz spectrum, then the band is effectively full. However this is not the way 802,11ac was designed to operate. Rather it was designed to be fair to legacy version of 802.11; 802.11ac will not use wide channels if it detects all or part of the wide channel is in use or has been requested. In these situations, 802.11ac will fall back its channel width[150]. We describe this process with reference to Figure 5-2.

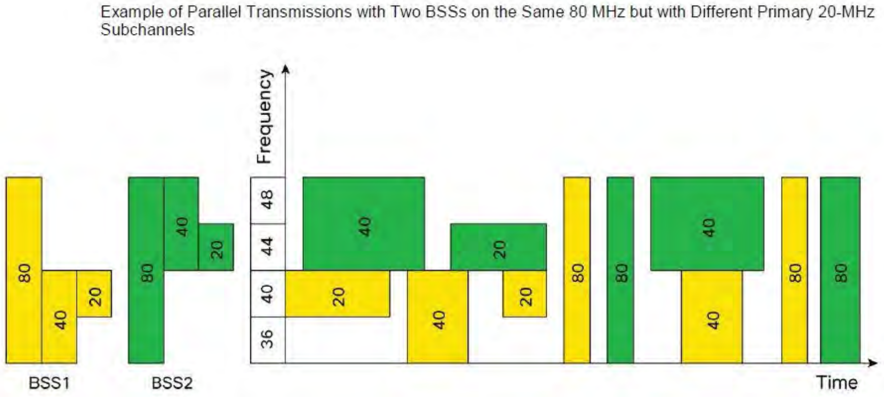

Figure 5-2 802.11ac channel fall back procedure for legacy system compatibility[151]

Figure 5-2 shows two access points (AP), each with 80/40/20MHz channel capability over the same four 20 MHz channels. However each AP employs 20 MHz sensing on different channels. (20 MHz sensing is maintained for compatibility with legacy 802.11 devices). In brief, when one AP is transmitting in its 40 MHz part of the band[152], the other AP is restricted to its own 40 MHz. During this time either AP may transmit over 20 or 40 MHz channels. In order to transmit over the 80 MHz channel, the AP must be sure its 20 MHz sense channel is free (as is normal Wi-Fi protocol) and, just before transmission, must also check the full 80 MHz is free. If this is the case, then the full 80 MHz channel may be used.

This example may be extended to cover the case where one AP is only 40 or 20 MHz channel capable; the wide channel AP will still sense and fall back its channel width to avoid the first AP.

Implications of fall back behaviour

The fall back behaviour is a double edged sword; in order to provide fairness to legacy users, wide channel users must give up some of their advantage. In situations like managed networks, this may not become a problem as the network can be planned and

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[149] Figure source: Quantenna White Paper, US case shown.
[150] IEEE 802.11ac is currently forming its Standards Association ballot pool, but this behaviour is not expected to change.
[151] Figure source: Cisco.
[152] i.e. in that part where its normal 20 MHz sensing is operating.

sufficient capacity can be deigned in and maintained. In a situation where networks are unmanaged, such as many offices and the home, this fall back procedure (which reacts to neighbouring users) is likely to frustrate wide channel users. After all, these users will likely have purchased 802.11ac as they perceive a need for the maximum bandwidth. In this case, if neighbouring users cannot be managed or restricted, more spectrum will be required to utilise 802.11ac to the full.

Summary

In summary the fall back procedure is welcome as it means all versions of 802.11 can coexist with fair access to spectrum; in other words 80 MHz channels will not 'break' Wi-Fi for other users. However, channel fallback is clearly no substitute for those cases where full speed is required by users – only more spectrum can accommodate that. We note especially that users of handheld, battery powered devices (smartphones, tablets) who are practically restricted to a single antenna will require an 80 MHz channel, in order to achieve the fastest, hence lowest power drain connection.

Therefore our conclusion that we anticipate more spectrum will be needed at 5GHz remains appropriate, based on a detailed understanding of wide channel operation. It is also evident that extra spectrum will need to be contiguous, since fragmented spectrum might not allow wider channels to be created efficiently or indeed at all. We next evaluate the number of channels required; from a frequency re-use perspective in a dense environment.

5.2.2 **Number of channels needed for dense Wi-Fi deployment**

Although users have been restricted to three independent Wi-Fi channels at 2.4 GHz for some time and networks have indeed been constructed, such a small number of channels is considerably less that the optimum for a dense deployment. With such tight frequency reuse, interference between channels is quite large as we will show. The reason this has not been a fatal problem is that Wi-Fi operates such a useful back-off algorithm, which ensures successful communications via randomised packet re-tries.

If a uniform, dense network is assumed, then for a given path loss exponent and carrier to interference ratio (C/I) at the cell edge, the ratio of cell size to frequency reuse distance can be found using a simple path loss equation. From this the number of cells in a cluster can be deduced; this the number of independent frequencies needed in the network to attain the required C/I. We may construct a simple table of the number of different channels required for various path loss exponents and two different C/I ratios, Table 5-1.

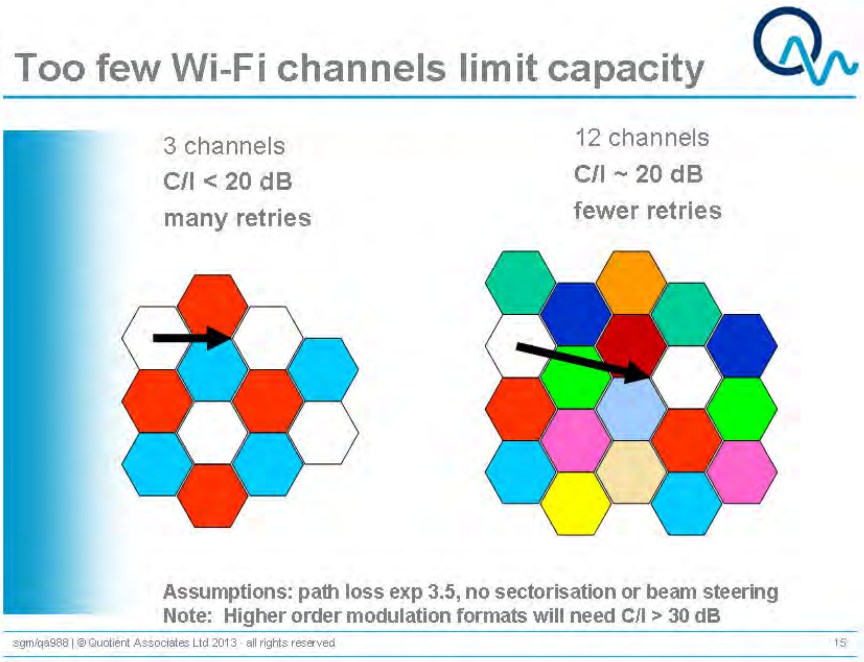
Path loss exponent	*C/I = 20 dB*	*C/I = 30 dB*
2	100	1000
2.5	40	251
3	22	100
3.5	14	52
4	10	32

Table 5-1 Number of channels needed versus path loss exponent and desired C/I

We note that a path loss exponent of 3.5 has often been assumed in ETSI and IEEE 802 work on HiperLAN and 802.11. For that figure, which describes moderate RF clutter, we see that 14 channels are needed to attain a C/I of 20dB. Such a C/I is representative of lower order modulation schemes. If we take a figure of 30dB, intended to represent the higher order modulation used by higher data rata Wi-Fi, then more than 50 channels are needed.

Clearly the calculation rests on simple assumptions, and the path loss exponent could be debated; for instance it could be increased when in a very dense urban environment. On the other hand it could be reduced towards 2 when an open environment is encountered. However our point is not to be precise about the number of channels needed, it is simply to show that a realistic number of channels to avoid packet retries due to inter cell interference is likely to be well in excess of 3 or 4, in typical situations.

We illustrate this diagrammatically in Figure 5-3, where the reuse distance for a 12 channel system is shown to be approximately than of a 3 channel system, leading to better performance in a dense network.



Too few Wi-Fi channels limit capacity

3 channels
C/I < 20 dB
many retries

12 channels
C/I ~ 20 dB
fewer retries

Assumptions: path loss exp 3.5, no sectorisation or beam steering
Note: Higher order modulation formats will need C/I > 30 dB

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Figure 5-3 Effect of frequency re-use factor on carrier to interference ratio (C/I).

5.2.3 **Spectrum required at 5 GHz**

Our conclusion is that more spectrum is needed at 5 GHz and that this should allow a respectable number of 80 MHz channels, certainly more than three or four. This is most efficiently achieved in a contiguous block of spectrum.

We suggested how to construct such a block of spectrum in Chapter 4[153]. This requires the creation of two extension bands with appropriate sharing mechanisms and the repurposing of band C to allow license exempt Wi-Fi. If this were done, the contiguous spectrum available would be 775 MHz. This would be enough for, say, eight or more

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[153] See Figure 4-4, page 66.

80MHz channels in theory, depending on the detailed requirements of sharing mechanisms and noting that the creation of channels which could span regions of spectrum subject to different sharing mechanisms would be best avoided.

We noted in Chapter 4 that sharing would need to be with aeronautical spectrum, and that sensing schemes such as DFS have not been without problems. We believe there is a lesson to be learned from white spaces, the USA small cells band and elsewhere, namely that geolocation approaches may be better suited than sensing as a component part of a sharing mechanism.

5.3 **MoD release spectrum**

We have discussed the plans of the MoD to release spectrum over the coming years. The first tranche at 2300 and 3500 MHz does not necessarily represent the most attractive option for license exempt use. While, at first glance, the 2300 band is well suited to share economies of scale with 2.4 GHz WI-Fi, we note the following objections[154]

- This band is not available globally, for example in the USA, where portions of this band are likely to be allocated to Medical Body Area Networks (MBANs)
- LTE has already included 2300 MHz in its ‘land grab’, and TDD mode has been suggested in this band for Europe[155].

MoD bands to be released further into the future may be of more interest. 2.7 GHz may be just close enough to 2.4 GHz to enable economies of scale with present 2.4 GHz Wi-Fi designs, similarly with respect to 4.4 GHz and present 5 GHz Wi-Fi designs. It is recommended to make an early start to investigate the harmonisation possibilities and sharing requirements of these bands.

5.4 **Summary**

The need for new spectrum

We have shown that more spectrum is needed for license exempt use. We have highlighted the specific case of Wi-Fi at 5 GHz, as no plans yet appear to be in place to cope with the excess demand expected here. We expect the new spectrum will be acquired by sharing, and we gave two key reasons why sharing should aim to create a large contiguous block of 5 GHz spectrum

- To avoid fragmentation and thus foster the most efficient creation of wide channels
- To recognise the importance of harmonisation and the leveraging of existing technologies and chipsets

We proposed specific shared extension bands in Chapter 4. These will require rigorous co-existence analyses which may take some time.

The need for a middle ground

We believe that there is a need for a middle ground between licensed and license exempt (or lightly licensed) spectrum, in order to create classes of use or tiered sharing[156]. We expect this middle ground will require approaches to spectrum sharing which require several conditions to be applied. These might include combinations of geolocation

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[154] Described in Chapter 4.
[155] This making MBANs at this frequency in Europe less likely.
[156] See also Section 4.5.

methods to avoid primary users, and registration and politeness rules to allow uses to both co-exist and solve their own disputes. Bands where polite and impolite users are expected to share (such as the present 2.4 GHz band) are no longer very attractive.

On sharing versus application and technology neutrality

The need for increased sharing brings into question the principles of application and technology neutrality. We have given examples of where application neutrality is being compromised for medical applications above and below the 2.4 GHz band for the good reason of avoiding congestion from general purpose users. Technology neutrality is being increasingly broken by the needs for increasingly complex sharing schemes. This stems from simple DFS at 5 GHz, through geolocation for TV white space devices, to the more complex and varied set of restrictions required to use the new small cells band in the USA.

The need to share in order to attain new spectrum is unquestionable and we expect the conditions that need to be set on sharing devices will continue to need to be complex and restrictive. Having said that, this should not be seen to preclude cases where technology neutrality cane be encouraged at the communications technology level. In other words, specific and complex sharing technology may be mandated, but the underlying communications technology may still be allowed to be as neutral as possible in order to continue to foster innovation.

6 REVISITING THE ECONOMIC FRAMEWORK

Spectrum management covers the technical and service rules governing the allocation of spectrum. It is an important part of telecommunications policy and regulation, as it can significantly influence economic growth and prosperity of countries.[157] This has become even more relevant recently as wireless technologies have become the main means of connecting businesses and households to voice, data and media services.

In the first part of this Chapter we review the different ways in which licensed and licence exempt devices can derive benefits to society. We first review the different approaches to managing spectrum and describe the principal arguments that have been put forward in the literature to explain the costs and benefits attributed to each regime. The suitability of each option is then analysed by describing the impact each regime is likely to have on a range of economic factors, such as barriers to entry, and how these are likely to change by type of application. The first part of the Chapter concludes by showing how, between the licensed and licence exempt paradigms, there lays a grey area where both approaches may prove similarly attractive and how in some cases a hybrid approach combining the two may be preferred.

As we will show, selecting a management regime needs to be performed on a case by case basis, taking into account the impacts of each option. There have been multiple attempts to measure the different impacts of spectrum allocation and these are reviewed in the second part of this Chapter, describing the principal features and weaknesses of the different studies. The final part of the Chapter proposes a new approach to valuation, enumerating the list of dimensions that should be taken into account for informing decisions on the balance between license and licence exempt approaches in different situations.

6.1 Allocation approaches for spectrum management

We briefly review the approaches commonly used.

6.1.1 Administrative model

Traditionally, the management of radio spectrum was undertaken by national regulatory authorities where assignment of spectrum was done by issuing licenses to specific users for specific purposes. This model is referred to as the administrative approach (or command and control) and was initially developed to coordinate frequency use internationally, to avoid interference.

The progressive liberalisation of the telecommunications and broadcasting markets in recent times and the increasing growth in demand for radio spectrum gave rise to criticism over the lack of flexibility of the administrative approach, especially in response to the introduction and development of innovative technologies. This was because the licensing process often involved selection procedures that were slow and cumbersome.

Another criticism arises related to the difficulties of managing such a system. It is believed that in order to ration current and future demand between competing users, spectrum managers would require “detailed knowledge of supply and demand trends, technology developments, and the relative value to society of alternative services”. This is

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[157] “World Telecommunication Development Report: Re-inventing Telecoms”, ITU, Geneva, 2002.

a formidable central planning task, which is probably beyond the scope of any regulatory body[158].

For these reasons, attention has recently focused on two alternative approaches[159]

- Market mechanisms, where spectrum is managed by the market, subject to license terms set by the spectrum regulator;
- Commons model, where nobody controls the use of the spectrum.[160]

6.1.2 Market-based approach

Market-based approaches assign property rights (through a license) which provide a degree of exclusivity of access to spectrum. Exclusivity of access to spectrum means that licensed users should not be affected by interference from other users.

In recent times, approaches based on license auctions have been increasingly used (for example, auctions have been used for mobile licences in the EU).

6.1.3 Collective use

Spectrum allocated for collective use (often referred to as “spectrum commons” and “licence exempt”) allows access to the spectrum to anyone conforming to the regulatory conditions attached to the allocation. In contrast to the market-based approach, users do not have exclusive access to spectrum, nor are they afforded legal protection from radio interference, and users typically share frequency bands with other users, although technical restrictions may be applied to the manner in which the spectrum is used in order to accommodate this type of spectrum sharing.

6.2 Characteristics of the different approaches

The principal characteristics of the market-based approach and collective use directly determine their principal strengths and weaknesses. Spectrum market-based approaches can provide services without interference because access to spectrum is protected by a license. In contrast, all users can access licence exempt spectrum (access is free) but they may encounter congestion and interference.

The importance of congestion/interference and entry barriers provides a significant input when determining the suitability of one approach over another. A number of additional economic impacts are also possible, but the extent and importance of these differ depending on the applications considered, as we show next.

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[158] The Cave Audit of Spectrum Holdings, 2002

[159] There are also many hybrid suggestions. For example, implementing unlicensed spectrum but allowing users to pay a fee to access depending on the current level of congestion; or allocating all spectrum as licensed but enabling license holders to create “private commons”, a form of unlicensed access which they charge for in some form (Cave and Webb, 2004).

[160] A wide range of alternatives are available under this approach. Mott MacDonald (2006) define the following possibilities for collective spectrum use: Specific applications (where equipment must comply with specific standards): Light licensing (in cases registration or notification is required); Private Commons (individual right required but access may be “sub-let”); Experimental Commons (experimental licenses are intended for use on an experimental basis for some predefined and limited period of time); Underlay (spectrum is used for other licensed or LE use but at very low power levels); Overlay (permits higher powers that could cause interference to existing users, but overcomes this risk by only permitting transmissions at times or locations where the spectrum is not currently in use).

6.2.1 Congestion and interference

The main disadvantage associated with the licence exempt approach is congestion and interference. In contrast to licensed usage, where interference is typically managed and controlled by specific network entities, in licence exempt regimes interference may, at best, be mitigated by the wireless devices themselves. The absence of centralised control can lead, in certain circumstances, to overuse of the resource (a phenomenon referred to as the "tragedy of the commons"[161]) which could ultimately result in situations where a minimum quality of service cannot be guaranteed. It should be noted that the impact of interference depends, in any case, on the nature of the wireless service, and is only significant when the spectrum is congested.

The impact of interference between applications can be controlled to some extent via a number of mechanisms, and these have been recognised in Ofcom's Licence Exempt Framework Review of 2007, for example

- in many circumstances, geographic separation and shadowing caused by obstacles provide adequate attenuation of inter-application interference. This is helped by the characteristics of the licence exempt transmitters which are typically associated with small power outputs;
- polite protocols such as carrier-sensing and frequency-hopping can mitigate the impact of interference in instances where radio isolation cannot be guaranteed.

6.2.2 Low entry barriers

The main benefit of licence exemption is its low entry barriers which make spectrum easier and faster to access. Licence exemption presents no access or usage fees (compared with auction payments and licence charges) and no coverage or other obligations. This also translates into relative certainty of obtaining access to spectrum (as there is no competition or time delays for granting access), and considerable certainty of tenure, because of the greater difficulties associated with reversing licence exempt allocations.

Two of the most important consequences of the low entry barriers associated with licence exemption are the potential increases in competition and innovation in the market. The increase in competition can come from different sources, for example

- Firstly, the low barriers to entry enable a market with many suppliers of wireless services. This may reduce concentration in the markets, something the exclusive licensed model does not allow. Further, this may overcome one of the important disadvantages of the property rights system, namely that the allocation of spectrum may be imperfect. The auction systems currently used in many countries have led to a highly concentrated market structure in mobile telephony, which is the result of licenses being won by "firms that expect to use them most profitably and not necessarily by firms that might create competitive pressure that lowers prices"[162]. In addition, in the licensed model re-allocation tends to be a slow and difficult process as the market for spectrum trading is not well developed;
- Secondly, licence exemption may remove the threat of the "hold up" problem which can arise in cases where rights are being used to prevent resource use by potential

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[161] Tragedy of the commons refers to the overuse of a scarce common resource as benefits accrue to private parties and costs are borne by all participants. Because nobody owns the resource, "no-one can be excluded from its use, and since the use of the resource is rival and profitable, scarcity ensures depletion" (ACMA, 2007).

[162] Milgrom, Levin and Eilat , 2011. (see Section 6.3.1)

competitors. This might occur because the profits from monopoly make it worthwhile for an incumbent to buy additional spectrum and "lay it idle rather than allow market entry and face competition"[163], although it is recognised that such a strategy could become costly and unfeasible in a context with more than one incumbent. The hold-up problem can also restrict innovation if this is seen as a threat to pre-existing businesses. If, in addition, the innovation requires coordination of multiple spectrum owners, the implementation process may become cumbersome and too costly to implement.

- The low entry barriers associated with licence exemption increase the flexibility for new entrants to adopt different technology and applications, which enables innovation. It also allows for the possibility to develop niche-market applications at low cost (RFID applications in medicine, download of music or videos to smart phones, or banking and payments by smart phones) which could develop into new industries[164]. In other circumstances, however, the lack of property rights may work against incentives to invest (by building a costly network for example), if the owner fears this can be appropriated by others or cannot secure the revenues to finance the cost of the investment.
- Perhaps the most interesting benefit of licence exempt is that it allows innovative forms of competition using different technologies and business models. In particular, services operating under licence exemption increasingly compete with services offered by operators that rely on licensing. This can be seen, for example, by observing the proliferation of voice calls on Wi-Fi networks (using applications such as Skype) increasingly competing with calls on traditional cellular networks; or by witnessing how new business models coming from Apple, Google and Amazon are challenging the traditional telecommunications and media industries (making use of different smart TV applications for tablets, for example. This is what Cooper has defined as the "systemic diversity" being created by the unlicensed model[165]. This recognises the important characteristics of the system, such as variety (the number of firms), balance (market shares of firms) and disparity (the differences between the firms), all of which help creating value, enhancing innovativeness and building resilience or the networks, at the time they promote other social values. A different business model introduced into the communications ecology "provides the uniquely significant benefit of introducing a different perspective that is ideal for enhancing diversity".

6.2.3 **Effects on consumers**

Licence exemption facilitates the take-up and spread of new applications in situations where access or usage fees are low and services are not congested. This may in turn rapidly increase the consumer base which may improve the value of the service being offered (increasing further consumer take-up). This is typical of situations with network externalities, commonly found in communication markets, where the benefit of the application to any one individual depends on the number of other individuals who use it. This may be especially important in applications which require achieving a critical mass or in applications operating with increasing economies of scale.

The adoption and spread of technologies can also bring benefits from diverse distributions of deployment costs among market players. Licence exempt opens up possibilities for

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[163] Ofcom Spectrum Framework Review, 2005.

[164] SCF, 2012. (see Section 6.3.1)

[165] "Efficiency gains and consumer benefits of unlicensed access to the public airwaves", Cooper, 2012.

business models involving sharing, where both suppliers and users contribute to the development and expansion of the network. This would firstly increase allocation efficiency, where investments are being undertaken where users view it as worth. It also allows for the development of community networks, supported in many cases by customers and users, and supplemented by local authorities. It has been suggested that suggested that many such networks could amalgamate to form a "wireless grid" that could compete with and/or augment existing mobile networks and also the fixed local access infrastructure, with significant benefits for the public[166].

6.2.4 Complementarity effects

There are other benefits arising from complementarities between licence exempt and licensed usage of spectrum. Examples of such complementarities exist with Wi-Fi which serve to offload data from licensed networks, or enable smart phones users to transfer data using broadband internet instead of cellular[167].

6.2.5 Other social benefits from licence exemption

Additional social benefits of the usage of spectrum could stem from a range of supplementary activities. Some of these could be related to a macroeconomic perspective, for example direct and indirect employment generated, additional GDP growth, benefits derived from changes in the production structure (as a result of innovation or competition), and additional costs or benefits for the State (in the form of tax income). In this regard, the rapid introduction of Wi-Fi into new products has facilitated several knock-on effects, especially related to industry development and growth across products as diverse as laptops, e-readers, tablets, home security systems, or smartphones.

Other wider social benefits could take the form of increasing social cohesion, contributions to culture or education, or improving citizen's overall quality way of life. It ahs been suggested that spectrum sharing would have an impact on the following dimensions: social networking, aspirational value to self (including lifestyle organization, social mobility, gender equality), personal safety and security, entertainment, education (including vocational), employment search, family cohesion, support for frail and elderly in the home, health and telemedicine, convenience services, E-government, mobile shopping, networks for safety of life (emergency services, utilities, and transport)[168].

6.3 Factors affecting the balance of licensed and licence exempt approaches

Both licensed and licence exemption models present a number of distinctive attributes and it would be tempting to ask which one is better. However, there is no single answer, as it will depend on the characteristics of the applications using the spectrum. What is clear is that the benefits need to be compared with any potential impact of interference that may be suffered with licence exemption compared to exclusive use. In other words, it should be established whether any marginal increases in interference are an acceptable price to pay for marginal benefits derived from a reduction in concentration or potential innovation. As we will show, in some circumstances there will be a clear preference for licence exempt use whereas in others a licensed approach will be more appropriate.

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[166] SCF, 2012. (see Section 6.3.1)
[167] Milgrom, Levin and Eilat , 2011. (see Section 6.3.1)
[168] SCF, 2012. (see Section 6.3.1)

First and foremost, it seems clear that in cases where applications involve safety, health or security issues requiring a minimum level of quality, spectrum access should be limited administratively (command and control model). This is because overuse could result in congestion and critically reduce the quality of service. This explains why the administrative model is the preferred model for the allocation of frequencies related to defence, aeronautical and maritime applications, for example.

Applications relying on a high quality of service (QoS) provided to a wide area of subscribers would generally require exclusive access to spectrum. This is because the operator would need to know the interference environment in order to be able to plan the network capacity, for a required QoS. Hence, broadcasting and cellular telephony would typically operate in a licensed environment to be able to control the ease of use and access of the services provided to users (including reliability, speed, quality, security or coverage).

On the other hand, use of licence exemption is particularly attractive for applications operating in environments where the risk of interference is low and the quality of the service required is not paramount. Services operating over short distances, or transmitting occasionally or intermittently are suitable candidates for licence exemption. It is also appropriate where the cost of the equipment used to access the spectrum is very low (compared to the costs of licensing) and where its use is essentially autonomous (there is no need for direct connection to a wide network). Hence the main applications of collective use of spectrum are low-cost and short-range devices such as cordless phones, key fobs, WLANs, and other wireless apparatus (doorbells, garage door openers, and the like), which are typically intended to operate over distances of 100 metres or less.

For a number of other applications the solution may not be so clear-cut, as it may depend on the evolution of a number of additional factors. Furthermore, it could be that in practice a hybrid approach may be preferred for the provision of some services. in summary, the following factors should be considered

- The balance between licensed and licence exempt allocations will be determined by the future demand growth of the applications using spectrum and the likelihood that this becomes congested. In cases where congestion is unlikely spectrum should be allocated as licence exempt[169];
- The evolution of technology and the implementation of technical constraints could play a significant role in mitigating the risk of interference. For some types of services where QoS is of particular importance, the probability of interference could be minimised by new technology developments (protocols designed to cope with hostile interference), installing additional infrastructure (more resistant to interference), or through the encouragement of use of power limits and coordination with other users (implementing regulatory arrangements, such as light licensing);
- The evolution of consumer preferences could also play a role when deciding on the allocation of license or licence exempt spectrum. This would encompass the introduction of new applications, but would also include any moves towards new opportunities for using licence exemption which allow relieving congestion in licensed spectrum bands. An example of these opportunities is the increasing number of cellular applications making use of licence exemption in cases where consumers may not be affected by minor delays and interruptions (for example for downloading data);

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[169] Cave, M and Webb, W, “Spectrum licensing and spectrum commons – where to draw the line”, University of Southern California. October 8-9, 2004.

- A number of factors related to the economic environment may also play a role in determining the optimal balance between licensed and licence exempt spectrum. These can be linked to the likelihood and consequent impact of development and implementation of innovations and easing the access to markets for new entrants. This includes competition from new business models, or effects of the "systemic diversity" as mentioned above;
- Finally, other social benefits derived from externalities should also be regarded as potential determinants of the appropriate allocation balance.

6.3.1 **Determining the balance - review of previous studies**

Placing a reliable economic value on spectrum is recognised as a difficult task because of the number of existing applications using it and the different ways in which they do so. There have been a wide range of studies and approaches analysing the value of spectrum or applications using spectrum. Common to such approaches is the consideration of different stakeholders such as consumers, producers, other sectors and society as a whole.

For analytical purposes it is useful to differentiate between private, external and social values. A representation of private, external and social values is provided in Figure 6-1.

Private value is the benefit accrued by both consumers and producers directly from the consumption and supply of a service. In economic terms it is equal to the consumer and producer surplus (this can be measured as the difference between consumer's valuation of a service and its cost of production).

External value includes any benefits indirectly transmitted to other sectors and the broader society as a result of the supply of the service. These can be in the form of economic activity generated for other sectors (particularly in the case where services act as enablers of a different type of services), benefits derived from changes in the production structure (increased competition), or consequences to the wider society (in the form of increasing social cohesion, contributions to culture or education, or improving citizen's overall quality way of life, for example).

The social value encompasses both private and external values.

Figure 6-1 Private, external and social value.

A number of earlier studies have been examined to gather a representative range of approaches undertaken when calculating the economic value of spectrum. We provide a brief review of

- Europe Economics (2006);
- Thanki (2009);
- Thanki (2012);

- Milgrom, Levin and Eliat (2011);
- DECC-Smart meter roll-out for the domestic sector (2012);
- Indepen, Aegis and Ovum (2006);
- MottMcDonald (2006).

We subsequently provide an overall critique of the approaches employed.

Europe Economics (2006)

In a project for Ofcom in 2006, Europe Economics used consumer and producer surplus to measure the economic impact of the use of radio spectrum for public mobile, broadcasting, satellite links, fixed links, wireless broadband, private mobile radio and a range of other uses. The methodology for estimating consumer surplus was based on calculations which used the individual consumer benefit (estimated from different sources) and the number of users. Following the approach in previous studies by the Radiocommunications Agency, the Europe Economics study used company accounts to calculate producer surplus as the difference between revenue and economic cost. Whereas turnover was considered equivalent to company revenue in the accounts, economic costs were identified as the sum of labour, other non-labour (materials or broadcasting content), capital goods (buildings, vehicles and plant and machinery) and stocks. An estimate of cost was derived after several adjustments for the calculation of capital stocks and for segmenting the companies' accounts to the relevant sector and jurisdiction (the UK).

In addition to the direct effects, this study recognised two types of additional indirect contributions: linkage and induced effects. Linkage effects refer to the jobs created in the supply or distribution chain (for example in a mobile handset manufacturing firm). Induced employment or the income multiplier is the effect that arises due to expenditure of the incomes earned by employees in the sector. The report used multipliers derived from Input-Output tables as a suitable method for assessing sector-level linked and induced effects (the tables provide detail on the flows between various industries and also between industries and the final demand sector). Such linkages were used to estimate the extent to which any given industry contributes to the various final demand sectors.

Thanki (2009)

In a study supported by Microsoft, Thanki estimated the economic benefits of unlicensed spectrum between 2009 and 2025 for Wi-Fi in home, hospital and RFID in clothing, using consumer surplus calculations.

The analysis for Wi-Fi derived a demand curve for Wi-Fi homes based on a study of the consumer surplus generated by broadband in the USA. To estimate the demand of broadband overall, the study extrapolated additional willingness to pay figures to all US households.170 Based on assumptions of households' preferences with respect to the use of Wi-Fi, the study further derived additional willingness to pay for broadband amongst households using Wi-Fi. The central premise of the study was that households would be less willing to pay for their broadband services without the wireless connectivity171 and this would hence reduce the incremental demand for broadband services. As such, the

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[170] Orszag, J., Dutz, M., & Willig, R. (2009). "The Substantial Consumer Benefits of Broadband Connectivity for US Households". Retrieved from Internet Innovation Alliance, July 2012.

[171] The study modelled three scenarios, a low case with 10% of broadband value derived from Wi-Fi, a medium case with 20% and a high case with 30%.

economic value of Wi-Fi was calculated as the consumer surplus generated by Wi-Fi and the incremental demand for broadband due to Wi-Fi, which summed to $4.3 to $12.6 billion per year. As the study recognises, the analysis accounts only for the value that consumers might place on wireless broadband but excludes a number of other uses for a home Wi-Fi network (such as online gaming using consoles, the ability to stream rich media content and large files around the home, and, increasingly, benefits derived from of home automation and smart metering applications or smartphone applications using Wi-Fi networks).

Building on the findings from an American apparel study, Thanki estimated the economic value of RFID in clothing industry to the US economy between 2009 and 2025[172]. The study modelled the economic value of RFID in two ways. Firstly, it recognised that the new system using RFID could reduce labour time on replenishment for stocks which can be directly translated into gain in producer surplus. Secondly, the study reported how RFID could also improve the consumer surplus by lowering the search cost to purchase the desired items[173]. The estimated economic benefit was between $2 to $8.1 billion per year using three different assumptions on the take-up of RFID technology[174]. Although the study realises that the greater benefit to retailer is the increase in sales revenue due to reduction in stock-outs, this is not added into the calculation of economic gain since it cannot be directly regarded as consumer or producer surplus. The study also did not capture the potential economic value from the reduction in shrinkage, inventory holdings or other possible use for commercial purposes.

Thanki (2012)

This study provided evidence on the substantial economic benefits that are being delivered by technologies using licence exempt spectrum and strongly advocated for policy makers and regulators to increase the supply of licence exempt spectrum. The study also provided evidence on the role of licence exempt spectrum in three areas: delivering broadband connectivity to people, facilitating machine to machine connections and networks, and developing robust and adaptable networks.

Thanki expanded his 2009 study on licence exempt spectrum to a global scale and estimated that Wi-Fi has generated approximately $52 to $99 billion of consumer surplus worldwide through the enhanced use of fixed home broadband. In addition, Wi-Fi also improved the connection of around 50 to 114 million fixed broadband connections around the world.[175]

The study also investigated the costs in the absence of Wi-Fi in order to quantify unneeded network investments in the mobile industry. The study estimates that an additional $250 billion investment in additional sites would have been needed to be built to cope with the data demand up to 2016, without Wi-Fi (least expensive solutions involving femtocells or picocells would still require an investment of up to $45 - $60 billion).

Additional value of licence exempt spectrum can also be linked to the success and benefits of Internet of Things. Because almost all of the connections to the Internet of Things will be made using licence exempt devices (more than 95% of all connections) it is reasonable

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[172] The American Apparel pilot – Robert W. Baird & Co, 2009.

[173] The study assumes that each instance of stock-out lead to 15 minutes of time lost per consumer and the time cost is valued at the average hourly US salary.

[174] The study used 60% as the maximum level of take up for high scenario, 30% for medium and 15% for low.

[175] The study also examined the significant role of rural wireless internet service providers (WISPs) which rely on Wi-Fi technologies to serve the remote communities that would otherwise be unreachable with the wired or wireless data services. Examples discussed include ZittNet in Nigeria which uses Wi-Fi to provide internet connectivity to 150,000 people.

to expect that, in absence of licence exemption, the Internet of Things would not reach the scale that is widely expected. By assuming that the least-valuable 50% of devices would not be connected, Thanki estimates that around $560 to $870 billion a year of economic value could be foregone in 2020. This is equivalent to around one-third of the total value that might be generated by the Internet of Things.

Devices and networks utilising licence exempt spectrum are also significantly contributing to the overall reliability and adaptability of communications networks, according to the study. The facility for deploying licence exempt technologies encourages the creation of networks from the bottom up, facilitating the adaptability of networks to changing demands or in response to emergency situations (such as interruption of communications networks). This is because deployment of licence exempt networks does not require any specialised equipment and off-the-shelf components can be used to create broadband networks.

In assessing the efficient balance between licensed and licence exempt spectrum, Thanki considers that a strong case can be made in favour of licence exempt as it is far more likely to expand access to broadband to meet the growing demand for data. This is because that the majority of the traffic from PCs, laptops, smartphones and tablets is carried over Wi-Fi.

Milgrom, Levin and Eliat (2011)

This study provides an approximation to the value of licence exempt in the Apple iPad tablet. The analysis started from a producer surplus estimate of $300 (calculated using a retail price of $599 and sale costs of around $300, as provided by several analyses). Using the same figure for consumer surplus and total sales, the study deduced a total surplus for 2010. The authors believe that most of this value is attributable to Wi-Fi as it seems hard to believe that a product which has no cellular access as standard would have been nearly as successful or widespread without Wi-Fi.

The authors noted other benefits arising from complementarities between Wi-Fi and licensed spectrum. Examples of such complementarities are the offload of data from licensed cellular networks, or Wi-Fi capabilities for smartphones which enable users to transfer data using broadband internet instead of cellular. The benefit of using Wi-Fi is in the form of higher speeds in data transfer, reduced congestion on cellular networks, and access in areas where cellular reception is imperfect, such as indoors.

DECC-Smart meter impact assessment (2012)

In the impact assessment on the Government's roll-out smart metering program, DECC conducted a cost-benefit analysis of the use of smart meters on different stakeholders. The consumer benefit was modelled using the roll-out assumption under which different installation rates were implemented in three stages to reach 100% of consumers converge.[176]

The study estimated the total consumer benefits of £4.43 billion. This was derived from a sensitivity analysis which captured the change in the consumer behaviour leading to energy demand savings of 2.8%.[177] The other sources of benefits included bill savings attributed to the shift in consumption patterns between peak to off-peak times and micro-generation. Total business benefits include a reduction in site visits and reduced inquiries

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[176] The installation rates of each stage were targeted to reach 10% between 2012 - 2014, 90% by 2018 and 100% in 2020 respectively.

[177] The saving ranged from 1.5% in the lower benefits scenario to 4% in the higher benefits scenario.

and customer overheads (£8.47bn), and network, generation and carbon-related benefits (£884m, £738m and £1.2bn).

In parallel to the economic assessment on domestic sector, DECC also carried out a cost benefit analysis of the use of smart metering to the non-domestic customers in UK. Similar to the domestic sector, the study included benefits generated from a shift of demand allocation from peak times to off-peak times as well as micro-generation. The total consumer and supplier benefits derived from the study amounted to £1.7 and £1.2 billion.

Non-monetised benefits were also considered including the benefits from the development of a smart grid, development of innovative energy management tools (home automation and smart appliances), and stronger competition between energy suppliers. Smart meters will also improve customer experience due to better information and more convenient payment methods.

Indepen, Aegis and Ovum (2006)

Study work was commissioned by Ofcom to estimate the economic value of licence exemption.[178] The main goal was to develop methods to estimate the future economic value of licence exempt applications (up to 2026), to be able to inform decisions about whether to license the use of these bands or designate them as licence exempt. Among the wide range of applications for which licence exempt spectrum is used, the study selected 10 applications for detailed study.[179]

The study describes two types of interference effects which may affect value under situations of spectrum scarcity. These are intra-application interference or congestion (quality of service declines as density increases) and inter-application interference (devices for one application interfere with the use of another one). However, the effects of interference are not taken into account in the final estimates of economic value. The study also excludes a number of costs and benefits for which it is believed that quantification would not be credible.[180]

The results of the study show that the expected net present value of the applications varies considerably (from less than £1 billion for road user charging and fixed wireless links to over £100 billion for public access Wi-Fi) and highlights public access Wi-Fi, RFIDs in retail and automotive short range radar as the three potential major licence exempt applications.

Calculations are necessarily based on strong assumptions related mostly to the likely evolution of consumer take up and traffic, consumer response to changes in prices (elasticities), and the different type of benefits derived from use of applications and the costs of implementing them.

The study also notes the considerable uncertainty in these projections, depending on the scenario chosen. It was recommended that Ofcom reduce this uncertainty by monitoring take-up of the most important applications and by studying in more detail the use which UK households make of wireless devices.

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[178] Indepen. Aegis and Ovum (2006): "The economic value of licence exempt spectrum". December.

[179] The applications were the following: 1. Road user charging; 2. Short range radars; 3. Blood glucose sensors; 4. RFIDs in retail; 5. Public access Wi-Fi; 6. Home data networking; 7. Wireless building automation; 8. Fixed wireless links; 9. Telemetry in utilities; and 10. Wireless home alarms.

[180] For example, any increase in road capacity or reduction in congestion as a result of fewer accidents in short range radar in cars; the time saved by patients not having to attend so many out patient clinics when using in-body blood glucose sensors; or the costs and benefits of home entertainment and home automation in home networking applications.

Mott McDonald (2006)

Mott McDonald considers the circumstances in which market transactions could be used to determine licensed or licence exempt allocations. Since it is recognised that an implementation of markets leads to optimal economic outcomes, the use of private commons (where an organisation buys spectrum and makes it available to others on a collective basis) is suggested as a first way of introducing market forces. However, because of the likely presence of the "commons problem" and the inability of market forces to take into account the social benefits, the report concludes that general decisions about the balance between licensed and licence exempt spectrum need to be made administratively. To address the potential impact of licensed versus licence exempt spectrum access regulatory impact assessment are required, it was recommended to use the EC's regulatory impact guidelines[181].

In any case, decisions should be made in a transparent manner considering all feasible options and using all available information on the costs and benefits of these options. These should use information on current use and trends in the deployment of applications and equipment, gathered through monitoring activities by the national regulators, supplied by industry or collected through consumer surveys conducted.

The report notes that the adoption of impact assessments can be a costly exercise, so warns against adopting rigorous impact assessments for all frequency bands, and recommends, instead, simple and quick feasibility studies which would identify whether the exercise is worth pursuing in more depth.

6.3.2 **Critical review of the different approaches**

Studies assessing the economic value of spectrum empirically all suffer from the unavoidable limitations of lack of data and absence of reliable parameters upon which to base the calculations. This is important when using estimates of costs and consumers valuations, but it is particularly relevant in making projections on the evolution of technologies in the future. Unavoidably, critical assumptions need to be made and uncertainty scenarios constructed when making the calculations. In the end this means that typical studies may be able to make specific projections, but these are subject to a high degree of uncertainty or are estimated using very large confidence intervals.

Because of the difficulties associated with obtaining wider data, most studies limit their scope to the measurement of the quantitative benefits of spectrum, typically approximated with computations on consumer and producer surplus. Given the differences which social impacts can have under different licensing regimes (as seen, in terms of competition, innovation, social values) and their importance, it would seem that these are the very parameters that should be focused upon in order to explain the different performance of applications under a licensed or licence exempt regime. In many of the studies, these additional parameters are reported only qualitatively and are not included in any final assessment.

In line with many of the studies, we believe that congestion and interference should be considered the most important driver when assessing the balance between licensed and licence exempt spectrum. Most commentators and regulators seem to agree that in the absence of harmful interference a licence exempt approach should be preferred, but in practice congestion and interference are hardly taken into account in valuations. A better

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[181] The guidelines establish a number of steps for reaching a conclusion: identify the problem; define the objectives; develop main policy options; analyse the impacts; compare the options; and outline policy monitoring and evaluation.

assessment of congestion costs is needed and, in particular, as detailed a quantification as possible to be able to assess the impacts with respect to the type of consumers affected, their geographic location and time-based usage.

6.3.3 **A marginal utility suggestion**

Economic valuations typically perform the calculations for applications as a whole. Unsurprisingly, this often results in attributing higher value to those applications with a larger number of users. In some cases it has been suggested to employ a per-user or per-MHz to compensate for volume differences, but this is unlikely to summarise appropriately the different distribution of individual consumer valuations. We suggest that in a context of spectrum scarcity (as could happen under licence exemption) allocations or rights should be based on the assessment of the individual valuation of the different users, that is, marginal and not total utilities. This would allow seeing higher benefits in applications with a small pool of consumers (but high marginal utility) than in others with high number of consumers (although low marginal utility).

For example, we could ask what would be the optimal balance in a situation with 2 applications only and valuations defined by the values in the y-axis in the graphs in Figure 6-2. Assuming negligible costs, the total valuation approach would estimate the consumer surplus of application 1 as 64 (the sum of the bars for all units/users) and 24 for application 2, and conclude that economic private value is higher for application 1. If only 8 units of spectrum were available these should all be assigned to application 1.

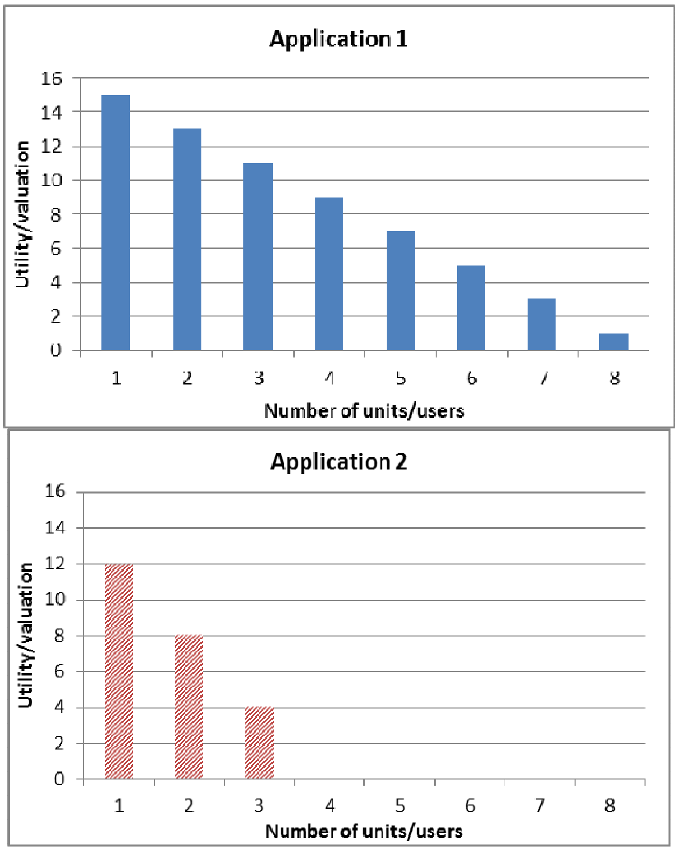

Figure 6-2 Consumer utility (valuation); example applications 1 and 2.

The analysis however is distorted by the fact that application 1 has larger number of consumers (with few of them valuing the application more than those using application 2). If we take into account the individual or marginal utilities the analysis would produce a different result. The allocation mechanism should start from the higher valuation and follow progressively downwards for the remaining ordered valuations (irrespective of whether these are in application 1 or 2). This could be represented in a joint demand function for application 1 and 2, as shown in Figure 6-3. The striking difference is that with 8 units of spectrum available, an allocation based on marginal utility would assign 6 units to application 1, but 2 units to application 2.[182] Assuming negligible costs this new allocation would result in a consumer surplus of 80, which is higher than the surplus of the allocation considered in Figure 6-3.

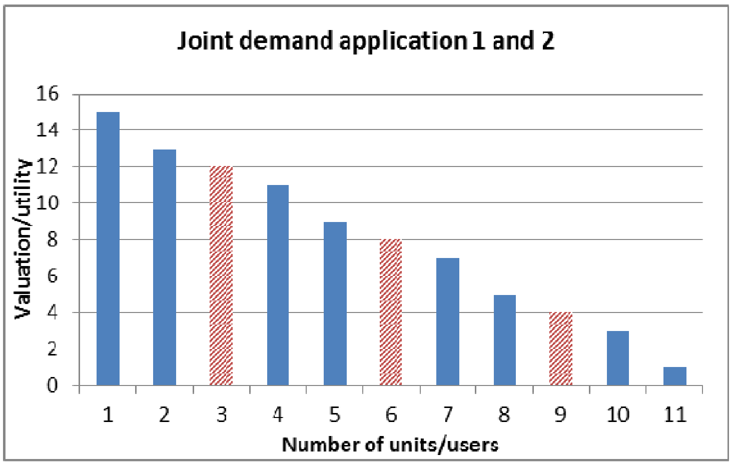

Figure 6-3 Consumer joint utility (valuation).

6.4 A proposed framework for addressing the optimal balance

Given the limitations of the valuation methods used in the different studies, Ofcom have requested ideas for a new methodological framework. This should include the range of factors to be taken into account in the assessment of the balance between licensed and licence exempt spectrum. Because of the wide range of factors and drivers, it was suggested that a qualitative approach may be appropriate encompassing both economic and social values.

We believe that any approach should be based on two types of analyses: (1) the assessment of the emerging needs for spectrum and whether these can be fulfilled with current supply or alternative allocations, and (2) an analysis of the efficient use of spectrum by different applications and allocations. The review of spectrum allocation and use should follow three phases[183].

Phase I: A first phase would require assessing future demands for spectrum and this should include trends in technology and development of new applications. The aim will be to identify the key applications that are likely to drive spectrum demand (in the timeframes considered).

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[182] To make things more complex in a context with network externalities it could be possible that a reduction of the consumer base in application 1 could further decrease the utility valuation of other users. This would mean that the consumer utility of application 1 changes after allocation of spectrum, which may in turn imply that another allocation should be considered.

[183] These are based on the approach described in RSPG12-408, 2012

Phase II: In a second phase the availability of spectrum and actual use under current frequency allocations should be established. This phase would also propose alternative allocations and management regimes. Part of the analysis of spectrum availability would include, where possible, information on congestion and interference.

Phase III: The final phase would review the efficiency of different applications by assessing their performance in relation to economic and social valuation, while considering the technical feasibility of provision under the different proposed management regimes (licensed or licence exempt). Determining efficiency under alternative spectrum allocations will be the most challenging aspect of any assessment. Following the opinion provided in RSPG12-408, we believe this would require assessing technical, functional, economic efficiency and external value

- Evaluation of **technical efficiency** means assessing the operability of applications in different bands (license or licence exempt). The key aspect of the technical efficiency is to identify the extent to which some applications could be in-operational in certain bands, as this would limit the possibilities of alternative allocations;
- **Functional efficiency** assesses the ease of use and access to a service for users. Reliability, speed, quality, security, coverage, or availability to make group calls, are all part of functional efficiency of services. Functional efficiency should be measured by different market segments, as attributes of usage may be valued differently by different type of customers (e.g. emergency services compared to leisure usage);
- **Economic efficiency** or **private value** would assess the economic costs and benefits of applications in different allocations (licensed or licence exempt) in relation to consumer and producer surplus measured in terms of their marginal private value (the individual valuations of consumers and producers);
- The **external value** would imply evaluating the efficiency in terms of additional social benefits, which would include assessing the implications for sustainable growth, competitiveness, productivity, and social benefits, as well as the effectiveness of alternative allocations in improving sectoral outcomes (such as competition and innovation), as described in the previous sections.

6.4.1 **Approach to quantification of efficiency**

Having established the four dimensions for measuring efficiency, it becomes crucial to provide a credible way of comparing the performance of applications under each allocation.

We believe that providing an impact assessment for all the applications, efficiency dimensions and license regime can be a costly exercise and hence an alternative approach should be followed. For those efficiency measures which can be quickly quantified, the costs and benefits could be compared in monetary terms. In areas where it is difficult or not feasible to produce quantitative estimates if may be useful to calculate efficiency scores which assess the expected performance of each option against the efficiency criteria. Scores would be estimated using input from the stakeholders, and results from additional materials collected, for different applications and allocations.

By assigning different weights for each of the criteria (to reflect their relative importance to the decision) it would be possible to derive an overall efficiency score. This would allow a quick assessment in cases where options are being dominated by others (in the sense that their efficiency scores are lower) without the need of further analysis. Efficiency scores could also be used to rank options, to short-list a limited number of options for subsequent detailed appraisal, or simply to distinguish acceptable from unacceptable possibilities.

6.4.2 Example of how to implement the proposed approach

We now explain how the proposed approach could be implemented by describing the steps of the assessment of licence exempt needs. For simplification purposes we consider only two example applications within an imaginary licence exempt band: Wi-Fi and healthcare applications.

The first phase of the assessment would require forecasting future demand needs of all applications operating in licence exempt bands. This should include a review of trends in technology development and consumer attitudes and take-up of new applications (consumer requirements for mobility, faster speeds, higher bandwidths, flexibility... should be considered). It should also provide an estimate of the key applications which are likely to drive the future demand for spectrum (uncertainty in growth in demand and the economic climate could be modelled with low, medium and high scenarios). As a result of the first phase, one may conclude, for example, that demand for Wi-Fi will significantly increase in the next years, while that for healthcare applications would show a moderate growth.

The second phase would establish whether demand (current and future) could be met with the existing allocation of licence exempt bands: that is, under the current status quo (or in a situation which we can define as a “do nothing” option). It is important at this stage to assess any potential problems of congestion and interference and the extent to which these are likely to affect users, in a situation without any policy intervention. In particular this should investigate the levels of congestion in time and across geographic space. In general, if congestion is unlikely, spectrum should be licence exempt. But the analysis should also establish in particular whether congestion is present in certain geographic locations (rural areas) or at different times of the day (off-peak), in which cases it would also justify a preference for different segments of licence exempt bands. The extent to which congestion is harmful to users is also an important issue: cases where consumers have access to suitable alternatives or are tolerant to a certain level of congestion would indicate that current licence exempt allocations are being accepted by the users. The situation under a “do nothing” option should also consider the evolution of technologies which increase the possibilities of spectrum sharing and alleviate congestion (such as geographic separation, mechanisms for attenuation of interferences or technical improvements in polite protocols).

When studying Wi-Fi and healthcare devices, the analysis of the second phase may show some likelihood of congestion and interference but only for a very limited number of highly dense areas and during a few peak hours of the day. It may be also possible to conclude that in such areas and peak times there are no possible alternatives to spectrum and that congestion and interference affects demand in a way that further intervention is required. In cases where congestion and interference are seen as a problem under the status quo, alternative options should be considered. The options should be chosen such that they achieve a reduction in congestion and interference. For illustrative purposes we will consider only three policy options

- Option 1: do nothing;
- Option 2: expand the bands operating under licence exempt;

- Option 3: limit access to licence exempt bands.

The final stage would assess the efficiency of the options. It is firstly important to establish that such options are feasible in terms of technical and functional efficiency. In cases applications become in-operational in alternative allocations (technical) or do not adequately fulfil consumers' expectations in terms of quality or coverage (functional efficiency) the options should be reconsidered. This stage should also establish how the different options could be implemented. In the case of Option 2 it may include assessing alternative potential uses of the bands envisaged for expanding licence exemption. This should include studying the private and social benefits of alternative applications to establish the opportunity cost of spectrum. In the case of Option 3 this may require establishing a priority of users in the congested situations, which may be achieved by various models of private commons, light licensing, establishing politeness rules defined by regulatory bodies, or using polite protocols defined by manufacturers of equipment. For example, we discussed tiered sharing in Chapter 4.

Finally, the economic efficiency and additional social value would be assessed for the range of factors identified earlier. The assessment of private value would include consumer surplus valuations which would require establishing the valuation or willingness to pay of the users of the different applications (marginal utilities).

Hence, we may find that individual utilities decrease in the status quo ("do nothing" option) with high congestion and interference as consumers view the applications as unreliable and find it hard to have access to substitutes or alternative services.

Expanding the bands (Option 2) would then improve the valuation of individuals, but this might be achieved at the expense of lowering the economic value of the new band (compared with the cost of opportunity of potential alternative uses of the band, such as licensed allocation to mobile operators).

Limiting the access of uses in licence exempt band (Option 3) would clearly reduce the utility of those excluded, but it may also translate into an economic improvement if this loss is compensated by the increase in utility of the users as a result of avoiding congestion. It is also possible that the analysis of marginal utilities would conclude that some users of healthcare applications achieve higher benefits than the bulk of Wi-Fi users, which would justify limiting the access according to joint consumer valuations. In this case, regulatory rules, politeness protocols or light licensing should be established in order to separate the users of both applications according to their joint valuations. A preference should be given to consumers with higher valuations in either application, as shown in the example of Figure 6-3 earlier.

As for the external value, it is necessary to consider the implications for sustainable growth, competitiveness, productivity, and social benefits. Through a matrix of efficiency scores for the different valuation criteria (estimated through subjective analysis and valuation of different stakeholders) it may be concluded that both Option 2 and Option 3 dominate (in a sense of bringing higher social benefits) over the status quo, but the criteria may not allow discriminating between those two options.

The analysis employed in our example may be summarised in the following steps.

Phase I may show a significant growth in Wi-Fi and healthcare applications, which is likely to result in problems of interference and congestion, albeit in a limited number of high dense areas and during peak times.

Phase II proposed a range of options to deal with the problems related with congestion and interference.

Phase III assessed the efficiency of the different options and concluded that they were technically and functionally feasible, and Option 3 implied higher values for consumers. Both options 2 and 3 dominated Option 1, but no conclusion could be reached when comparing options 2 and 3.

As a result, the analysis would conclude in favour of Option 3, as it is clearly superior to Option 1 and is superior or equal than the benefits achieved by Option 2. A summary table is shown in Table 6-1, below.

Phase	*Action*
Phase 1: Forecast demand	Significant growth in Wi-Fi, moderate in healthcare applications
Phase 2: Assess congestion/ interference and establish options.	Option 1 – Do nothing: Wi-Fi congestion and interference with healthcare devices but only for a very limited number of highly dense areas and only during a few peak hours of the day. Option 2 - Expand the bands operating under licence exempt, Option 3 - Limit access to licence exempt bands in congested situations.
Phase 3: Assessment of efficiency	Technical and functional efficiency: assess feasibility of options and ways of implementing them (private commons or light licensing). Economic private value: individual (marginal) utilities concludes that: Option 1: implies a significant reduction of consumer surplus due to congestion. Option 2: increase in consumer surplus which is lower than the valuation from mobile applications. Option 3: consumer surplus using joint valuation is higher than other two options. External and social value Option 2 and Option 3 dominate Option 1 in terms of the implications for sustainable growth, competitiveness, productivity, and other social benefits. Comparison of Option 2 and 3 inconclusive.
Conclusion	Option 3 is clearly superior to Option 1. Option 3 is superior or equal to the benefits achieved by Option 2.

Table 6-1 Illustrative case study for Wi-Fi and healthcare: steps of impact assessment

6.5 Summary

In this section, we have presented different ways in which licensing and licence exemption can derive benefits to society by focusing on the different approaches to managing spectrum. We have shown how the key characteristics of the market-based approach and collective use determine their principal strengths and weaknesses. Market-based approaches can provide services without interference because access to spectrum is protected with a license. In contrast, all users can access licence exempt spectrum but they may encounter congestion and interference. The suitability of each option is then analysed by describing the impact each regime is likely to have on different type of applications.

The low barriers to entry under licence exemption allow additional suppliers of wireless services into the market and facilitate the adoption of different technologies and applications. This can be translated into the development of new innovative applications, but also in the proliferation of technologies and business models which may introduce new forms of competition with traditional suppliers.

Licence exemption also facilitates the take-up and spread of new applications which may be essential for generating greater benefits in situations with network externalities, and also enables sharing of deployment costs between suppliers and users, which can contribute to the development and expansion of networks. Other benefits could include the complementarities between licence exempt and licensed applications (allowing for offload data from licensed network) or additional social benefits (such as increasing employment, increasing social cohesion, or contributions to culture or education).

When deciding which approach to adopt, one should always compare any marginal cost increases from interference with the marginal benefits derived from reduction in concentration or potential innovation. In some circumstances there will be a clear preference for licence exempt use or licensed approach, whereas in others a hybrid approach maybe more appropriate.

A wide range of different studies and approaches were reviewed, analysing the value of spectrum or applications using spectrum. Wwe have shown how many of these differentiate between private, external and social value.

The studies assessing the economic value of spectrum empirically all suffer from the unavoidable limitations of lack of data and absence of reliable parameters. This translates into high degrees of uncertainty in the results, normally provided using very large confidence intervals. Although studies often recognise the social impacts under different licensing regimes, because of the difficulties of measuring such impacts, these are only reported qualitatively and are normally not included in any final assessment. Congestion and interference are recognised as important drivers of the balance between licensed and licence exempt spectrum, but because of measurement difficulties are hardly taken into account in the valuations. The costs of congestion thus need to be better understood.

Economic valuations consider the whole consumer base and often result in attributing higher value to those applications with a larger number of users. Allocations or rights should be based on the assessment of the individual valuation of the different users. This would allow seeing higher benefits in applications with a small pool of consumers (but high marginal utility).

Our proposed approach to valuation is based on three phases. A first phase would require assessing future demands for spectrum and this should include trends in technology and development of new applications. A second phase should establish the availability of spectrum and actual use under current frequency allocations and propose alternative allocations and management regimes. The last phase would review the efficiency of different applications by assessing their performance in relation to economic and social valuation, while considering the technical feasibility of provision under the different proposed management regimes. An impact assessment for all the applications, efficiency dimensions and license regime can be a costly exercise and we propose to calculate efficiency scores (estimated using input from the stakeholders) in areas where it is difficult or not feasible to produce quantitative estimates.

7 CONCLUSIONS

Our conclusions from this study may be grouped into several areas. In terms of applications and technology

- We see Wi-Fi, smart meters and RFID as the strongest growth applications;
- Wi-Fi technology for wider channels will target the 5 GHz band only and this will become the key Wi-Fi band. 80 MHz channels will be important for handheld devices with single antennas;
- With 80 and 160 MHz channels, Wi-Fi will be Gb/s capable and no faster versions are currently planned by 802.11 working groups;
- 802.11's future direction includes very low power for Internet of Things applications, 'White-Fi' for white space operation and country specific Wi-Fi extensions.

In terms of future spectrum needs

- The planned increase to the spectrum available for UHF SRDs in Europe should go a long way towards redressing the relative paucity of sub-1 GHz licence exempt spectrum which has put Europe at a comparative disadvantage to the USA for example, especially with respect to innovative solutions such as smart meters;
- An increase in the spectrum available to WLANs at 5 GHz is needed. Unlike SRDs we are not aware of firm plans to investigate this at the present time;
- We have suggested how 70% more contiguous spectrum could be released at 5 GHz by investigating sharing in two extension bands and allowing RLANs in UK band C. This would likely mean that eight or more 80 MHz channels would be available over the 5 GHz band.
- Shared RLAN spectrum at 5GHz would absolutely need to be verified by compatibility studies. This could be an involved process, so any such studies should start without delay.
- More spectrum for SRDs and 5GHz WLANs is expected to reduce pressure on the 2.4 GHz band and white space spectrum;
- We do not expect to see an excess demand for spectrum at 60 GHz and above.

In terms of sharing

- We expect increasingly complex sharing mechanisms will be needed and we have given examples of how such approaches are already beginning;
- More complex sharing schemes will allow the creation of a middle ground between the extremes of licensing and licence exemption. Such tiered sharing or soft licensing could be introduced in new bands;
- Sharing schemes based on sensing such as Dynamic frequency Selection may have to give way to combinations of alternative approaches such as geolocation, registration and dynamic station enablement, for example;
- Although sharing technologies will need to be specified to have the desired effect, the underlying communications services may still remain technologically neutral.

In terms of the framework needed to assess economic value and hence licensed versus licence exempt decisions

- We note that congestion and actual band usage are key inputs to the process, but information on these aspects (including for example the costs of congestion) is often lacking and hence they are often not fully accounted for in evaluations;
- The social benefits of an application can have a very large effect on value, but this is one of the most challenging values to quantify;
- We have suggested an outline for a new framework approach which includes aspects such as marginal utility for socially attractive applications which may have high utility for a small number of users, and a scoring system for parameters which are difficult to quantify.