Quotient Associates

5G Candidate Band Study

Study on the Suitability of Potential Candidate Frequency Bands above 6GHz for Future 5G Mobile Broadband Systems

Final Report to Ofcom, March 2015

www.QuotientAssociates.com

Contributors
Steve Methley, William Webb, Stuart Walker, John Parker

Quotient Associates Limited
Compass House, Vision Park, Chivers Way,
Histon, Cambridge, CB24 9AD, UK
EMAIL Enquiries@QuotientAssociates.com
WEB www.QuotientAssociates.com

Version 02
Status Approved
History Reviewed by Ofcom
Type Public

EXECUTIVE SUMMARY

Objective and scope

Within industry and academia there is significant activity in research and development towards the next generation of mobile broadband technologies (5G). Coupled with this there is increasing interest in identifying the frequency bands that will be needed to deliver 5G services. At the moment there is no overall consensus on what 5G will actually be. Work in ITU-R (WP5D) is ongoing to develop a vision for 5G (IMT 2020) including identifying the target capabilities. It is, however, widely accepted that at least one element of 5G will require the use of spectrum bands at much higher frequencies than those that current mobile broadband technologies can make use of, e.g. bands above 6 GHz.

A first step currently being discussed is a proposal for an agenda item for the World Radio Conference after next (WRC-19) to identify suitable high frequency spectrum for 5G in the ITU Radio Regulations. Our aim in this study has been to assess how far it is possible to narrow down the broad range of spectrum of interest for 5G millimetre wave, which is presently a rather broad 'above 6GHz', while bearing in mind that 5G scenario development is a work in progress. The driver to perform this work has been the desire to enable a more efficient discussion process in subsequent studies, such as those anticipated at WRC. The scope of our work is illustrated in Figure 1.

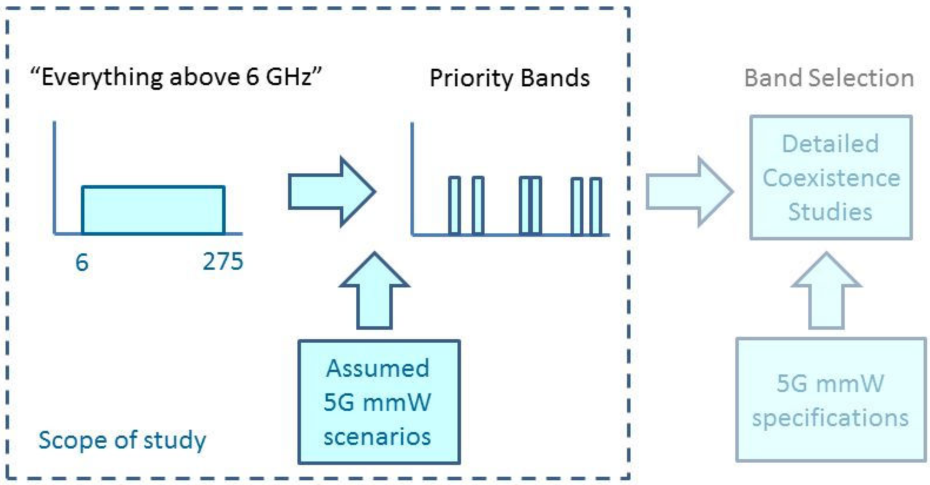


Figure 1 Scope of this study work.

In summary we seek to identify bands which merit priority investigation. Detailed coexistence studies are out of scope.

Overall Approach

The foundation of our approach has been to collate what is presently known about 5G above 6 GHz and thereby to create likely usage scenarios. Following this we have firstly evaluated the effect of any constraints and enablers due to fundamental physical limits, technology or the anticipated usage scenarios. Secondly, we have performed a band-by-band analysis from 6-200 GHz in terms of the band sharing opportunities which may be most feasible. Taken together these two lines of enquiry have enabled us to identify several frequency bands which we believe are worthy of priority investigation with respect to their suitability as candidate bands for 5G above 6 GHz.

Throughout this work we have maintained a strong interaction with industry including by engaging in bilateral consultations, by reporting our progress at the UK Spectrum Policy Forum and by interacting with international research activities.

Assumed 5G above 6 GHz scenarios

Deployment scenarios and models are not yet fully developed for future 5G access systems, but to date the industry has assumed that the key applications will be in the outdoor dense urban environment and large indoor public spaces.

The geographic target areas would thus be cities and transport hubs. These are localised areas and this might make it possible to share with other services. It would also be possible for sharing to be opportunistic and dynamic, such as under the control of a geo-location database.

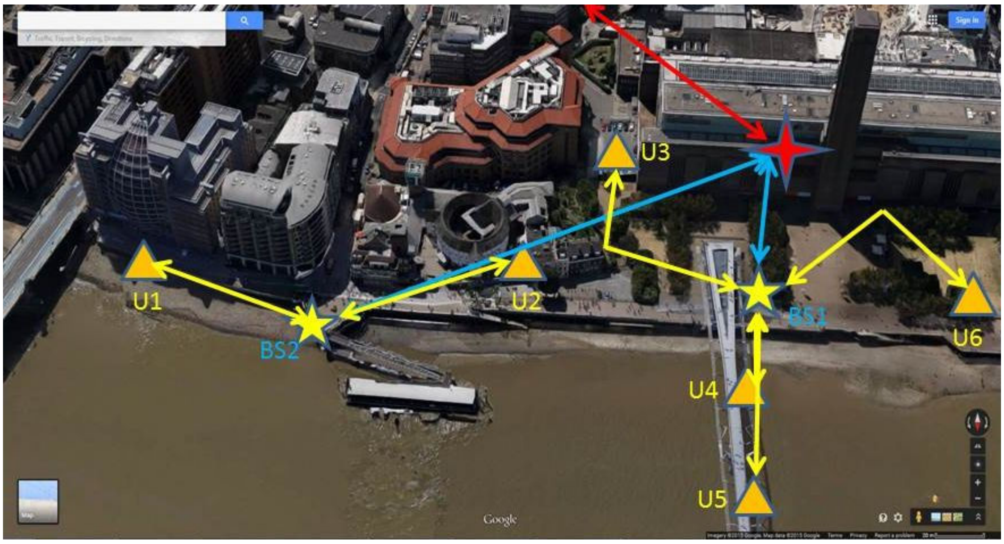


Figure 2 Potential deployment scenario.

Figure 2 illustrates a potential deployment which shows the directional nature of links and the use of reflection rather than diffraction to circumvent obstacles. Steered beams are expected at user terminals and base stations, but backhaul could use fixed antennas.

Future spectrum demand above 6 GHz

A very wide range of bands from 13 – 86 GHz has been proposed by industry for 5G above 6 GHz access and proponents of backhaul have expressed interest up to 110 GHz. There is good industry agreement that of the order of 1 GHz bandwidth will be needed with maybe as low as 500 MHz considered if necessary. This would be a per-operator figure in multi-operator scenarios. A premise is that relatively simple modulation could be used, increasing the need for broad bandwidth. Channel bonding is seen to add significant complexity at millimetre wave, so contiguous bandwidth is preferred. In a multi-operator environment individual bands would not need to be contiguous with each other, but would ideally need to be close enough so that similar propagation conditions would apply.

At the same time, other users of spectrum above 6 GHz are reporting an increase in their density of use and in many cases the services in question, e.g. satellite and fixed, are those which will be needed as part of any 5G infrastructure which aims to avoid digital divides.

For the purposes of assessment we have found it convenient to split up 'over 6GHz' into separate ranges of 6-30 GHz, 30-100 GHz and over 100 GHz, based on the characteristics of the spectrum use in each range.

We have taken a two-pronged approach to identifying potential candidate frequency bands above 6 GHz for future 5G mobile broadband systems.

- Firstly we looked from a physical perspective at barriers and enablers arising from propagation behaviour, technology readiness and the anticipated application scenarios.
- Secondly we looked at the possibilities for sharing spectrum with incumbent services with an emphasis on finding sufficiently wide bands which could be accessed most easily with the greatest prospects for global harmonisation.

Barriers and Enablers

In terms of the technologies required to make 5G millimetre wave antennas, devices and packages, we found evidence that products up to at least 100 GHz will be available within the next 5 years. Furthermore, we found that at the short distances anticipated, of the order of 200m, fundamental limitations such as the effects of gaseous absorption are not a limiting factor up to at least 100 GHz. Therefore neither fundamental nor technology limitations should be the key reason to prefer one millimetre wave frequency over another from 6 to 100GHz. In other words, key limitations are expected to arise from elsewhere. From an application perspective, given that directional antennas will be appropriate at frequencies above 6 GHz, we note that operating above approximately 30 GHz will enable steerable array antennas to be more easily integrated into handsets. 30-100 GHz is thus an attractive range from the perspective of physical considerations.

Band-by-band analysis

Leaving physical considerations to one side, we looked for sharing possibilities with incumbent services between 6 and 200 GHz. Our first objective was to create a very top level view of incumbent services in each range, noting that a broad bandwidth of around 1GHz or more is required for 5G above 6 GHz.

We did not consider all incumbent services initially. The services considered first are shown in Figure 3, with a UK focus as a starting point. In plotting these services, we are not proposing that any other service not plotted is of any lesser importance; it is simply the first stage in our analysis. From our analysis we infer that detailed compatibility studies would be needed to determine whether co-existence is possible with the services plotted and that dedicated spectrum would be preferable if available.

Importantly, the analysis illustrated that in the higher ranges, some potential exists where certain incumbent services are absent, although allocations exist. These bands were left uncoloured (white), see Figure 3, and they merited further investigation. The top five results from our analysis included two areas where 5G might be introduced with apparently few coexistence challenges and a further three where coexistence seems feasible[1].

[1] Subject to detailed coexistence analysis.

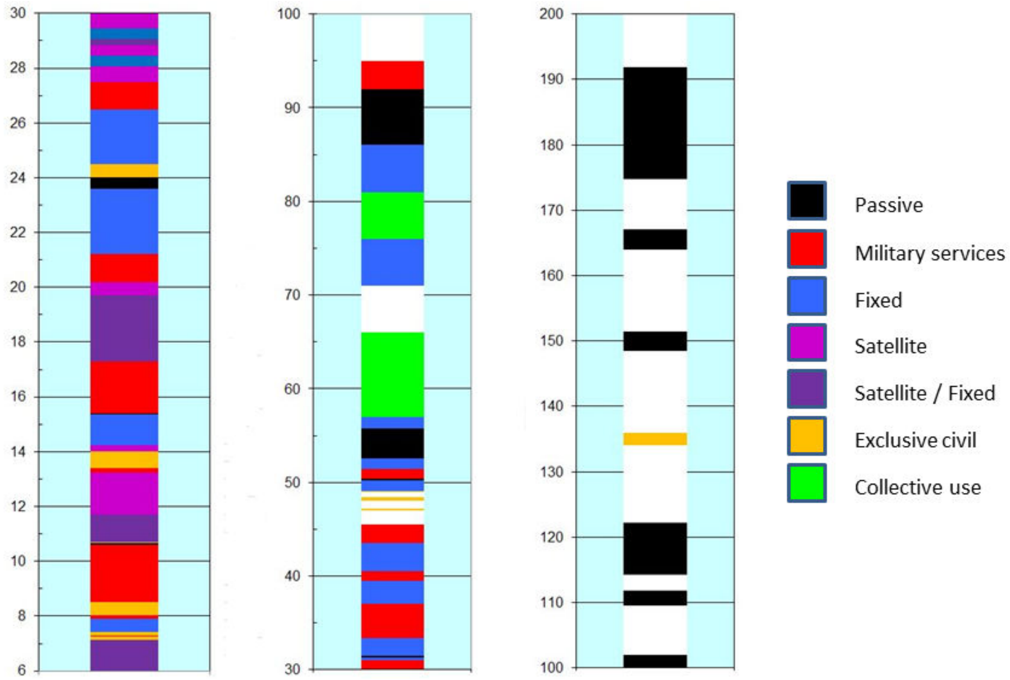


Figure 3 Band-by-band analysis.

Priority bands

We identified the five spectrum options with the highest likelihood of being suitable for 5G above 6 GHz, see Table 1. We identified these options from an initial UK perspective, in order to facilitate a focussed global assessment.

Rank	*Band, GHz*	*Usage, trend*	*Sharing or clearance required?*
1	66-71	Low or none, fallow	No current use found
2	45.5-48.9 (three sub-bands)	Low or none, fallow	No current use found
3	40.5-43.5	Low, low growth (except in UK auctioned portion)	Either sharing with, or clearance of fixed; allocation to mobile; UK auctioned band is already technology neutral;
4	71-76; 81-86	Medium, growing	Sharing with fixed under light licensed regime[2]
5	57-66	Medium, growing	Sharing under licence exemption

Table 1 Top five priority bands.

The first band is 66-71 GHz which sits above the 57-66 GHz collective use band targeted most recently for high speed indoor applications, for example via the Wi-Fi Alliance's WiGig. Economies of scale may thus be very attractive. Where a future handset includes

[2] Parts of these bands are coordinated in the UK.

WiGig by default, then 66-71 GHz, being an immediately adjacent band, opens up the attractive possibility of using a single RF chain to address both bands.

We made several general observations

- Our two highest ranked options appear to be free of incumbent users, based on our top-level analysis[3];
- The selection of two (or more) bands might be most appropriate to maximise the potential for innovation;
- Our third ranked option requires i) clearance of an underused[4] fixed link band opened in 2010, having previously been sterile while harmonised for the un-adopted Multimedia Wireless System, and ii) its allocation to mobile use (this band was auctioned in the UK);
- Our fourth and fifth ranked options require sharing with light licensed or licence exempt bands;
- All the bands could be considered for collective use as the interference range is shorter at these higher frequencies

Global perspective

From a global usage analysis, the 66-71 GHz band and 45.5-48.9 sub-bands do not appear to need to share with any currently active service, although allocations exist. The other bands may need to share or co-exist with

- Satellite;
- Fixed links;
- PMSE;
- Amateur;
- Licence exempt devices
- Radio Astronomy.

However the actual usage of some of these services appeared to be low in many cases.

As this study concluded, NATO released an updated version of the Joint Frequency Agreement, which contained more detail than previous versions[5], but this did not alter our conclusions with respect to the top five candidate bands suggested for priority investigation.

We note that all the bands identified in Table 1 from a sharing perspective are from the range 30-100 GHz. This matches the range identified from the earlier investigation of physical properties, which makes this range attractive for two independent reasons. Although we found that in the range 6-30 GHz it was relatively more challenging to find suitable spectrum, there may still be opportunities in this lower range for 5G bands with a lower bandwidth requirement than 1GHz per operator.

[3] Detailed coexistence studies will still be required.
[4] As of 2011.
[5] NATO Joint Civil/Military Frequency Agreement (NJFA), 2014.

Conclusions

We have taken a two-pronged approach to identifying potential candidate frequency bands above 6 GHz for future 5G mobile broadband systems. We identified a short list of five bands which we suggest are suitable for early consideration as 5G candidate bands above 6 GHz. At a general level the range 30-100 GHz is attractive from both considerations of physical aspects and from the potential for sharing and harmonisation. Another way to consider this is that 5G above 6 GHz, very short range systems do not necessarily need to compete for spectrum in the lower range, i.e. 6-30 GHz.

While we found that devices technologies exist to use high frequencies and that sufficient spectrum is available, remaining sources of uncertainty include the completeness of the above 6 GHz scenarios and models, and the resulting detailed understanding of how beamsteering will be required to work in practice.

Recommendations

We make the following recommendations.

1. A holistic view of the needs of 'above 6 GHz' 5G systems should be taken. Spectrum will be needed for the data plane (e.g. new frequencies above 6GHz), and the control plane (e.g. existing coverage frequencies), as well as the backhaul (existing backhaul frequencies or new frequencies above 6 GHz);
2. More than one new 5G band above 6 GHz may be appropriate to maximise the potential for innovation;
3. The broad range 'above 6GHz' should be split into a number of ranges for future evaluation, for example at least the ranges 6-30 GHz and 30 -100 GHz, with 'above 100 GHz' if required;
4. Our five priority candidate bands are all in the range 30-100 GHz, nonetheless frequencies in the range 6-30 GHz could be considered with a focus on a lower bandwidth requirement[6];
5. The earlier recommendations from Ofcom's Spectrum Framework Reviews[7] should be followed, by considering the merits of licence exemption / collective use for higher frequency spectrum;
6. Some uncertainties remain over the completeness of the above 6 GHz scenarios and models, and the consequent detailed understanding of how beamsteering will need to be made to work in practice, hence more research is needed in these areas.

[6] Most likely accepting that substantially less than 1GHz bandwidth per operator may be realisable, for example several hundred MHz, but that this may nonetheless be useful to the wider 5G system.
[7] Spectrum Framework Review, Licence Exempt Framework Review.

Contents

1 INTRODUCTION

1.1 Background

Ofcom have commissioned this study on the suitability of potential candidate frequency bands above 6GHz for future 5G mobile broadband systems. The motivation for the study includes that work within CEPT on a European proposal for a WRC-19 agenda item refers broadly to 'bands above 6 GHz'. Ofcom, in preparation for the next World Radio Conference (WRC-15), seeks to develop its view on how an agenda item for WRC-19 could be more efficient.

1.2 About Quotient Associates Ltd

Quotient is an international technology, strategy and economics consultancy to the radio communications industry specialising in wireless communications, wireless technology, spectrum regulation and spectrum management.

1.3 Independence of analysis

The discussion, evaluation and interpretation of the evidence presented in this study is that of Quotient Associates Ltd.

1.4 Economic value of applications

All services considered in this document are assumed to be of significant economic benefit to the UK and globally, both now and into the future, and we do not seek to differentiate on any economic basis in this document.

1.5 Content of report

The structure of the report is as follows

- In Chapter 2 we describe our objective, scope and approach;
- In Chapter 3, we establish 5G above 6 GHz key requirements as far as they are known;
- In Chapter 4 we describe the frequency ranges we work with and the future spectrum requirements from within and outside the 5G above 6 GHz space;
- In Chapters 5 and 6 we examine fundamental and non-fundamental barriers and enablers respectively;
- In Chapter 7 we perform a band-by-band analysis, searching for potential spectrum of the order of 1GHz bandwidth per operator[8];
- In Chapter 8 we highlight the bands we propose are suitable for priority investigation.

We give conclusions and recommendations in Chapters 9 and 10 respectively. A glossary of terms and abbreviations is given at the end of the document.

[8] We assume at least three operators will require spectrum.

2 OBJECTIVE, SCOPE AND APPROACH

2.1 Objective and scope

Within industry and academia there is significant activity in research and development towards the next generation of mobile broadband technologies (5G). Coupled with this there is increasing interest in identifying the frequency bands that will be needed to deliver 5G services. At the moment there is no overall consensus on what 5G will actually be. Work in ITU-R (WP5D) is ongoing to develop a vision for 5G (IMT 2020) including identifying the target capabilities. It is, however, widely accepted that at least one element of 5G will require the use of spectrum bands at much higher frequencies than those that current mobile broadband technologies can make use of e.g. bands above 6 GHz, which the industry commonly refers to as '5G millimetre wave'.

A first step currently being discussed is a proposal for an agenda item for the World Radio Conference after next (WRC-19) to identify suitable high frequency spectrum for 5G in the ITU Radio Regulations. Our aim in this study has been to assess how far it is possible to narrow down the broad range of spectrum of interest for 5G millimetre wave, which is presently a rather broad 'above 6GHz', while bearing in mind that 5G scenario development is a work in progress. The driver to perform this work has been the desire to enable a more efficient discussion process in subsequent studies, such as those anticipated at WRC. The scope of our work is illustrated in Figure 1.

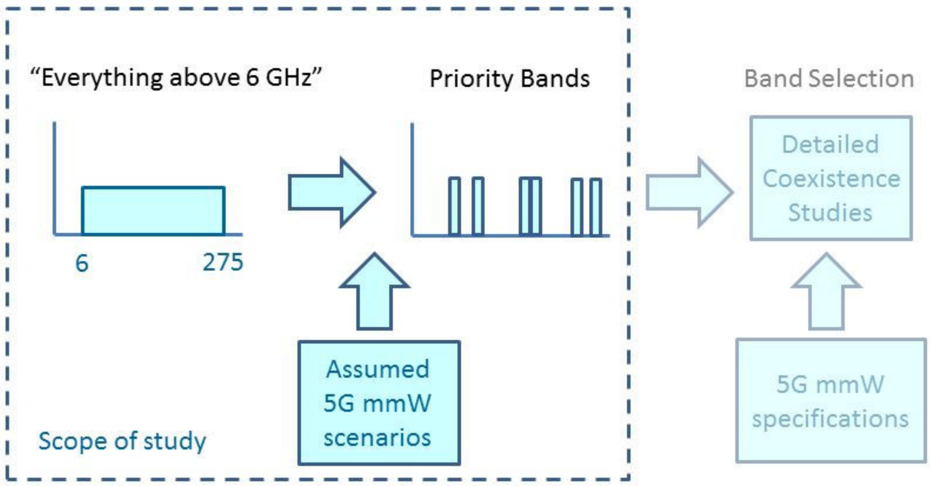


Figure 1 Scope of this study work.

Our report is not about whether 5G above 6 GHz will succeed, nor are we attempting to design it. It is about how suitable spectrum might be made available in case 5G above 6 GHz is successful, since it certainly will not succeed if no spectrum is identified.

In summary we seek to identify bands which merit priority investigation. Detailed coexistence studies are out of scope. Also out of scope are any considerations of any health aspects which may or may not arise from the use of millimetre waves in a user handset.

2.2 Approach

Definition of millimetre wave (mmW)

In 5G discussions this has invariably referred to frequencies above 6 GHz, although strictly speaking the correct term would be cm and mm waves. We follow the convention and use 'mmW' to encompass 5G frequencies above 6 GHz in this study.

Study approach

The foundation of our approach has been to collate what is presently known about 5G millimetre wave and thereby to create likely usage scenarios and key requirements. Following this we have firstly evaluated the effect of any constraints and enablers due to fundamental physical limits, technology or the anticipated usage scenarios. Secondly, we have performed a band-by-band analysis from 6-200 GHz in terms of the band sharing opportunities which may be most feasible. Taken together these two lines of enquiry have enabled us to identify several frequency bands which we believe are worthy of priority investigation with respect to their suitability as candidate bands for 5G millimetre wave systems.

Interaction with stakeholders

Throughout this work we have maintained a strong interaction with industry including by engaging in bilateral consultations, by reporting our progress at the UK Spectrum Policy Forum and by interacting with international research activities.

3 5G MILLIMETRE WAVE VISION AND ASSUMED SCENARIOS

3.1 Introduction

The promise of 5G is that the normal evolutionary cycle we have seen from 2G via 3G to 4G will be broken. The introduction of 5G is expected to be a revolution by comparison, since it will not be simply an increase in the speed of a cellular connection.

At the highest level, 5G aims to provide users with a 'mix and match' of technologies, bands and bandwidths, licence types and any other available options which could give the user the experience required at the time. But these efforts will never be seen by the user, who will simply experience an appropriate connection, regardless of whether his or her location or demands change within a service area.

Although there is no standard definition of 5G yet, several key aims began to be qualified and quantified during 2014, on a worldwide basis. For example, from Korea, Figure 3-1 shows 5G aims with quantification at a high level.

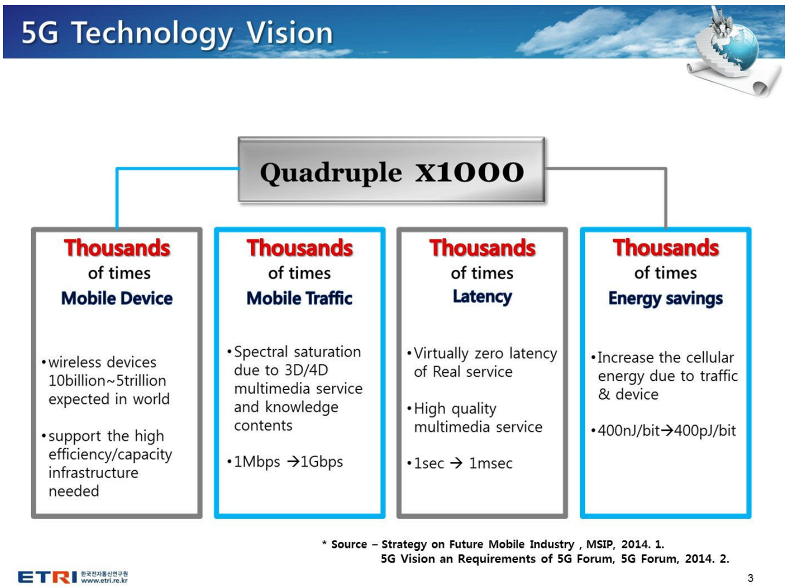


Figure 3-1 5G aims from Korea[9]

By way of another example, from the Americas, Intel is supporting a significant amount of 5G research in US universities, such as New York and Texas via its Strategic Research Alliance[10], and is a partner in the European Union MiWEBA[11] research project which has similar expectations of 5G.

Significant features of future 5G include speed and latency evolutions as might be expected. But also revolutions towards

- encompassing the Internet of Things;

[9] "Future Needs for 5G Spectrum – Introduction to Activities in Korea", Chung H K, EU Workshop on Spectrum Planning for 5G, Brussels , 13th November 2014.

[10] http://blogs.intel.com/intellabs/2013/07/15/next-generation-wireless-communication-5g-transforming-the-wireless-user-experience/

[11] www.miweba.eu

- maintenance of high performance levels even with a high density of active users;
- the idea that the user is 'followed' by the desired service level in order to maintain the user experience;
- a decrease in energy per bit transmitted, if the solution is to achieve the scale required;
- a need for very much higher speeds, which implies working at higher frequencies, such as millimetre wave.

3.2 5G as an integrated system

Past and current EU projects have been a useful focus for the convergence of the aims of 5G, and today progress is beginning to be made towards a more specific architecture for 5G, see for example Figure 3-2.

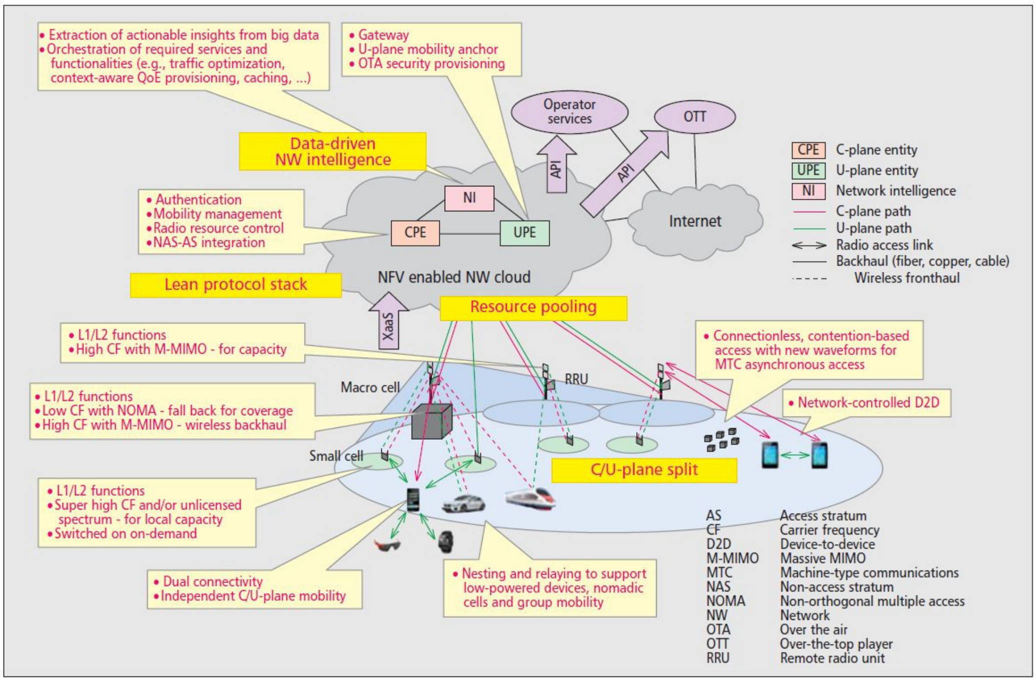


Figure 3-2 Proposed 5G Network Architecture[12]

We do not need to examine every detail of Figure 3-2, but there are a number of technology enablers which are worthy of further attention with respect to higher frequencies for 5G.

Firstly, different carrier frequencies are envisaged for different types of 5G communication scenarios. Specifically, high frequencies ('High CF' in the diagram) are envisaged to provide high capacity, in conjunction with antenna arrays, for both users and backhaul. In addition, 'Super high carrier frequencies' are expected for local capacity provision, such as millimetre wave. Figure 3-3 from Ericsson shows a simple representation of the frequency ranges likely to be needed to satisfy the whole 5G concept.

[12] "Design Considerations for a 5G Network Architecture", Agyapong P et al, IEEE Communications Magazine, November 2014.

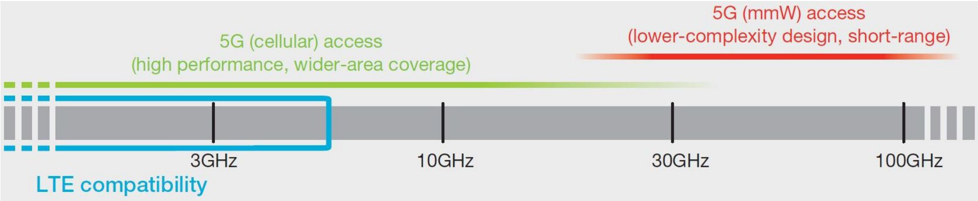


Figure 3-3 The need for 5G spectrum below and above 6GHz[13]

Secondly, the control and user (C/U) planes are separated for users with the highest data rates. There are a number of reasons for this. For example, with such a split, users have the most efficient data connection to the backhaul, since control packets are no longer interspersed. Equally important is that the umbrella macro cell can control the connection of user equipment, via a constantly present network discovery and management function. This reduces the demands on the mmW link considerably[14].

Thirdly, it is clear that a large number of diverse technology enablers are needed. For example, there needs to be provision for machine type networks (MTC), which need to be highly energy efficient and employ sleep cycles. Device to device (D2D) communication must be provided for, which is a further driver for a C/U plane split. Higher up the architecture, Network Function Virtualisation (NFV) is required so that the network may be flexibly reconfigured and reduced in scope in order to save energy at times of low demand, via Software Defined Networking (SDN).

Finally, 5G is not a replacement network. Rather 2G, 3G and 4G will continue and will in fact be essential to remain in place as the 5G architecture encompasses these existing systems.

Our motivation for this study arises from the need for higher speeds, the wider bandwidths which this implies and hence likely operation at frequencies above 6 GHz.

3.3 Possible 5G millimetre wave scenarios

While requirement specifications are still under development, at least some aims are clear with respect to a 5G millimetre wave (mmW) scenario. Specifically, 5G mmW systems are to be targeted at providing hotspot access via very small cells, where a wide bandwidth of the order of around 1 GHz is required. In cases where multiple operators are expected, this will be 1 GHz per operator. The industry focus has been on outdoor or large indoor public spaces, with in-home coverage continuing via today's Wi-Fi at 2.4 and 5 GHz, plus future WiGig and UWB solutions at 60 GHz[15].

At mmW frequencies, propagation is highly directional and the coverage mechanism is by line-of-sight or via multiple reflections, in contrast to the broader coverage by diffraction around obstacles at traditional, lower cellular frequencies. This directional type of propagation is valid for all the frequencies in our study[16].

Figure 3-4 illustrates a possible coverage scenario outside Ofcom's offices in London, UK which emphasises the line-of-sight nature of mmW communications.

[13] "5G radio access", Ericsson Review, vol 6, June 2014.
[14] The importance of this will become more apparent when propagation models are discussed in Section 6.3.
[15] See for example the EU MiWEBA project, D1.1, www.miweba.eu
[16] See Chapter 6.

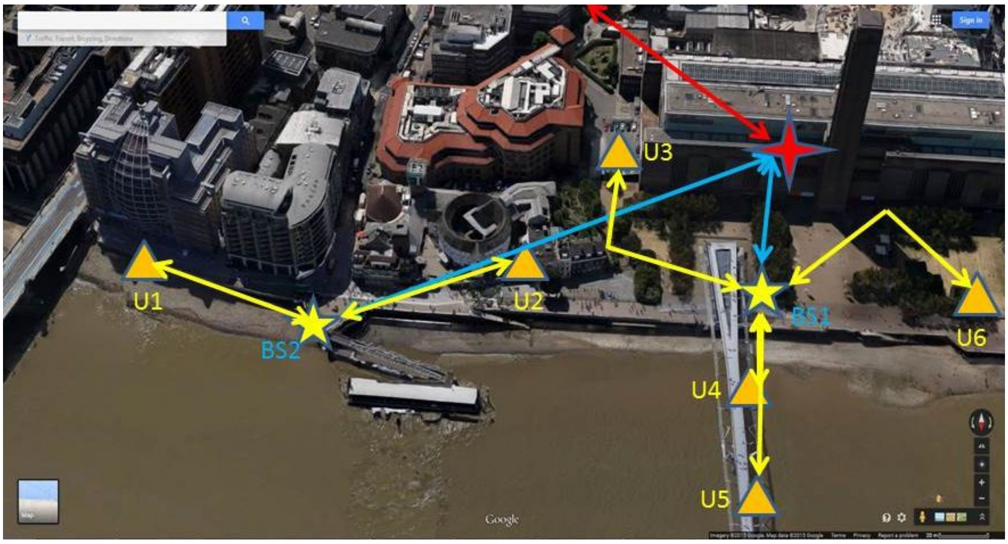


Figure 3-4 Diagram of possible 5G mmW access and backhaul links

In the scenario, the users (U1-U6) communicate via the nearest base station using directional beams and the base station serves them by steering its beam. The communication paths in the low level, dense urban environment (yellow) may need to include reflections to go around obstacles such as foliage, since diffraction and penetration capabilities are poorer than at conventional cellular frequencies. Base stations (BS1, BS2) have an initial backhaul to rooftop height (blue) and onwards above the rooftops (red). The inter-site distance is approximately 200m, therefore if different operators were involved in this scenario then either frequency planning or some other co-ordination would be required.

Supporting our assumed scenario is Figure 3-5 which shows the results of channel sounding in a measurement campaign in New York City, where multiple paths and multiple reflections were observed between transmitter (yellow star) and receiver (green disc).

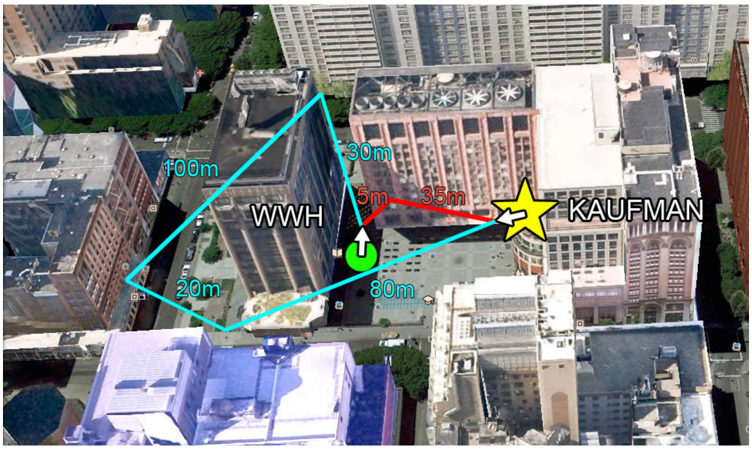


Figure 3-5 Diagram of 5G mmW channel sounding measurements[17]

[17] Azar et al, "28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City", IEEE International Conference on Communications (ICC), June 9-13, 2013.

Directional antennas are needed for two reasons; to both ensure a workable loss budget and to select a single ray or group of rays with a sufficiently small delay spread.

3.4 Assumed key requirements for 5G above 6 GHz

We adopt the widely held industry view that 5G mmW will employ per-operator bandwidths of the order of 1 GHz as a key priority, indeed this is the prime reason to look towards working at mmW frequencies. In addition, access systems will need a form of beam steering, ideally including at the user handset, although backhaul systems could use fixed antennas. Generally in this study we focus on the access system, but comment on backhaul systems where appropriate.

4 FREQUENCY RANGES CONSIDERED

4.1 Introduction

We first split the broad 'above 6 GHz' spectrum of interest into three more manageable ranges based broadly on what types of opportunities might arise in each range, as we understood them at the commencement of the study. We then look at what future spectrum requirements have been highlighted by industry stakeholders, both for 5G mmW and incumbent applications in the same mmW space.

4.2 Frequency ranges considered in this study

We consider the following broad frequency ranges as a useful division of the 'above 6GHz' frequency space under consideration.

- 6-30 GHz;
- 30-100 GHz;
- above 100GHz.

These ranges were chosen since they represent a useful segregation of spectrum for the purposes of discussion within this study. An alternative option might have been to consider only the bands which presently have a mobile allocation. However, much of the mmW spectrum is co-primary for mobile, so this would not have been a very strong filter, yet it might still have excluded some possibilities.

We first review the drivers for choosing each of our frequency ranges and the potential opportunities which may available in each range. We focus on each of the same three ranges throughout our evaluation of fundamental and non-fundamental limits in Chapters 5 and 6 respectively, and then in our band-by-band analyses in Chapters 7 and 8. In other words our objective in the rest of the study is to challenge and refine the initial perspectives in this Chapter.

4.2.1 6 to 30 GHz – initial perspective

Propagation in this range is line-of-sight. An attraction is that existing technology and architecture might be adapted to work in this range, which is closest to existing cellular frequencies.

Our chosen upper bound of this range represents firstly the approximate upper limit of mainstream civil satellite bands, Ka band[18], and secondly the approximate working limit of more traditional circuit construction techniques, using bond wires for example. Sharing challenges are traditional, with fixed, satellite and many other services to be considered in this well-used frequency range.

Potential opportunities

The lower end of this range is of specific interest as it might be able to employ existing cellular technologies with little additional development required, although studies of urban propagation at these frequencies have reported that refection rather than

[18] Higher bands such as Q/V bands are expected to be for niche applications in future; see for example Avanti, "Fixed Satellite Service Broadband Spectrum", UK Spectrum Policy Forum, May 2014.

diffraction is the dominant mechanism in this higher range[19]. At the top end of the band, interest at 28 GHz is high for 5G mmW in some countries and trials have been reported.

4.2.2 **30 to 100 GHz – initial perspective**

Propagation in this range is line-of-sight. This range contains an oxygen absorption peak at 60GHz, which led to the band around 60 GHz being made licence exempt. IEEE 802.11ad 'WiGig' systems have been developed in this range using low cost silicon system-on-a-chip (SoC) integration and flip-chip construction techniques[20]. At higher frequencies, silicon-germanium (SiGe) performance now covers the 70/80GHz bands. It is conceivable that in the next five years this whole range of frequencies will be accessible using silicon technologies and low cost packaging processes.

Potential opportunities

In this range any sharing would need to consider fixed but not satellite[21], although other space use is present. Due to the need for strong beamforming to capture sufficient energy, and the increasing atmospheric attenuation, the interference environment may become less of a concern and light or unlicensed operation may thus be a possibility in certain bands. The available bandwidth is significantly greater than in lower ranges, with potentially more sparse coexistence concerns and better prospects for harmonisation.

This range contains the 60 GHz unlicensed band around the oxygen absorption peak. It also contains the 70/80 GHz bands which are typically light licensed. Although there are concerns over practical power/antenna gain limits, 5G mmW systems might successfully share the 60GHz band, perhaps by working at the band edges or by augmenting the band, if were to be possible.

Sharing with the 70/80 GHz bands might be attractive since the same operators may wish to operate access and backhaul in-band and to handle the coordination challenges themselves. Other techniques for sharing include real time geo-location database approaches. It would be attractive to have a 5G mmW access band close to WiGig (60 GHz) and/or backhaul bands (70/80 GHz), for economies of scale in production.

4.2.3 **Above 100 GHz – initial perspective**

Propagation in this range is line-of-sight. This band contains a number of water and oxygen absorption peaks, with a narrow ISM band around the first oxygen peak at 120 GHz in some countries. Point to point links have been demonstrated near 120 GHz and were used as far back as the 2008 Beijing Olympics to carry multiple HDTV channels at 11 GB/s . However device and packaging technologies remain specialised in this range, although silicon circuit working frequency is anticipated to reach 300 GHz by 2030[22]. This range remains of interest because of the huge bandwidths which are possible. ITU Radio Regulation allocations presently extend to 275 MHz, but there is research interest in going beyond into the THz region, since this would allow 100GB/s transmission using only simple modulation[23]. Range is short and highly directional, hence unlicensed operation would be appropriate, although pre-existing allocations, for example to radio astronomy, would need to be respected.

[19] See Chapter 6.
[20] See Chapter 6.
[21] Civil satellite systems are not expected to operate beyond 30 GHz, see Section 4.4.1.
[22] International Technology Roadmap for Semiconductors, www.itrs.net .
[23] APT Report on Technology trends of Telecommunications above 100 GHz, Manila, 2011.

Potential opportunities

This region is largely unused apart from radio astronomy which has many allocations and some bands are restricted to be passive. Overall, over the next 5 years this band may be best suited for backhaul as the cost point of backhaul better supports the specialist technology required.

4.3 5G spectrum requirements above 6 GHz

In this Section we look firstly at industry-generated spectrum requirements for 5G mmW, and secondly at requirements from incumbent services in the same mmW space.

4.3.1 Spectrum bands suggested by industry stakeholders

There are a number of mmW bands under consideration for 5G internationally. We note that the EU Radio Spectrum Committee's spectrum inventory presently extends to only 6GHz, so this does not present a means to establish which bands are actually used. Because of this a common step by researchers has been to take the Radio Regulations and look for co-primary mobile allocations, see for example Figure 4-1, although as already mentioned this risks missing opportunities.

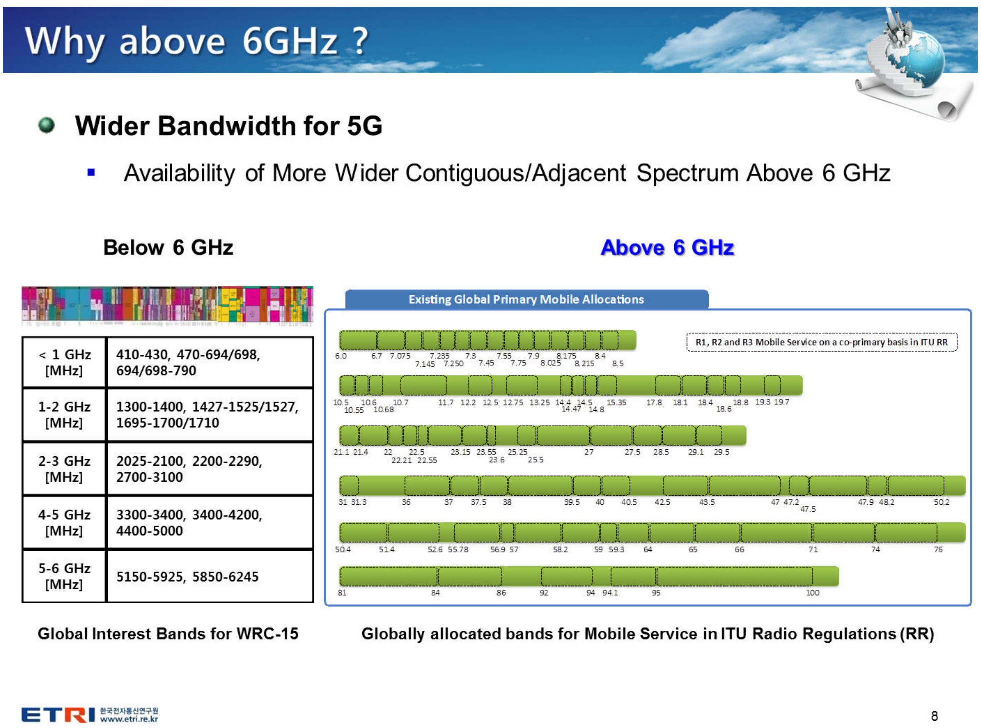


Figure 4-1 Spectrum allocated to mobile as global primary in the radio Regulations, each Region[24].

Although the choice of mmW bands is very wide, various industry stakeholders and research projects have begun to narrow this down somewhat. Nonetheless the overall range is still wide, with no agreed levels of priority, see Figure 4-2 .

[24] Future Needs for 5G Spectrum – Introduction to Activities in Korea", Chung H K, EU Workshop on Spectrum Planning for 5G, Brussels , 13th November 2014.

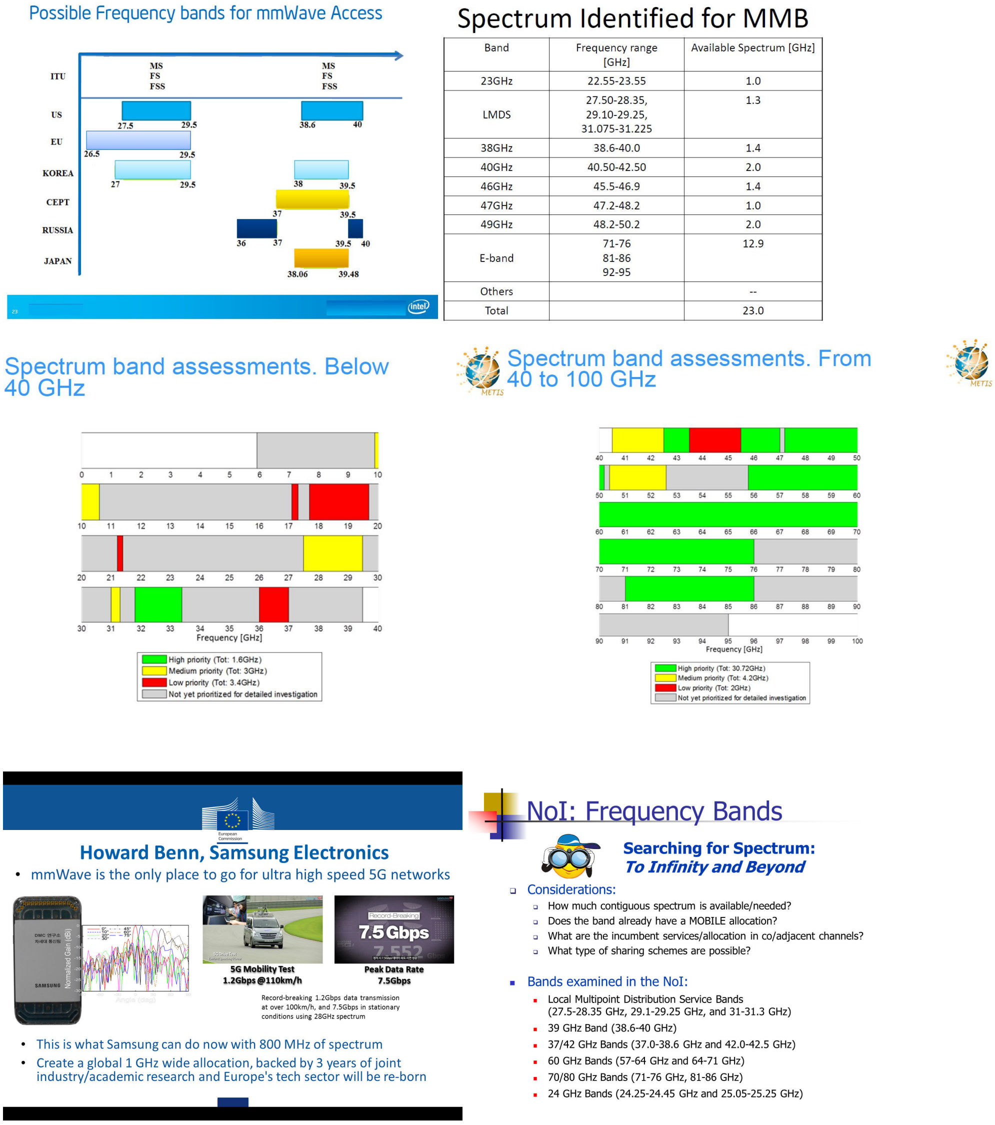


Figure 4-2 Examples of bands of interest for 5G mmW (not exhaustive)[25]

In Figure 4-2, we show some of the frequencies declared to be of interest internationally from the following sources, by way of example only.

- Intel;
- Samsung (2011, range of bands; 2014, trial in 800 MHz bandwidth at 28 GHz);
- METIS EU project;

[25] Figure sources: "mmWave Technology Evolution From WiGig to 5G Small Cells", Sadri A, IEEE ICC 2013, Budapest; "Millimeter-wave Mobile Broadband: Unleashing 3-300GHz Spectrum", Khan F, Pi J, WCNC 2011 , Cancun;" Description of the spectrum needs and usage principles" METIS deliverable 5.3 Summary, www.metis2020.com ; Benn H, panel session, EU Workshop on Spectrum Planning for 5G, Brussels , 13th November 2014; "Knapp J, invited keynote, ibid.

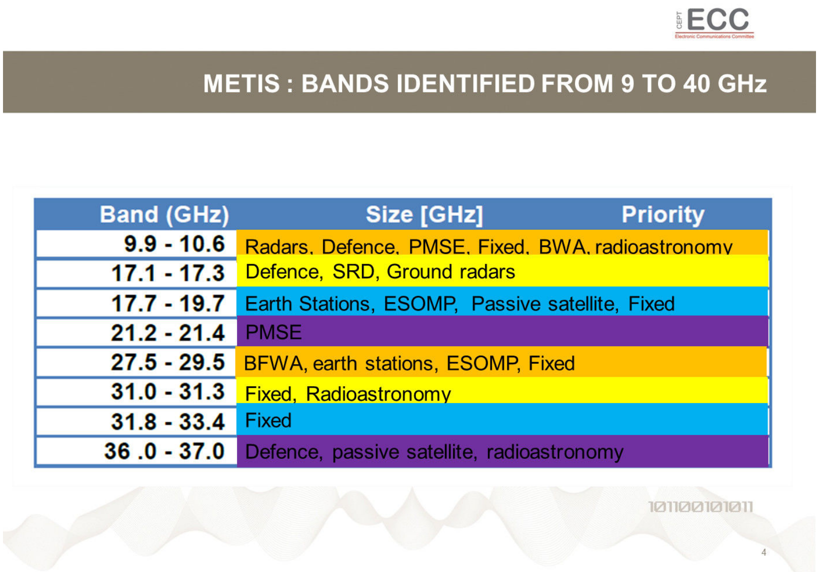
- USA/FCC (from Notice of Inquiry, based on industry input not FCC preferences).

For clarity we summarise the bands of interest in Table 4-1.

Source	*Bands of interest, GHz*
Intel	28 , 38-40
Samsung	23, 28, 38, 40, 46, 47, 49, 70/80
METIS EU project (high, medium)	10, 28, 31, 32, 36, 42, 46-50, 60, 70/80
USA	24, 28, 39, 39/42, 60, 70/80

Table 4-1 Summary of bands of interest from Figure 4-2

Of course none of these bands are necessarily empty. For example, Figure 4-3 confirms that bands identified by METIS already have specific other uses. A sharing or co-ordination approach will thus always be necessary in these bands.



Band (GHz)	Size [GHz]	Priority
9.9 - 10.6	Radars, Defence, PMSE, Fixed, BWA, radioastronomy	
17.1 - 17.3	Defence, SRD, Ground radars	
17.7 - 19.7	Earth Stations, ESOMP, Passive satellite, Fixed	
21.2 - 21.4	PMSE	
27.5 - 29.5	BFWA, earth stations, ESOMP, Fixed	
31.0 - 31.3	Fixed, Radioastronomy	
31.8 - 33.4	Fixed	
36 .0 - 37.0	Defence, passive satellite, radioastronomy	

Figure 4-3 Bands identified by METIS for 5G mmW (high, medium, low) - current occupancy[26]

4.3.2 **Bandwidth required**

The motivation for moving up to mmW in order to obtain access to a high contiguous bandwidth in the region of 1 GHz has been a very commonly stated aspiration. Samsung have since demonstrated links with 800 MHz bandwidth, Nokia have suggested at least 300 MHz contiguous bandwidth per operator, Korea's ETRI have suggested at least 500 MHz

[26] "Addressing the 5G Requirement from the CEPT Perspective", Fournier E, EU Workshop on Spectrum Planning for 5G, Brussels , 13th November 2014.

and the METIS project proposed that between 200MHz to 3 GHz bandwidth is required, depending on the use case. METIS concluded that 'dense urban' was a highly demanding use case which would require 1-3 GHz bandwidth[27].

Given the challenges of practical components at mmW[28], contiguous bandwidth is presently preferable over band aggregation. In this study we adopt the view that 1 GHz bandwidth will be required. This will be per-operator in multiple operator environments. Ideally therefore more than 3 GHz would be needed. This whole multi-operator range need not be contiguous, although the individual bands do need to be contiguous.

4.4 **Spectrum requirements from incumbent users**

5G mmW is in the position of new entrant into the above 6 GHz range of spectrum, which is already used to a greater or lesser extent by incumbent users, such as satellite, space, fixed links and the military. It is likely that sharing techniques will need to be addressed by all stakeholders.

4.4.1 **Satellite**

The satellite industry covers the areas of

- Communications;
- Navigation;
- Remote sensing;
- Space science.

Communications

Satellite links for broadcast and broadband, both mobile and fixed, commonly use spectrum up to Ka band[29]. Future High Throughput Satellites (HTS) may use Q/V for feeder links only, in order to free up Ka band spectrum for more user links, although presently this is the subject of research. The growth in Ka band and below has been very strong recently and is expected to continue, see Figure 4-4. Above Q/V, the trend is to consider laser links rather than higher mmW bands due to path loss impairments[30].

[27] METIS D5.3, www.metis2020.com
[28] See Section 6.2.
[29] See Appendix 1 for a list of satellite bands and frequencies.
[30] Source: DLR (German Aerospace Centre).

Usage Of Spectrum – Trends - Today & Tomorrow

Frequency Band	Today (2014 - 2015)	Medium Term (By 2024-2025)
C-band FSS	Very Significant	Increase in use Converged FSS+MSS+BSS Very significant
Ku-band FSS	Very Significant	Increase in use Converged FSS+BSS+MSS Very significant
Ka-band FSS / BSS	Fast ongoing take up Significant new investments	Rapid increase in use Converged FSS+BSS+MSS Very significant
Q/V Band FSS / MSS	Minimal	Highly limited (severe propagation impairments). Only for some specialised niche applications.

Figure 4-4 FSS broadband spectrum trends[31]

In various technical fora, satellite industry stakeholders have clearly stated that they believe there is no scope for shared use of satellite systems with 5G mobile systems in the Ka-band. In support of this, they point out that satellite must be preserved to play an essential role in 5G delivery, in order to target 100% user coverage.

Navigation

GNSS use for familiar services such as GPS, Galileo, GLONASS and COMPASS is all below 30 GHz. There are allocations at higher frequencies but we understand these are not currently used[32].

Remote sensing

Earth Observation is mainly in in L, S, C and X bands and hence below 12 GHz. Major meteorological bands are below 10GHz. ERDS (the space relay service) will have a Ka downlink (and lasers for the highest bandwidth inter-satellite links). This is part of a wider trend to move to Ka band for downlinks[33].

Over the longer term (10-20 years) EESS interests are set to increase in frequency, for example, EESS bands of future interest include

- 13.25 – 13.75 GHz;
- 17.2 – 17.3 GHz;
- 35.5 – 36 GHz;
- 37.5 – 40 GHz;
- 94 – 94.1 GHz;

[31] Avanti, "Fixed Satellite Service Broadband Spectrum", UK Spectrum Policy Forum, May 2014.
[32] Source: GSA, see Chapter 7.
[33] Source; Airbus.

- 130 – 134 GHz.

Space Science

Radio astronomy allocations cover a wide range of bands, including mmW, and extend to the highest frequencies presently allocated. There are well-publicised bands which are passive only, where no transmission may occur.

4.4.2 Fixed

ECC Report 173 surveyed the status and growth trends of fixed links in CEPT countries as of 2012. It found growth was high in most bands, including light-licensed bands, with the notable exception of 40.5-43.5 GHz, which was opened to fixed links only in 2010.

Fixed links also covers the area of High Altitude platforms (HAPs) which is experiencing something of a minor resurgence after failing to fulfil its initial promise. Both Google and Facebook have demonstrated an interest in HAPS for covering hard to reach areas including in other countries such as Africa, with Google having purchased a solar powered drone company. Another interest in HAPs arises from disaster recovery. There are HDFS allocations above 40 GHz for any future HAPs use.

4.4.3 Military

Some bands in the UK are managed by the MoD rather than Ofcom, although military use also occurs in jointly managed bands. NATO publish the Joint Frequency Agreement (NJFA) where usage is described at a high level. Typical uses include radar, mobile, satellite and fixed, with frequencies declared up to 100 GHz. Just before the conclusion of our study, we received an updated NJFA which had a little more detail on usage and which we have incorporated into our final analysis.

4.5 Summary

We have found it very useful to split 'above 6 GHz' into the ranges 6-30 GHz, 30-100 GHz and above 100 GHz.

There are clearly instances where the future use of spectrum for 5G mmW could conflict with its use or planned use by other industries. This includes other parts of the 5G industry itself, especially where there is a desire to pursue 100% coverage.

5 FUNDAMENTAL BARRIERS AND ENABLERS

Fundamental barriers are immutable and are based on basic physical effects which may not be altered by new technology or by regulation, for example.

5.1 Effect of fundamental barriers at very short range

Atmospheric attenuation

Under the specific condition that only several hundreds of metres range is the objective, fundamental barriers (e.g. atmospheric loss, rain fade, penetration loss and propagation characteristic) do not decisively favour one part of the mmW band over another, even in the narrow areas around the oxygen and water absorption peaks at 60 GHz, 120 GHz etc. This is in clear contrast to longer range systems such as fixed links and satellite, where working at lower frequencies is a key enabler. This has clear implications for 5G mmW spectrum planning.

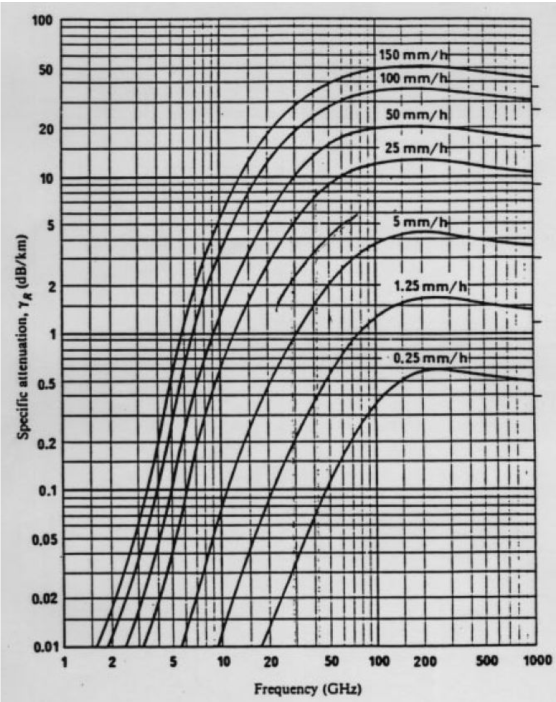


Figure 5-1 Fundamental limitations across mmW bands: Rain attenuation[34]

In other words, the pros and cons associated with these fundamental barriers are not the most highly relevant considerations for choosing, say, 30 GHz over 70GHz, or vice-versa. This is because in many cases the barriers lead to equal consequences[35] across the band for very short range operation, e.g. propagation is line-of-sight and is well characterised by a quasi-optical model[36], rain fade varies but is consistently less significant at such low distances and similarly atmospheric loss varies but remains small at 200m over the whole

[34] FCC OET Bulletin 70, "Millimetre Wave Propagation: Spectrum Management Implications", July 1997.

[35] To avoid doubt – the barrier parameters (loss etc.) do vary across the band, yet the consequences for very short links remain invariant.

[36] MiWEBA Deliverable 5.1, "Channel Modelling and Characterization", June 2014.

band. For example, Figure 5-1 shows that even heavy rain at 25mm/hr leads to no more than a few dB of additional attenuation over 200m. Figure 5-2 shows that even at the oxygen water peak at 60 GHz, attenuation over 200m is only a few dB.

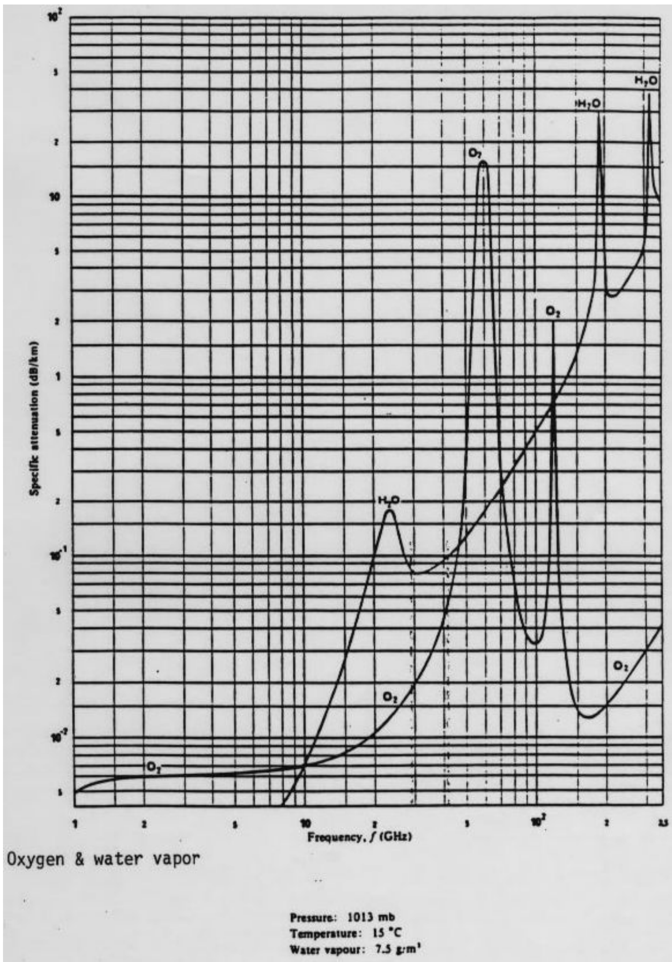


Figure 5-2 Fundamental limitations across mmW bands: O_2 and H_2O absorption[37]

Propagation Mechanism

It is well accepted that propagation at higher mmW frequencies is line of sight. Even when looking at frequencies down to 6 GHz, propagation has been shown to be due to reflections rather than diffraction[38].

Building Penetration Loss

Building penetration loss has been measured at spot frequencies up to 6GHz[39] and more recently at mmW frequencies of 28, 38 and 73 GHz[40]. Although penetration loss measurements showed significant spread, the trend is for loss to be at the level of 10dB at

[37] FCC OET Bulletin 70, "Millimetre Wave Propagation: Spectrum Management Implications", July 1997.
[38] "Measured path loss and multipath propagation characteristics in UHF and microwave frequency bands for urban mobile communications", Oda et al, IEEE vehicular Technology Conference, 2001.
[39] Aguirre et al., "Radio propagation into buildings at 912, 1920, and 5990 MHz using microcells", Third Annual International Conference on Universal Personal Communications, 1994.
[40] Rappaport et al, "Millimetre Wave Mobile Communications for 5G Cellular: It Will Work!", IEEE Access , **1**, pp335-349, May 2013.

UHF, rising to around 15dB at 1800 MHz and around 20 dB at 5GHz, and rising further to between 20-40 dB at 28 GHz and higher. It is the high penetration loss which leads to the convenient result that mmW may propagate efficiently by reflections around obstacles. These types of effects are thus as much enablers as barriers for 5G mmW access systems.

A corollary of high penetration loss is that, since indoor and outdoor systems may be so well isolated, in order to cover the user population (80% of mobile use is indoor[41]) some spectrum for indoor operation will also be needed. This might be the same spectrum as outdoor, but this would depend on propagation and penetration measurements being performed and analysed. Of course there are existing indoor systems such as WiGig at 60 GHz which, although presently in its infancy, may grow to become a significant market success in the period before 5G systems become available above 6 GHz.

5.2 Summary

In summary, other sources of constraints, such as technology or regulation, are likely to be more important than fundamental barriers for mmW over short distances. Another way to consider this is that 5G mmW very short range systems do not necessarily need to compete for spectrum at the lower millimetre wave frequencies from a propagation point of view.

[41] Mobidia White Paper

6 NON-FUNDAMENTAL BARRIERS AND ENABLERS

6.1 Introduction

Technology barriers are malleable in response to advances gained through research and development effort. An example is that system performance has consistently been increasing at higher frequencies, and notably so at mmW. Other non-fundamental barriers and enablers include those that arise from the chosen application scenario[42].

6.2 Specific technologies required above 6GHz

6.2.1 Semiconductor devices and packages

The spectrum opportunity created at 60 GHz was seized by industry and has very strongly driven low cost, high performance SiCMOS circuits and antenna array products over recent years. In addition and most recently the advent of lower cost SiGe based devices is revolutionising 70 and 80 GHz mmW systems. Looking ahead, these advances are set to continue; the roadmap for Si device performance is predicted to reach 1 THz cut-off frequency by 2030[43]. Device performance at RF and in signal conversion (DAC, ADC) directly influences the spectrum efficiency which may be achieved, due to the effects on both transceivers and electronic antenna steering architectures.

As operating frequencies increase, the power output of amplifiers is a growing challenge, although this can be helped by one PA per amplifier arrays, see Section 6.2.2. Oscillator stability is a further challenge and this can drive a preference for single carrier operation (rather than OFDM). In a system, single carrier is not a problem as it fits in with beamforming well. The reason is that there is little advantage in beaming a multiplex towards a single user – it is far more efficient to beam a single carrier of only the user's own data.

Figure 6-1 shows graphs of power amplifier output versus operating frequency for MMICs using III-V compound semiconductors, and for silicon CMOS processes. In each case, power outputs are lower beyond about 10 GHz[44].

[42] They are not fundamental limits in the sense that there exists the freedom to choose an alternative scenario in order to avoid the limitation.
[43] Source: "Asia-Pacific Telecommunity Report on Technology trends of Telecommunications above 100 GHz", Manilla, 2011. Note that cut-off at 1THz implies circuit performance up to 300GHz, as an engineering rule of thumb.
[44] MMIC = monolithic microwave integrated circuit; PA = power amplifier; LNA = low noise amplifier; VCO = voltage controlled oscillator. III-V semiconductors = gallium arsenide, indium phosphide etc.

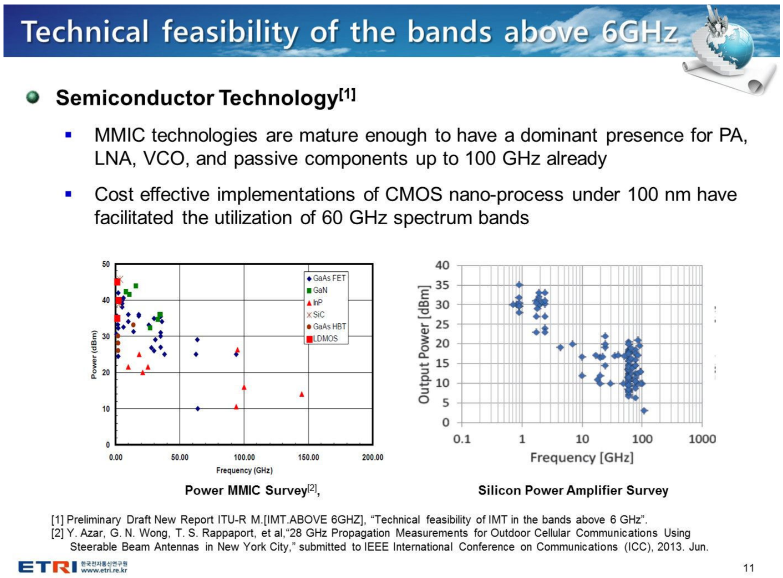


Figure 6-1 Power outputs of monolithic and silicon CMOS mmW power amplifiers[45]

Semiconductor processes are continually improving, but it is well accepted that beamforming is a good way to achieve increased power for 5G mmW in the short to medium term.

Packaging

At 60/70/80 GHz, advances in integration and packaging such as SoC and SiP[46] have necessarily been driven in parallel with device level advances. Low cost packaging techniques have had to keep pace with low cost devices and this has encouraged the take-up of the 'flip-chip' rather than bond wire solutions at RF, especially for attaching antennas. In flip-chip, the objective of reducing the loss due to interconnects is achieved by flipping over the antenna array and mounting it directly onto the RF chip. Interconnects are then as short as possible and may be metallic or capacitive. SiBEAM is an example of a flip-chip assembly, see Figure 6-4.

Device power consumption

Device power consumption from power amplifiers is a major challenge and a driver to use silicon CMOS processes. 60 GHz silicon transceivers are available today with relatively low power consumption[47]. In the receiver, ADCs are often the most significant source of power drain and so circuit design to use lower resolution (and hence lower power consumption) devices is being investigated[48].

[45] Future Needs for 5G Spectrum – Introduction to Activities in Korea", Chung H K, EU Workshop on Spectrum Planning for 5G, Brussels , 13th November 2014.

[46] System on Chip and System in Package, respectively.

[47] "State of the Art in 60-GHz Integrated Circuits and Systems for Wireless Communications", Rappaport et al, proceeding of the IEEE **99** 8, 2011.

"[48] High SNR Capacity of Millimetre Wave MIMO systems with One-Bit Quantization", Information Theory and Applications Workshop (ITA), San Diego, CA, Feb. 2014.

6.2.2 **Antennas**

The interest in new antenna technology comes from the widely accepted understanding that without beamforming for each user, then mmW communications will not achieve the required power budget at the bandwidth required. A beam may be formed by a mechanical dish or horn, which may also be turned or steered. However, such mechanical means, while adequate for point to point links, are neither small nor dynamic enough for use in a low height urban propagation environment with multiple user handsets. Figure 6-2 shows beamforming diagrammatically. The base station has been drawn as a traditional high tower, although this is unlikely to be the case in a real 5G mmW urban environment. Similarly, although beams are drawn to each user, this does not imply that these are simultaneous links.

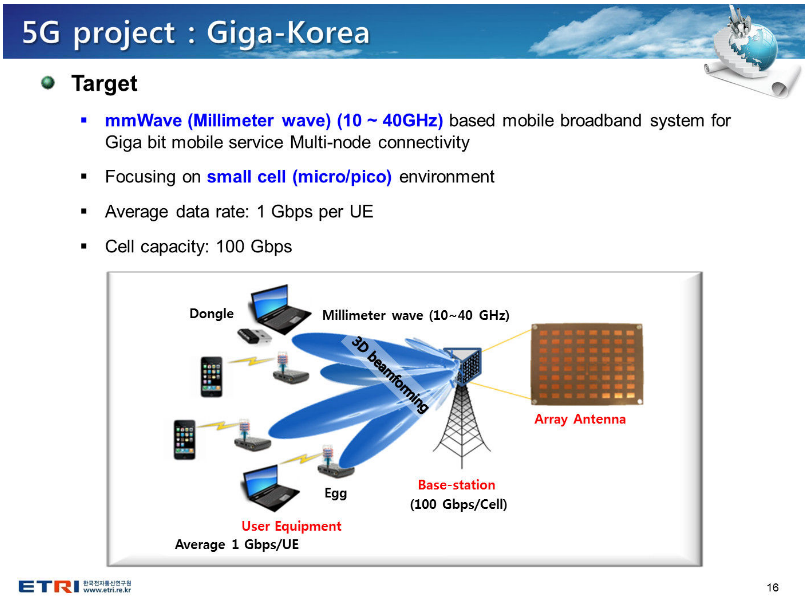


Figure 6-2 Generic example of beamforming in a 'cell', using antenna array[49]

A very promising solution already used in other applications is electrically steerable beams, which depend on an array of antenna elements[50]. While such devices may be used below 6GHz[51], the practical number of elements is limited due to the wavelength. Antenna arrays really come into their own at higher frequencies, where good beamsteering may be achieved with a significant number of elements in a compact overall size. This is easily illustrated by a simplified example: If a square base station antenna with 20cm sides is considered, then if 16 antennas will fit at 3.5GHz, it follows that 169 antennas would fit at 10 GHz and 676 antennas would fit at 20GHz, in other words, the number of elements scales as the square of the operating frequency[52]. Or, of course, a given antenna array can be made smaller as the frequency increases, which is a significant benefit of mmW systems

[49] "Future Needs for 5G Spectrum – Introduction to Activities in Korea", Chung H K, EU Workshop on Spectrum Planning for 5G, Brussels , 13th November 2014.

[50] IEEE 802.11ad 'WiGiG' product development at 60GHz has been responsible for much innovation in antenna arrays and attendant signal processing.

[51] Phase arrays are used in Wi-Fi products today, see our earlier work for Ofcom "Technologies and approaches for meeting the demand for wireless data using licence exempt spectrum to 2022", Quotient for Ofcom, http://stakeholders.ofcom.org.uk/consultations/spectrum-sharing/

[52] Assumes antenna linear dimensions are inversely proportional to frequency, square grid of elements.

since it facilitates integration into real-world equipment. In general, the greater the number of antenna elements, the greater the potential for effective beamforming.

Practical examples

An example of beamforming via an 8x8 square array of elements is shown in Figure 6-3. The gain would be expected to be in the region of 15dB. A further consideration is that when the number of individual elements becomes large, it may be preferable to interconnect a number of smaller arrays to create a larger modular antenna array (in order to avoid the practical issue of feeder loss). Such a modular array is still physically small, as shown on the right hand side of the figure (which shows one of the 16 elements required). The gain for the modular array would be expected to be of the order of 25-30dB. The main disadvantage of nodular arrays is a loss of flexibility with respect to array performance and potentially a reduced power output.

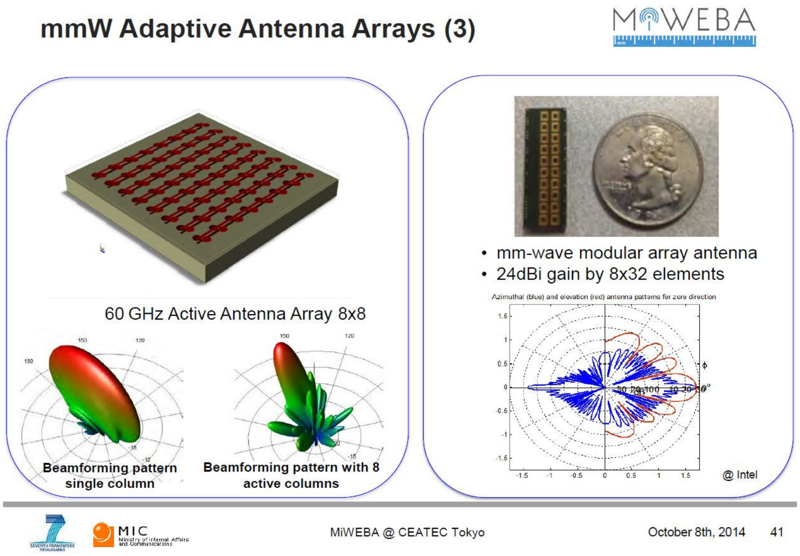


Figure 6-3 60GHz 8 x 8 antenna and radiation pattern and a physical modular antenna element[53]

Phased arrays are presently produced for use in WiGig at 60 GHz. An example is shown in Figure 6-4. The RF chip is under the antenna array.

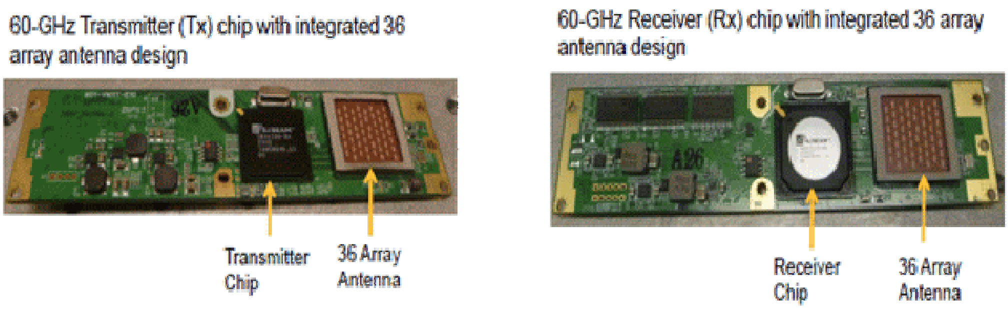


Figure 6-4 SiBEAM Silicon CMOS antenna array

[53] "Harvesting Millimeter Wave Spectrum for 5G", Haustein T and Sakaguchi K, Millimeter for 5G Workshop at CEATEC Tokyo, Japan, October 8th, 2014.

This antenna array is not modular; rather it has one power amplifier (PA) per antenna element and represents highly advanced manufacturing techniques applied to a product available today. The need for RF connections at 60 GHz is avoided by using only baseband signals to interface with the RF chips, which are internally connected to the active, steerable antenna arrays of 36 elements by flip-chip techniques.

Having one PA per element is a good way to increase the output power over a single PA or over a modular antenna array. In 90nm silicon, a single PA can achieve only up to approximately +13dBm due to device breakdown characteristics. With one PA per element, the output power scales as the square of the number of elements.

In more detail, the SiBEAM approach uses a low data-rate return channel to coordinate the beam-steering using a closed loop servo approach. The phase shifting is implemented directly at 60 GHz as shown in Figure 6-5.

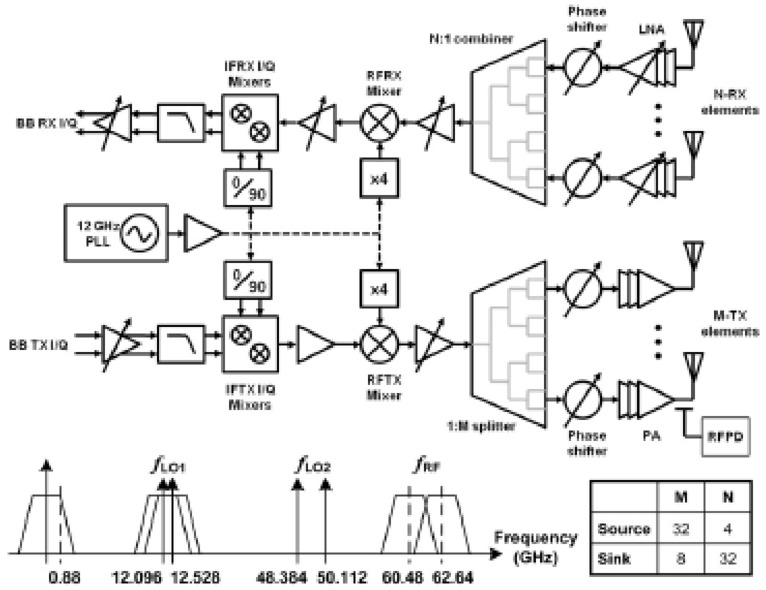


Figure 6-5 SiBEAM beam-steered, modular array.

The antennas, PAs and phase-shifters are all on the same substrate with baseband connections to the MAC/control chips. The 60 GHz up/down conversion is implemented in two stages with a 12 GHz I/Q mixer followed by 4 x12 GHz up-conversion stage.

Antenna research

The University of Essex has constructed micro- and mm-wave leaky-feeder antennas with encouraging results. Figure 6-6 shows a novel, 60 GHz, slotted, semi-rigid cable-based antenna with 15.3 dBi gain[54].

[54] "A coaxial, 60-GHz, 15.3-dBi slot antenna array", Quinlan et al., IEEE Antennas and Wireless Propagation Letters, **13**, pp.818-821, 2014.

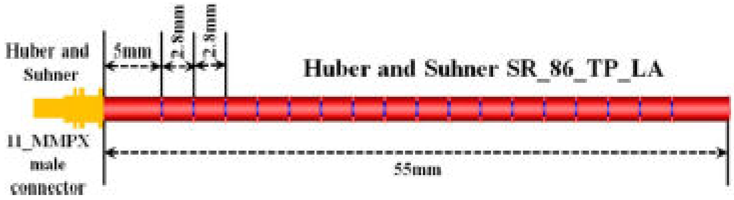


Figure 6-6 60 GHz semi-rigid slot antenna.

The slots were laser ablated to form Babinet dipoles. As can be seen, the slot spacing was carefully chosen in the sub-λ/2 region to avoid grating lobes. Self-apodization across the 55mm span removed the need for any end termination. The radiation patterns shown in Figure 6-7 highlight the quasi-discoidal radiation pattern and also the 'squint' due to end-feeding.

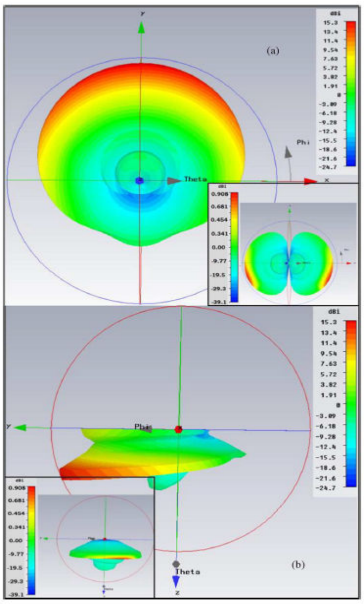


Figure 6-7 Copolar E-plane radiation patterns at 60 GHz; corresponding cross polar radiation patterns inset (a) top view and (b) side view.

Recent simulation work on up to quad arrays of these antennas has shown close to the expected 6 dB gain enhancement.

The University of Essex has also performed preliminary experiments which demonstrated orbital angular momentum (OAM) generation in conjunction with commercial 60 GHz antenna arrays[55]. It is possible that OAM may provide a further means for spatial multiplexing in future. Figure 6-8 shows the test set-up which features in-house fabricated phase plates, while Figure 6-9 gives a general overview of the apparatus.

[55] "4-Gbps Uncompressed Video Transmission over a 60-GHz Orbital Angular Momentum Wireless Channel", Mahmouli et al., IEEE Wireless Communications Letters, **2**, 2, pp.223-226, April 2013

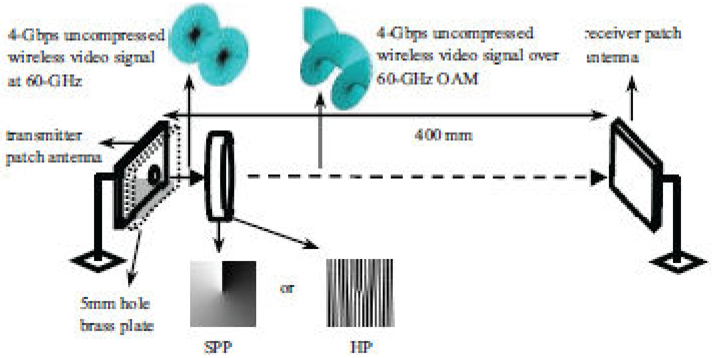


Figure 6-8 A 4-Gbps uncompressed wireless OAM experimental setup.

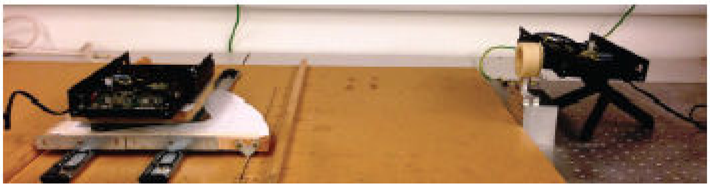


Figure 6-9 Practical experimental setup including transmitter on the right and receiver on the left.

6.3 Application–specific constraints and enablers

Channel propagation model

A key piece of design data for the 5G mmW scenario is the propagation model[56] , but this is presently not fully understood. This is not to say there are no mmW propagation models – there are, but they are for high-tower, point to point links. Such mmW line-of-sight connections are in common use and serve links of several km at 70/80 GHz, for example, or up to a km or so at 60 GHz, due to higher absorption[57].

The main challenge of the urban environment arises from common obstacles which have very high loss at mmW, compared to the more traditional cellular frequencies. A corollary of this is that links are typically made up of reflected rays. Figure 6-10 show examples of measurements in the non-line-of-sight urban environment, illustrating available range versus the gain of the antennas used. Propagation is confirmed to be very different to mmW high tower, point-to-point links.

[56] We note this is outside the scope of ITU WP 5D, but within wider ITU-R remit.
[57] See for example www.sub10systems.com

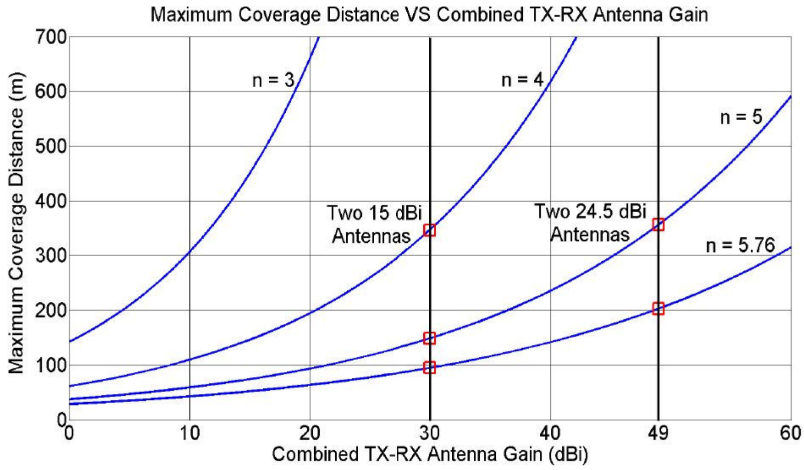


Figure 6-10 28GHz measurements of coverage distance (signal detection) versus total antenna gain[58]

Figure 6-10 was constructed by using high gain antennas at both transmitter and receiver and sweeping their pointing angle until maximum signal was achieved[59]. The definition of coverage was by a signal power detection threshold, and no actual data transmission was involved in this measurement. The value n is the exponent of a calculated path loss curve; n=4 is often used as a rule of thumb for the conventional cellular path exponent. It can be seen that the best mmW performance is on par with this, but on average, the mmW cell loss is higher than at conventional cellular frequencies. A higher loss results from a narrower antenna as might be expected, but the attraction of a narrower antenna is a reduction in delay spread (not represented in the figure).

Explicit in the research results is that

- directional antennas are necessary;
- the antennas must be continually steered to the best angle;
- a high total gain from the directional antennas is key in both satisfying the power budget and in reducing the delay spread of reflections.

While these research results are encouraging there must remain questions over the practicality of the high gain antennas at both ends of the link and the absence of a method to steer them, other than manually, plus real data traffic needs to be demonstrated over the link, to assess the transmission quality.

There are a number of channel measurements beginning to appear in the literature for 200m links for 5G mmW cells. More confirmatory results are needed and actual communications testing (as opposed to channel sounding) is required.

Receiver performance

A potential issue for receivers is that of blocking where the RF front end is saturated by adjacent signals (which may be in band or out of band). Both receiver selectivity and antenna array spatial filtering could be used to address this, although we have seen no

[58] "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!", Rappaport T et al, IEEE Access, May 2013.
[59] A 15dB antenna offers a 30 degree beam width and a 24.5 dB antenna offers a 10 degree beam width.

published work in this area. In order to determine the extent of this issue, practical measurements in an appropriate environment would be needed.

Type of reflections

Where the user is not in line of sight of the base station, then propagation will be via reflections[60], since diffraction is very lossy at millimetre wave[61].This brings into question they type of reflection which will be present. We expect that both specular and diffuse reflections are possible and this will depend on both operating frequency and building material. This is a further area where measurements are needed, as we know of little or no published work in this regard.

Size of antenna versus handset form factor

The size of antenna array, which needs to be the order of several wavelengths long, is partially a fundamental limitation, but also one which may be improved to some degree by technology choices, such as substrate material. Nonetheless, this leads to a limitation at lower mmW frequencies due to the size of practical antennas, simply because they may be too big to fit into a handset. The practical extent of this limitation is driven by the application scenario. To take a specific example consider 30GHz, where the wavelength is 1cm and prototype antenna arrays have been shown in normal handsets with a shortest dimension of around five centimetres[62]. In contrast at 10GHz, the array would be expected to be 3x larger and thus likely to be impractical for inclusion in handsets[63].

There is also the issue of fractional bandwidth to consider, which is bandwidth expressed as a percentage of centre frequency. As frequency decreases, fractional bandwidth increases for a given absolute bandwidth. Larger fractional bandwidths pose more design challenges. As a general rule of thumb, fractional bandwidths above 20% generate additional challenges in RF and antenna design. A bandwidth of 3GHz at 30 GHz represents a 10% fractional bandwidth whereas 3 GHz at 10 GHz would represent a 33% fractional bandwidth.

Large arrays at mmW

At high mmW, large antenna arrays are generally aiming to achieve beamforming, rather than multiuser MIMO or spatial multiplexing. This is firstly because it is already challenging to achieve (single user) beamforming at mmW due to the layout/device limitations already mentioned, for example the number of elements. Even more elements will be needed for multiuser MIMO. Secondly the mmW line-of-sight paths with sparse multipath[64] and many reflections per path do not necessarily provide an appropriate environment to support spatial multiplexing.

Large arrays are needed at mmW to ensure sufficient directionality is present to satisfy the power budget, but also to reduce delay spread and thus enable high speed transmission

[60] See Figure 3-4 on page 7.
[61] See Chapter 5.
[62] See for example "Comments of Samsung Electronics America, inc. and Samsung Research America" in response to "Use of Spectrum Bands above 24 GHz for Mobile Radio Services" NoI from the FCC, Appendix B, Jan 15, 2015.
[63] Inclusion in laptops and tablets might be practical at 10 GHz, but this would adversely segment the market opportunity.
[64] mmW channels are sparse in terms of multipath components, as the number of significant scatterers tends to be smaller than microwave channels, see "Coverage and Capacity of Millimeter-Wave Cellular Networks", Bal et al, IEE Communications magazine, September 2014. .

and reception[65]. In summary, this means that the massive MIMO antennas suggested for lower frequency base stations to support multi-users and spatial multiplexing are not necessarily appropriate for mmW applications.

System level considerations

A highly directive antenna is very useful for user plane communications (i.e. the user's data stream), but not so good for control messages. This is because control messages generally need to communicate with all users regardless of location in a cell (and so not only where the beam is pointing). This is a major driver for a separation of the control and user planes, referred to as the C/U split. If the control plane is handled separately by an omnidirectional link such as a macro layer, then the highly directional user plane link is free to maximise data transfer rates.

Antenna control aspects

Technology is needed at the MAC layer in order to provide for a device discovery process. This may be aided by a macro layer to which a 5G mmW device is always dual-connected, in other words the split C/U plane. Regardless of the medium over which control is achieved, algorithms will be needed in order to discover base stations, establish an initial link and to maintain that link as the user moves. While this has already been standardised within 802.11ad for indoor WiGig devices, operation outdoors may be more challenging due to higher levels of movement in an environment with a greater variety of obstructions. It therefore remains to be seen whether algorithms developed for WiGig may translate to the 5G mmW outdoor scenario.

Antenna control will need to operate in real-time in order to combat the effects of changing reflections as the user moves, or the path becomes blocked by foliage, vehicles or other people, for example. This is an area where investigation is needed.

6.4 Summary

Devices, packaging and beamsteering antenna technologies have made significant advances and are contained in 60 GHz indoor products today. It is likely that in the next five years, these low cost technologies will become available up to 100 GHz. Antenna steering algorithms need verification for application to 5G mmW outdoor systems. The steering algorithms and implementations have not yet received adequate attention and we expect this technology aspect will be challenging. Urban environment measurements are needed to support the investigation of the antenna steering challenges.

Spectrum will be needed for the data plane (e.g. new mmW frequencies) and the control plane (e.g. existing coverage frequencies) as well as the backhaul (existing backhaul frequencies of new mmW frequencies.

[65] "Radio propagation at microwave frequencies for line-of-sight microcellular mobile and personal communications", Rustako et al, IEEE Transactions on Vehicular Technology, **40** (1), February 1991.

7 BAND BY BAND ANALYSIS

7.1 Overview

We now move to consider usage within each of our spectrum ranges

- 6-30 GHz;
- 30-100 GHz;
- 100-200 GHz.

An overview of all three ranges is shown in Figure 7-1. Each range will be discussed in detail and an overall candidate band ranking will be provided.

We analyse each band in turn at the top level in this Chapter, with a UK / European bias as a starting point. In Chapter 8 we analyse our top five candidate bands in further detail including more consideration of incumbent use from a global perspective.

Our first objective is to create the very top level view of incumbent use in each range, noting that a broad bandwidth of around 1GHz or more is required for 5G mmW.

In order to make the approach tractable, only selected users of spectrum are shown. Services which use lower amounts of spectrum are deliberately less visible in Figure 7-1. Both these aspects ensure a high-level view, where potential large bandwidths options for 5G mmW may be more easily seen.

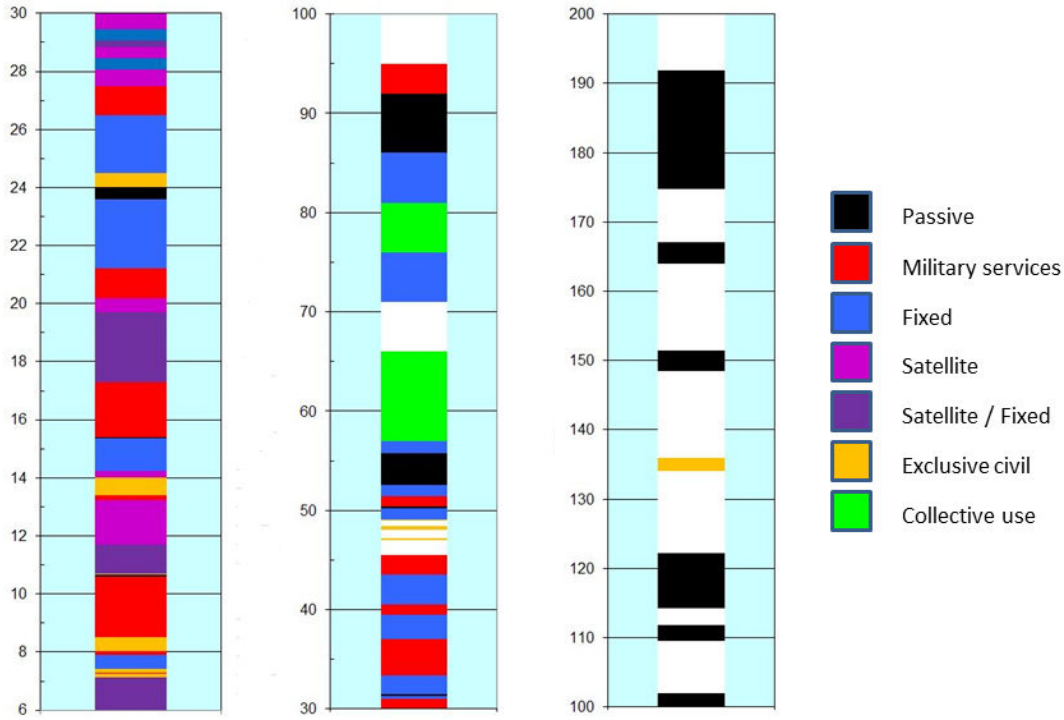


Figure 7-1 Overview of bands from 6-200 GHz; best sharing potential is in 'white' bands.

7.2 Incumbent services considered

At this point, we do not consider all incumbent services. The services[66] considered are shown in Table 7-1. In plotting these services, we are not proposing that any service not plotted is of any lesser importance; this is simply the first stage in our analysis.

Service	*Plotted colour*	*Sharing potential with 5G access*
Passive services	Black	None
MoD (various)	Red	Low, since these are NATO harmonised bands for radar, satellite links etc. However, there may be some potential for sharing, although there has been insufficient information to properly evaluate.
Fixed	Blue	Low, but with some potential for sharing which depends on usage. Alternatively these bands could be used directly to satisfy demand for 5G backhaul. Includes light licensed bands, where self-co-ordination might be envisaged were an operator to have rights to both backhaul and access in a band.
Satellite	Light purple	Lowest. Internationally harmonised, some scope for sharing.
Fixed/Satellite	Dark Purple	Lowest. Internationally harmonised, some scope for sharing.
Exclusive civil uses (PMSE, Amateur etc.)	Orange	Low, since these bands are designed to offer exclusivity. Some bands may be little used. Overall however, the amount of spectrum is small.
Licence exempt	Green	Potential exists, but only on a non-protection basis.
Other	White	Best potential – but although usage appears to be low, these are not unallocated bands.

Table 7-1 Services and colour codes plotted in Figure 7-1.

From Table 7-1 we infer that detailed compatibility studies would be needed to determine whether co-existence is possible with many of the services identified and that dedicated spectrum would be preferable if available.

7.2.1 Band by band analysis: 30-100 GHz

This band is dominated by passive, fixed, MoD and collective use. Non-military satellite usage is low and is expected to stay low[67]. The exclusive civil use bands are too small for independent 5G mmW use.

[66] We have included MoD / NATO bands in the service list as a convenient label, but these bands are really a collection of services under a NATO / MoD umbrella.

There are three areas of 'other' usage (white bands in Figure 7-1.)

- 45.5-48.9 GHz, containing two relatively small exclusive civil bands;
- 66-71 GHz;
- 95-100 GHz.

There is no potential to share with passive bands (black) and potentially little with NATO harmonised bands[68] (red).

But there is potential with fixed links (blue) and specifically there is an 'old' harmonised band for Multimedia Wireless Access (MWA)

- 40.5-43.5 GHz.

This has been an underused band and is one which has recently been opened to the fixed service.

The fixed bands which are typically light licensed bands also merit discussion (blue).

- 71-76 GHz;
- 81-86 GHz.

There is potential to share with licence exempt (green)

- 57-66 GHz (wideband data, e.g. WiGig);
- 76-81 GHz.

Discussion - 'Other' usage bands(white)

The 66-71 GHz band has a mobile allocation which is unused. It also has allocations to RNAV and RNSS, which are either not in use or not expected to be a major coexistence issue[69]. There is no declared NATO military interest here for present or future use.

> This band is suitably wide at 5GHz and is adjacent to the WiGig band, so that low cost technology should be available. If WiGig at 57-66 GHz is included in future handsets, then a single RF chain could probably serve 66-71 GHz as well. Several operators could be supported in this band with individual 1 GHz assignments.
>
> This band could be collectively used[70], allowing access by 5G mmW and other devices meeting specific band conditions. Alternatively, even with a partition to accommodate 5G mmW via bespoke conditions, there could still be bandwidth available for other collective use. Collective use is most appropriate since the probability of interference is lower at higher frequencies.
>
> Internationally, this band is allocated to mobile in at least Europe, China, Japan, South Korea and USA. In the ECA table there is a note which reads 'Future Civil Systems' for this band, although we have not been able to trace the origin of this.

The 45.5-48.9 GHz band includes two relatively small exclusive bands used for the Amateur service and PMSE. The PMSE band might be suitable for clearance since no

[67] Q/V band only for niche applications, see Section 4.4.
[68] See updated discussion in Section 8.3.
[69] Confirmed with European GNSS and Space Agencies.
[70] e.g. under licence exemption.

allocations were made in 2014. The Amateur service however is the 6mm band, in which there is clear usage.

Even if these exclusive bands were avoided, then 2.8 GHz is available in total, although not contiguously. However, this could be split naturally into three bands of 1.5, 0.8 and 0.6 GHz, which could support 3 operators, albeit with unequal bandwidths. Alternatively four operators could use 0.75, 0.75, 0.8, 0.6 GHz for a more equitable distribution.

45.5-47 GHz is allocated to RNSS, but not used[71]. In the European Common Allocation (ECA) table the application column is blank and there is note which reads 'Not allocated', which appears contradictory, but may simply indicate that no active use is known.

47.2-48.9 GHz is blank in Ofcom's interactive spectrum map of usage, with the exception of the Amateur band, although allocations do exist[72]. The Amateur band is globally allocated.

Internationally, most of 45.5-48.9 has a mobile allocation in Europe, China, South Korea and USA. In Japan, the mobile allocation stops short at 47 GHz. In China we are aware that 802.11aj, the 'China mmW' version of WiGig has recently claimed part of this band (since there is insufficient spectrum at 60 GHz).

We note that Vodafone has suggested the wider range 43-47 GHz could be considered for 5G mmW[73], although 43.5-45.5 GHz is a harmonised NATO band for satellite uplink in current use, with potential for future mobile use.

These bands could be suitable for collective use, for the same reasons as given for 66-71 GHz.

The 95-100 GHz band has similarities to the bands in 100-200 GHz and will be discussed under that heading.

Discussion - Fixed bands (blue)

The 40.5-43.5 GHz band is the concatenation of two bands where the 40-5-42.5 GHz portion has no primary mobile allocation in Europe, although it is at least secondary in Region 1, China, South Korea, Japan and USA.

Despite this it is of interest since the 40.5-42.5 GHz portion was harmonised in Europe for the Multimedia Wireless Service which has not been the hoped-for market success at this frequency. Consequently it has recently been opened to the fixed service, but usage in 2011[74] was only 73 fixed links in Russia and 3 in Slovakia. We see no reason why it should not be re-considered for 5G mmW access, especially since this is in many ways a modern replacement for the unsuccessful MWS service.

This band was auctioned in the UK and is technologically neutral. In the ECA table, priority is given to civil networks and there is a mobile allocation in Europe, China and South Korea, although not in Japan or USA.

[71] Source: European GNSS Agency.
[72] These appear to be little used, see Chapter 8.
[73] Vodafone response to Ofcom WRC-15 Consultation, June 2014, http://stakeholders.ofcom.org.uk/consultations/wrc15/?showResponses=true&pageNum=8#responses
[74] ECC Report 173.

The 71-76 and 81-86 GHz, typically light licensed bands are relatively new bands suitable for backhaul, where low cost equipment is coming onto the market. In the UK and elsewhere part or all of these bands are light licensed.

> Due to performance concerns from the industry the self-managed light licensing regime has been reduced in the UK in favour of more centralised management. This bodes against sharing these bands with 5G mmW access.
>
> However we could envisage a situation where operators might want to self-co-ordinate between their own access and backhaul networks in portions of this band.
>
> 73 GHz channel sounding has been performed via industry-sponsored research[75], but we expect this choice of frequency may have been driven more by test and measurement availability and is simply meant to be representative of the higher mmW bands, since previous sounding covered 28 and 38 GHz.

Discussion – licence exempt (green)

The 57-66 GHz licence exempt band has spurred the creation of the Wi-Fi Alliance's WiGig for very high speed, indoor and outdoor connectivity (fixed outdoor use is excluded). It is an allocation which is available globally; at least in part (China does not have all channels at 60 GHz, for example).

> 5G mmW could enter this band directly via collective use; however the power / antenna limits may need to be re-assessed for outdoor operation at 200m. In any case, a better option would be to consider the adjacent band 66-71 GHz for outdoor use with appropriate limits, as suggested above, since this would expand the scope for innovation by not competing with WiGiG and any future collective use of this band.

The 76-81 GHz band contains vehicle radar amongst other services which may be a source of coexistence issues with 5G mmW.

> There is also no mobile allocation in any of Europe, China, Japan, South Korea or USA. Other bands within 30-100 GHz thus seem to be more immediately attractive.

Industry interest bands

There has been industry interest in the **38 GHz band**, especially from USA, but this band is well used for fixed links in Europe and is seeing a high increase in usage[76]. Given the other options above, this does not appear to represent a prime opportunity in this frequency range.

7.2.2 Band by band analysis: 100-200 GHz

This range differs in that it contains no confirmed MoD / NATO bands[77], no fixed bands, no satellite bands and only one exclusive civil band, the 2mm Amateur band. The 95-100 GHz band also exhibits the same properties.

Overall, there are many passive bands which are unavailable. Much of the remainder of the band is allocated to the Radio Astronomy Service. Subject to respecting RAS (which may

[75] At New York University.
[76] ECC report 173.
[77] It would be prudent to anticipate some military use in future.

be localised) and any future military use, the many bands coloured white have the potential to support backhaul for 5G mmW. The backhaul business case supports device technologies such as III-V[78] and fixed antennas, which are not suited to 5G mmW access. However, backhaul range will be limited by atmospherics, especially within the broad water absorption peak at 165-200 GHz. It is not yet clear to what degree more fixed link spectrum will be needed, beyond what is currently available.

7.2.3 Band by band analysis: 6-30 GHz

This range is very different to the other two already discussed. It has no 'white bands' it contains the key civil satellite services and more of its range consists of NATO harmonised bands. It is also naturally more difficult to find bandwidths of several GHz in this lower frequency range. There is strong interest from the satellite industry, including for High Density FSS, as well as for the fixed service, both of which are expected to support the wider 5G infrastructure under the aims of a fully connected society. The only fixed band showing low increase in usage is 10.7-11.7 GHz, but this is also in use for fixed and broadcast satellite downlinks.

Satellite uplinks[79] at 12.75-13.25 and 13.75-14.5 GHz are too narrow compared to the multiple GHz required for 5G mmW. 5.725-7.075 GHz and 17.3-18.4 are still relatively narrow and are shared with the fixed service, with the latter band in particular showing a high increase in usage[80]. 7.9-8.4 GHz containing uplinks is a NATO Class A band signifying a permanent and essential requirement. This band also contains Earth Exploration, with which it will be difficult to share, plus a fixed service. Satellite uplinks at 28 GHz are discussed below.

Given that sharing with satellite and fixed is likely to be challenging in this range and would offer limited bandwidth in any case, another potential option is that sharing could be negotiated with military users, but the harmonised NATO bands in this range are all classed as essential or important for current radar, satellite, fixed and mobile usage. The wider bands at 8.5-10.5 GHz and 15-7-17.7 GHz are both used by radar, including airborne, which will pose significant sharing challenges.

Overall, the bands already identified above 30 GHz all have greater bandwidth and lesser sharing issues. Nonetheless, there has been interest from the mobile industry in certain parts of the world.

Industry interest bands

The 28 GHz band has received a good deal of interest, especially in terms of experimental channel sounding measurements and link demonstrations. Caution should be exercised however, since this may mean only that the 28 GHz band has suitable test and development licence arrangements in some locations. In the UK, the fixed portions of the 28 GHz band were auctioned.

> The 28 GHz band in Europe is already segmented between satellite and fixed links bands. Detailed compatibility studies would be needed to determine whether coexistence is possible between services. Despite the high interest, detailed frequency proposals from the mobile industry are scarce. In our study work, an

[78] GaAs, InP etc
[79] See Appendix 1 for a list of satellite bands and frequencies.
[80] ECC Report 173.

ECC PT1 contribution[81] is the closest we have found to identifying specific bands. In the 25.25-29.5 GHz region this identified **26.5-27.5 GHz** as a low usage fixed link band. This usage can be confirmed via the ECC Fixed Links survey (Report 173) and the only country using this band is Russia, with fewer than 100 links.

However the reason for no CEPT usage of this band outside Russia may well be that it is a harmonised NATO band for already-planned fixed and mobile systems, which is not addressed in the PT1 contribution.

Interest is high from USA since there it is an LMDS band[82] which is underused, but this is not true in Europe. We show the overlap between the European and US LMDS bands in Figure 7-2, where a little over 500 MHz is common to both, contiguously[83]. Also shown is the frequency range used in a reported industry trial[84].

500 MHz is well below the target of 1GHz for each of multiple operators. However, there may be some value in pursuing this approach, if the bandwidth target were to be reduced in future (see below for an example of what might be achieved with lower bandwidth). For the purposes of this study, we note that we have already identified many larger bandwidth opportunities above 30 GHz.

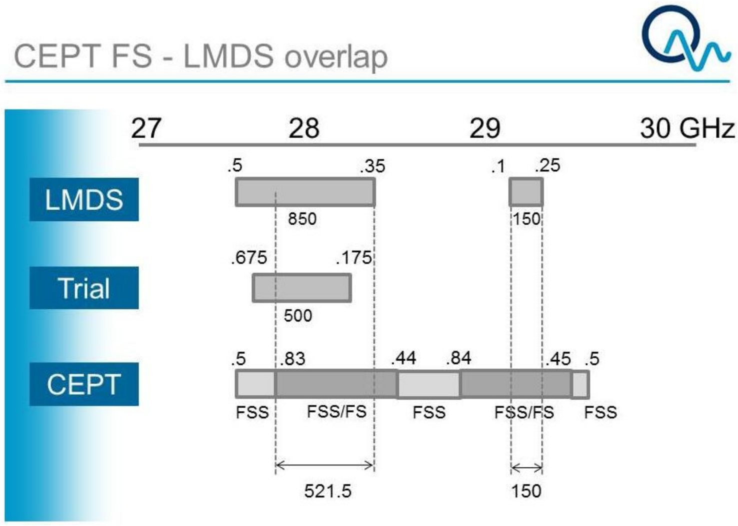


Figure 7-2 Overlap between US LMDS and European fixed bands

The 13.4-14 and 18.1-18.6 bands have been suggested by Korea; the former is a Ku satellite uplink band and the latter is a Ka downlink band shared with the fixed service in Europe. Moreover, these bands are too small for multiple operators to receive a reasonably wide bandwidth, such as 500MHz each.

81 from Alcatel-Lucent, BAE Systems, Intel and Samsung (April 2014).

82 27.5-28.35 GHz, 29.1-29.25 GHz, where local multipoint distribution services (LMDS) operates on a primary basis and fixed satellite service operates on a secondary basis in USA.

83 , Coordinated FSS earth stations can make use of the whole band 27.5-29.5 GHz, using established coordination procedures.

84 "Comments of Samsung Electronics America, inc. and Samsung Research America" in response to "Use of Spectrum Bands Above 24 GHz For Mobile Radio Services" NoI from the FCC, Appendix B, Jan 15, 2015.

Example of high speed data systems near 6 GHz

If there is future interest in lower bandwidths for 5G above 6 GHz, then we may obtain an idea of the performance achievable by looking at existing systems in nearby spectrum. IEEE802.11ac operates in the 5 GHz band and uses a combination of high order modulation, spatial multiplexing and wider channels than previous 802.11 systems, in order to target higher speeds[85]. However for mobile handsets only one antenna (and RF chain) is expected to be integrated, thus curtailing operation to a single spatial stream. In the case of an 80 MHz bandwidth, the theoretical speed is 433 Mb/s at the maximum order modulation of 256 QAM, doubling to 867 Mb/s in a 160 MHz channel bandwidth, for a single stream.

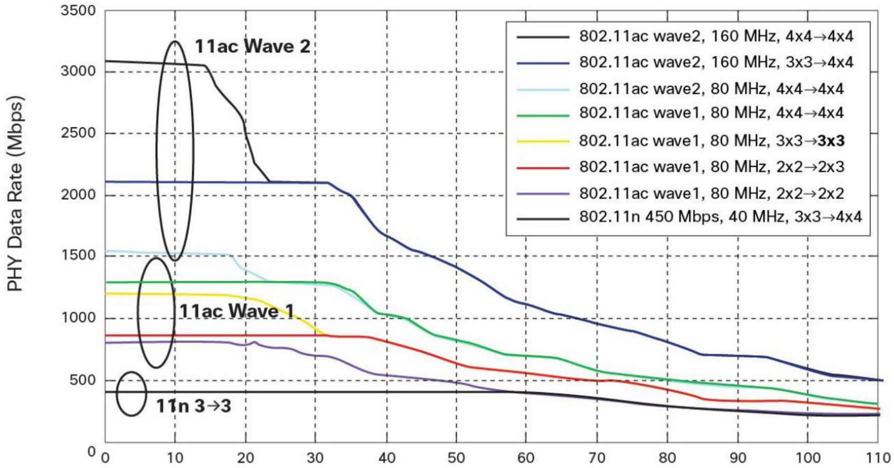


Figure 7-3 Rate against range (in meters) for IEEE 802.11ac[86]

These speeds are range dependent, see Figure 7-3[87]. In order to maintain the highest link speeds above several tens of meters (and ideally out to 200m for 5G mmW) an increase in power transmitted or a beam forming approach would be required at the base station. Nonetheless IEEE802.11ac is a useful example of how 5G mmW systems could be designed to operate in sub GHz bandwidths near the 6 GHz end of the 'above 6 GHz' range of interest.

While speeds lower than ideally desired[88] may be realised, we expect this could still deliver a performance boost likely to benefit the wider 5G eco-system.

7.3 Priority bands

The primary parameters we have used to prioritise bands are

- High available bandwidth
- Low incumbent usage

[85] "Technologies and approaches for meeting the demand for wireless data using licence exempt spectrum to 2022", Quotient for Ofcom, 2013, http://stakeholders.ofcom.org.uk/consultations/spectrum-sharing/
[86] "802.11ac: The Fifth Generation of Wi-Fi", Technical White Paper, Cisco, 2014.
[87] A single stream is not shown in the figure, but the trend for lower speeds as the range increases (due to falling signal to noise) will be similar.
[88] See Chapter 3.

Secondary parameters are

- Harmonisation potential (globally)
- Economies of scale (due to use in any other application)
- Ease of handset integration (assuming that WiGig at 60 GHz will be present in future handsets)

The top five priority bands drawn from all the bands discussed in Section 7.2 over the entire range 6-200 GHz are listed in Table 7-2.

Band	*Bandwidth*	*Incumbent*	*Harmonisation*	*Economies*	*Handset*
66-71	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
45.5-48.9	✓✓	✓✓	✓✓	✓	✓
40.5-43.5	✓✓	✓✓	✓✓	✓	✓
71-76; 81-86	✓✓✓	✓	✓✓	✓✓✓	✓
57-66	✓✓✓	✓	✓✓✓	✓✓✓	✓✓✓

Table 7-2 Priority bands and parameter ranking

We note that all the priority bands identified from the sharing perspective are from within the 30-100 GHz range. This finding fits very well with the finding from earlier Chapters that 30-100 GHz was favoured from the joint perspective of fundamental propagation behaviour, technology readiness and application constraints.

Our focus is bands for access, but we note that bands for backhaul could include all the existing fixed bands, plus bands up to around 165 GHz could be considered before water absorption significantly limits range.

7.3.1 **Ranking of priority bands**

We rank the five priority bands in Table 7-3 with a list of pros and cons. More details are provided in Appendix 3. We take these five bands forward for further analysis in the study.

Band (GHz)	*Colour*	*Rank*	*pros*	*cons*
66-71	White	High	Wide bandwidth; could support multiple operators. Fewest sharing challenges. Close to 60 GHz wireless data (WiGig) band for economies of scale, but with the benefit of lower attenuation. Collective use would be appropriate. Good harmonisation	Need to consider any future use for inter satellite links, which may arise.

Band (GHz)	Colour	Rank	pros	cons
			potential.	
45.5-48.9 (3 sub-bands)	White	High	Wide bandwidth; could support multiple operators. UK PMSE might be cleared to increase bandwidth. Collective use would be appropriate. Good harmonisation potential.	Need to avoid exclusive civil use sub-bands. Japan and China may not support the whole band.
40-5-43.5	White	High	Wide bandwidth; could support multiple operators. Opportunity due to failed Multimedia Wireless Service, for which 5G may be considered a successor. Collective use would be appropriate. Auctioned in the UK on a technology neutral basis.	The lower 2 GHz presently has only a secondary mobile allocation in Europe; recently opened to fixed links. The upper 1 GHz has no mobile allocation in USA, Japan.
71-76; 81-86	Green	Medium	Wide bandwidth. Potential to use via extensions to light licensing. Good harmonisation potential.	Commonly used for backhaul with high reliability. Concern that sharing may decrease reliability (unless access and backhaul are jointly managed e.g. by self-coordination).
57-66	Green	Medium	Wide bandwidth. Collective use would be appropriate. Good harmonisation potential.	A better choice would be 66-71, thereby creating more total bandwidth for both indoor and outdoor connectivity for all uses, including future innovation.

Table 7-3 Ranking table for 5G mmW access bands.

7.4 Summary

All the priority bands identified from the sharing perspective are from within the 30-100 GHz range. This finding fits very well with the earlier independent finding that 30-100 GHz was also favoured from the joint perspective of fundamental propagation behaviour, technology readiness and application constraints.

8 PRIORITY BANDS FOR FURTHER INVESTIGATION

8.1 Highest ranked bands

In our band-by-band analysis of Chapter 7 we identified three priority bands with a high likelihood of being suitable for 5G mmW and two with a medium likelihood. We now further analyse each of the top five options from a more global perspective. We also include MoD / NATO bands as a general option as we had been unable to eliminate these as a source of 5G mmW spectrum[89]. The ranked options are shown in Table 8-1.

Rank	*Band, GHz*	*Usage, trend*	*Sharing or clearance required?*
1	66-71	Low or none, fallow	No current use found
2	45.5-48.9 (three sub-bands)	Low or none, fallow	No current use found
3	40.5-43.5	Low, low growth (except in UK - auctioned)	Either sharing with, or clearance of fixed; allocation to mobile; UK auctioned band is already technology neutral;
4	71-76; 81-86	Medium, growing	Sharing with fixed under a light licensed regime[90]
5	57-66	Medium, growing	Sharing under collective use
-	MoD bands (in general)	Uncertain	Uncertain

Table 8-1 Top five priority bands, plus MoD/NATO.

We make several observations

- Our two highest ranked options appear to be free of incumbent users, based on our top-level analysis[91];
- The selection of two (or more) bands might be most appropriate to maximise the potential for innovation;
- Our third ranked option requires i) clearance of an underused[92] fixed link band opened in 2010, having previously been sterile while harmonised for the un-adopted Multimedia Wireless System, and ii) its allocation to mobile use (this band was auctioned in the UK);
- Our fourth and fifth ranked options require sharing with light licensed or collective use bands;
- Our final option is a re-examination of the MoD / NATO bands in general. More information was made available by NATO as the study concluded.

[89] More detailed data became available via NATO as the study concluded, see Section 8.3.
[90] Parts of these bands are coordinated in the UK.
[91] Detailed coexistence studies will still be required.
[92] As of 2011.

We next examine the global usage of our five highest ranked bands.

8.2 Global usage of priority bands

Table 8-2 shows usage of the priority bands in various areas the world, as far as we have been able to establish this during this study. The 66-71 GHz band and 45.5-48.9 sub-bands do not appear to need to share with any currently active service, although allocations exist. The other bands may need to share or co-exist with

- Satellite;
- Fixed links;
- PMSE;
- Amateur;
- Licence exempt devices
- Radio Astronomy (adjacent).

However the actual usage of some of these services appears to be low in many cases. We discuss each potential sharing situation in turn as it applies to our priority bands.

8.2.1 Sharing with satellite

In general it is often assumed that sharing with uplinks will be easier than sharing with downlinks. However, we would urge some caution in this regard, since sources of aggregated interference must always be considered[93]. The probability of interference is thereby directly linked to device density, which for 5G mmW is presently unknown.

In the 40-50 GHz range, there are allocations to the High Density Fixed Satellite Service, which potentially affects two of our priority bands, see Table 8-2. However, we know from bilateral industry consultations that civil satellite use is unlikely to extend above 30 GHz, except possibly for feeder applications, as is being investigated by EU project BATS. Alternatively feeder links above 30 GHz may use optical methods instead. Nonetheless, were feeder links to be introduced in the 40-50 GHz range, then a viable way to share this spectrum could be via geographic exclusion zones. This might be practical since satellite gateways would be outside the urban areas likely to be used by 5G mmW systems, but aggregation effects would still need to be taken into account.

In the 66-71 GHz band, any mobile use would have to not interfere with any space use, although no space use has been identified. In future, inter-satellite links might use this band, although a wide range of 50-75 GHz is under consideration. Given the attenuation at this frequency and the very large separation distance involved, sharing should be feasible.

8.2.2 Sharing with fixed links

There are three potential cases where sharing with fixed links might be necessary. Firstly with traditional licensed fixed links in the 40.5-43.5 GHz band, secondly in the 71-76 / 81-86 GHz bands which are typically light licensed, and thirdly with any potential High Altitude Platforms (HAPs) in the 45.5-48.9 GHz band.

[93] See, for example, "Comments of Samsung Electronics America, inc. and Samsung Research America" in response to "Use of Spectrum Bands Above 24 GHz For Mobile Radio Services" NoI from the FCC, Appendix D, Jan 15, 2015.

Band, GHz	*UK*	*Europe*	*USA*	*China*	*Japan*	*Global*
66-71	No use	No use	No use		No use	No use known, but allocated to GNSS, ISS. Mobile may cause no interference to space.
45.5-48.9 (three sub-bands excluding PMSE, Amateur)	48-48.4 no PMSE allocations in 2014	45.5-47 no use known; 47.2-47.5 HAPS; 47.5-47.9 HDFSS DL R1; 47.9-48.2 HAPS; 48.2-48.54 HDFSS DL R1;		42.3-47, 47.2-48.4 802.11aj (China mmW)	No use	(47-47.2 Am, AmSat) (PMSE is not global) Need to protect adjacent RAS
40.5-43.5	Auctioned	MWS unused, opened to FS in 2010	40.5-42 HDFSS R2; 42-42.5 underused, previously under consideration for PtP, PMP, mobile		41-42 PMSE	40.5-42.5 mobile is secondary; 40.5-42.5 FSS DL; 42.5-43.5 FSS UL
71-76; 81-86	PtP fixed links	PtP fixed links 71-74, 81-84 are NATO type F (future use), but ECA EU27 states civil sharing	PtP fixed links	PtP fixed links	PtP fixed links	PtP fixed links 71-76 FSS DL (71-74 MSS); 81-86 FSS UL (81-84 MSS); 74-76 BS, BSS, SRS (s-E); 75.5-76 Am, AmSat , no mobile
57-66	57-66 Wideband data	57-66 Wideband data	57-64 Wideband data	59-64 Wideband data	59-66 Wideband data	59-64 is a common global wideband data sub-band

Table 8-2 Global use of priority bands[94]

[94] Note USA and NATO both use 43.5-45.5 GHz band as satellite uplink for AEHF, DJCF, Skynet systems and possible future mobile use, which is not in any priority band.

We showed a possible 5G mmW scenario in Figure 3-4 on page 7, where there exists the possibility of conflict between 5G mmW access and some of its in-band serving backhaul links, i.e. fixed links. There are two possible interference scenarios

- Where the in-band fixed link is in a traditional licensed band used for mobile backhaul (e.g. 10- 42 GHz), and used for over-the-rooftop backhaul (red link), any beam to beam interference from 5G mmW is unlikely, due to the geometry of the scenario. In fact any 5G mmW interference to any over-the-rooftop fixed link is unlikely, whether for mobile backhaul or not.
- Where the in-band fixed link is in a higher frequency light licensed band, such as 70/80 GHz it is likely that backhaul for 5G mmW might also be considered in a below the rooftop scenario. An issue occurs since interference between the low level backhaul links (blue) and the user links (yellow) is likely. It would be usual to frequency plan in this case, to avoid conflict. In the light licensed case there exists the possibility for self-coordination, especially if the access and backhaul are jointly managed by a single controlling entity. This would entail modifying the light licence condition in some or part of a band. Nonetheless, where interference occurs there will be coverage penalty to be paid[95].

The third case considers the potential use of HAPs around 47 GHz, see Table 8-2. Operating HAPs in this spectrum may be more practical than operating satellites, so these bands could see future use. HAPs have been on the horizon for some time, as we noted when looking at the potential use of frequencies above 40 GHz for Ofcom in 2007[96]. However, HAPs never came to fruition with the barrier being the aeronautical platform itself, which was not fully feasible. The current Google project Loon is basically a much simplified version that uses weather balloons and Wi-Fi frequencies to communicate. Google also recently acquired a solar powered drone company[97] with a much greater payload capacity, showing that progress is being made against previous aeronautical limitations. Google has obtained an FCC experimental license to test the drones (project Titan), with frequencies of around 2.4 GHz and 900 MHz[98], together with a more recent frequency application thought to be for 24 GHz[99]. In terms of sharing, HAPs is still most often suggested for disaster relief and for bringing coverage to unserved large geographic areas, such as rural Africa. It is thus not expected that 5G mmW and HAPs would be operating in the same area, unless possibly HAPs were used for urban HDTV distribution (following very early HAPs scenarios), although we know of no commercial interest in this area.

8.2.3 **Sharing with PMSE**

There is an allocation within our priority 45.5-48.9 GHz in the UK. However this band saw no assignments in the previous year[100], so sharing may not be a current issue and this band might be cleared and made available to 5G mmW. PMSE is also allocated at 41-42 GHz in Japan, but we have found no information on the usage level. We expect that sharing with PMSE, if it were needed, would be challenging since PMSE use is likely to be in

[95] See, for example, "Point-To-Multipoint In-Band mmW Backhaul For 5G Networks", Taori and Sridharan, IEEE Communications Magazine, January 2015.
[96] "Higher Frequencies for Licence Exempt Applications", Quotient for Ofcom, 2007, available from www.ofcom.org.uk
[97] http://www.telegraph.co.uk/technology/google/10766490/Google-buys-drone-manufacturer-Titan-Aerospace.html
[98] http://www.techtimes.com/articles/15684/20140917/google-wants-to-test-drones-that-deliver-internet-access-in-new-mexico.htm
[99] http://www.slashgear.com/tags/project-loon/
[100] Source: Ofcom.

the same dense urban areas as 5G mmW. Geolocation database sharing would be an option.

8.2.4 Sharing with amateur

We propose that the 6mm Amateur band at 47-47.2 GHz is avoided using an appropriate method as it is in current use around the world.

8.2.5 Sharing with collective use

In any collective use band there is the danger of overuse, even where polite protocols are mandated. A better option than to introduce 5G mmW into an existing band alongside current users would be to open up additional bands to collective use, such as 66-71 GHz, i.e. Option 1 in Table 8-1. This would expand the spectrum available to legacy and new users, with benefits as discussed in Section 8.4.1.

In terms of self-coexistence, the short directional links of 5G mmW are likely to pose a reduced risk of interference on average. Bearing in mind the capacity argument above, it is appropriate to consider 5G mmW within future collective use bands.

8.2.6 Sharing with radio astronomy

There is no radio astronomy use within our priority bands, but we note it is adjacent to one band edge at 48.9 GHz. Suitable methods would need to be used to ensure this band was respected. This might include the use of guard bands and / or geographic exclusion zones.

8.3 Potential opportunities within military bands

Because we could not fully assess their sharing potential, we could not eliminate the military bands as a significant potential source of 5G mmW spectrum during the study.

However, as this study concluded, NATO released an updated version of the Joint Frequency Agreement, which contains more detail than previous versions[101]. This allows satellite uplinks to be identified with more confidence than before, although detailed co-existence studies would still be required. Satellite uplinks of potential interest[102] could include 30-31 GHz and 43.5-45.5 GHz, both paired with 20.2-21.2 GHz. However, both these bands are Class A, meaning that a permanent essential military requirement exists in NATO. In addition, 30-31 GHz has no mobile allocation. We have already proposed priority bands adjacent to 43.5-45.5 GHz, which have wider bandwidth and hence higher priority in our analysis.

Another wide band for NATO use we have noted in a similar range is 33.4 -36 GHz which is used by radars and is unlikely to be useful for sharing, unless geographic separation can be ensured, but we do not have sufficient details to assess this. Again, the bandwidth is not as high as our priority bands.

Finally, there is an MoD band at 39.5-40.5 GHz[103], but this is also allocated to Earth Observation, with which it will likely be challenging to share, plus once again we have identified larger bands elsewhere.

[101] NATO Joint Civil/Military Frequency Agreement (NJFA), 2014.
[102] We discussed NATO bands below 30 GHz in Section 7.2.3.
[103] Not identified as a present or future NATO band.

8.4 Adding new uses to a band

In this section, we consider how new uses could be added to a band in general terms.

At lower frequencies, such as those below 3 GHz, a change of status or usage in a frequency band typically follows a pattern of band clearance followed by an auction. This happened, for example in the 800 MHz band. In some cases, the clearance is partial and the band is auctioned with incumbents or, in a novel approach proposed in the US, an "incentive auction" can be held to simultaneously clear and award the band. This "clear and then auction" approach could be adopted in higher frequency bands, but the lighter use of these bands and the lower probability of interference opens up other possibilities.

One approach could be to simply add a new usage to an existing band – in this case probably "mobile" – and expect the new use to coexist with legacy uses. Studies would typically be performed to determine the feasibility of this in terms of interference potential.

An alternative is to open the band to collective use enabling all to access the band without concern over the type of usage within given parameters. This latter type of approach was followed at 60 GHz. While the history of the band is not fully documented, it appears that in around 2000 the FCC made the band licence-exempt[104] to enable innovation and new services. This eventually led to technologists proposing the band for a high speed variant of Wi-Fi termed WiGig. This development in turn led to calls for the FCC to increase allowed power levels within the band which was done in 2013[105]. There is now widespread expectation that this band will be used predominantly for indoor high speed operation.

8.4.1 General approaches to licensing and sharing

A frequency band can typically be licensed, light licensed or licence exempt / for collective use. Within these categories it can be exclusive or shared. There are multiple approaches to sharing from fixed to dynamic and the sharer can also be licensed, light licensed or licence exempt.

The Ofcom Licence-Exempt Framework Review[106] (LEFR) discussed how, as frequency increases, regimes should tend towards light licensing and then to licence exemption in line with the decreasing likelihood of interference. Specifically, it was suggested that

> "In the 40-105 GHz frequency range, the 59-64 GHz band (currently managed jointly by the MoD and Ofcom) and the 102-105 GHz band (currently unused) should be considered for use by licence-exempt devices."

The LEFR also recommended that polite protocols be adopted in shared bands where devices only transmitted when they needed to, and did so at the lowest possible power levels and with regard for other possible users.

Clearly, many of the bands under consideration for 5G mmW fall within this higher frequency categorisation. We might therefore expect a bias away from licensing, with all interested parties allowed to access the spectrum subject to varying degrees of requirement to pre-register or dynamically avoid creating interference. Such collective use spectrum is inherently shared, and as a result could typically equally well be shared

[104] See, for example, FCC Docket 94-124 and http://www.marcus-spectrum.com/page5/index.html .
[105] FCC Docket 07-113.
[106] http://stakeholders.ofcom.org.uk/consultations/lefr/statement/ .

across applications as well as within applications, although band-specific studies would be needed to confirm this.

However, 5G mmW systems are currently expected to be deployed by mobile network operators (MNOs), at least where they are outdoors. These MNOs have historically preferred licensed spectrum for the certainty of access it provides them and they might be expected to continue to prefer licensed access in these higher bands. Equally, they have recently moved towards using unlicensed spectrum, under three distinct approaches. Firstly, operators have deployed Wi-Fi access points for offload solutions and secondly operators have proposed access to core bands under a licensed shared access (LSA) approach. A third option is licensed assisted access (LAA) where a licensed band is coupled to an unlicensed band.

In LAA, the licensed band is used to provide the control channel and maintain continuity of connection while the collective use band is used opportunistically to add additional resources, such as further downlink bandwidth allowing a faster speed of connection. This partially overcomes the concern about interference in unlicensed bands limiting quality of service since a minimum service level is always provided via the licensed spectrum. It might also allow central coordination of collective use, potentially increasing capacity through intelligent planning although there is as yet little evidence to support how beneficial this might be. It is not clear whether the collective use element should be fully unrestricted in terms of users or have some form of restrictions placed upon access, as in the LSA approach[107]. This has major implications for the continued benefit available from collective use bands into the future, since the way collective use bands are shared might change.

On the one hand, the sharing approaches favoured by the MNOs restrict interference levels by restricting entry, i.e. they employ admission control. A set of licenses to access the spectrum might then be issued, often under auction. How license distribution under LSA or LAA might differ is not yet well defined. On the other hand, proponents of technologies such as Wi-Fi argue that there is substantial demand for unlicensed spectrum usage from consumers and others. If part of a collective use band were to be licensed to operators instead, then this would increase the congestion experienced by the collective users. From a holistic point of view we would suggest that more spectrum is needed rather than a re-partitioning of the current spectrum in a different way. In other words the preference should always be to add more bands where possible. This is directly relevant to our discussion of priority bands, especially 57-66 GHz and 66-71 GHz.

In summary, the question of how access should be granted to a new band at mmW is complex, has limited precedent and may be affected by legacy operational models. It will require consultation and discussion. However, we suggest some guidelines could include the following

- The band does not necessarily need to be cleared since at higher frequencies there is generally more scope for sharing, due to shorter propagation distances, although this is application dependent;
- With substantial bandwidth, short range and narrow beams of radio energy the probability of interference is relatively low making light licensing and licence exemption the preferred approaches;

[107] Such a restriction could be temporary.

- Where greater certainty against unexpected interference is required, light licensing might be preferred;
- A critical question is whether the number of entrants into a new band should be restricted, as is implicit in licensed approaches such as LSA. MNOs and others may not invest in technology development and coverage provision unless they have sufficient certainty of service quality via restricted entry, at least initially;
- A lower or lowest tier of opportunistic dynamic access could additionally be envisaged. This could be allowed where it would not cause interference to the MNOs, or other operators that may emerge. A similar approach is being adopted in the US at 3.5GHz[108].

[108] See our earlier report for Ofcom "Technologies and approaches for meeting the demand for wireless data using licence exempt spectrum to 2022", Quotient Associates , 2013, available from http://stakeholders.ofcom.org.uk/consultations/spectrum-sharing/ .

9 CONCLUSIONS

We have taken a two-pronged approach to identifying potential candidate frequency bands above 6 GHz for future 5G mobile broadband systems.

- Firstly we looked from a physical perspective at barriers and enablers arising from propagation behaviour, technology readiness and the anticipated application scenarios.
- Secondly we looked at the possibilities for sharing spectrum with incumbent services with an emphasis on finding sufficiently wide bands which could be accessed most easily and harmonised most globally.

In terms of the technologies required to make 5G millimetre wave antennas, devices and packages, we found evidence that products up to at least 100 GHz will be available within the next 5 years. Furthermore, we found that the short distances anticipated, of the order of 200m, fundamental limitations such as the effects of gaseous absorption are not a limiting factor up to at least 100 GHz. Therefore neither fundamental nor technology limitations are likely to be the key reason to prefer one millimetre wave frequency over another from 6 to 100GHz. From an application perspective, given that directional antennas will be appropriate at all frequencies above 6 GHz, we note that operating above approximately 30 GHz will enable steerable array antennas to be more easily integrated into handsets. 30-100 GHz is thus an attractive range from physical considerations.

In terms of finding suitable bands for 5G mmW, our method has been to eliminate spectrum which was firstly too small (less than the order of 1GHz) and secondly least attractive for sharing, over the range 6-200 GHz. We identified a short list of five bands which we suggest are suitable for early consideration as 5G candidate bands above 6 GHz with the fewest co-existence challenges[109], as shown in Figure 9-1. All the bands in Figure 9-1 are suitable for consideration for collective use as the interference range is smaller at these higher frequencies.

Rank	*Band, GHz*	*Usage, trend*	*Sharing or clearance required?*
1	66-71	Low or none, fallow	No current use found
2	45.5-48.9 (three sub-bands)	Low or none, fallow	No current use found
3	40.5-43.5	Low, low growth (except in UK - auctioned)	Either clearance of fixed and allocation to mobile; UK auctioned band is already technology neutral, or 5G mmW sharing with fixed;
4	71-76; 81-86	Medium, growing	Sharing with fixed under a light licensed regime
5	57-66	Medium, growing	Sharing under collective use

Figure 9-1 Short list of candidate bands identified

[109] Detailed co-existence work must nonetheless be performed.

The first band is 66-71 GHz which sits above the 57-66 GHz collective use band targeted most recently for high speed indoor applications, for example via the Wi-Fi Alliance's WiGig. Economies of scale may thus be very attractive. Where a future handset includes WiGig by default, then 66-71 GHz, being an immediately adjacent band, opens up the attractive possibility of using a single RF chain to address both bands.

We note that all the bands identified in Figure 9-1 from a sharing perspective are from the range 30-100 GHz. This matches the range identified from the earlier investigation of physical properties, which makes 30-100 GHz attractive for two independent reasons. Although we found that in the range 6-30 GHz it was relatively more challenging to find suitable spectrum, there may still be opportunities in this lower range for 5G bands with a lower bandwidth requirement than 1 GHz per operator.

At the conclusion of the study more information became available from NATO, but this did not alter our findings with respect to the top five candidate bands suggested for priority investigation.

Finally in our work we have identified that while device technologies exist to use high frequencies and that sufficient spectrum is likely to be available, remaining sources of uncertainty include the completeness of the above 6 GHz scenarios and models, and the resulting detailed understanding of how beamsteering will be required to work in practice. It is in this area that we suggest more research is required.

10 RECOMMENDATIONS

We make the following recommendations.

1. A holistic view of the needs of 'above 6 GHz' 5G systems should be taken. Spectrum will be needed for the data plane (e.g. new frequencies above 6GHz), and the control plane (e.g. existing coverage frequencies), as well as the backhaul (existing backhaul frequencies or new frequencies above 6 GHz);
2. More than one new 5G band above 6 GHz may be appropriate to maximise the potential for innovation;
3. The broad range 'above 6GHz' should be split into a number of ranges to enable an efficient and manageable evaluation process, for example at least the ranges 6-30 GHz and 30 -100 GHz, with 'above 100 GHz' if required;
4. Our five priority candidate bands are all in the range 30-100 GHz, nonetheless frequencies in the range 6-30 GHz could be considered with a focus on a lower bandwidth requirement[110];
5. The earlier recommendations from Ofcom's Spectrum Framework Reviews[111] should be followed, by considering the merits of licence exemption / collective use for higher frequency spectrum;
6. Some uncertainties remain over the completeness of the above 6 GHz scenarios and models, and the consequent detailed understanding of how beamsteering will need to be made to work in practice, hence more research is needed in these areas.

[110] Most likely accepting that substantially less 1GHz bandwidth per operator may be realisable, but that this may nonetheless be useful for 5G overall.

[111] Spectrum Framework Review, Licence Exempt Framework Review.

11 ABBREVIATIONS AND GLOSSARY OF TERMS

(B)FWA	(Broadband) fixed wireless access
C/U plane split	Control, user plane separation
EESS	Earth Exploration Satellite Service
EO	Earth observation
ERDS	Space data relay service
ESA	European Space Agency
GNSS	Global Navigation Satellite System
GNSS	Global Navigation Satellite Service
GSA	European GNSS Agency
HAPS	High Altitude Platforms
HDFS	High Density Fixed Service
HDFSS	High Density Fixed Satellite Service
HTS	High throughput satellite
ISL	Inter-satellite links
LE	Licence exempt, a major sub-set of collective use
LEFR	Ofcom's Licence Exempt Framework Review
LOS	Line of sight
MAA	Modular antenna array
MAC	Medium access control
mmW	millimetre wave
NLOS	Non line of sight
RNSS	Radio Navigation Service
SiCMOS	Low cost silicon process
SiGe	Silicon germanium, relatively low cost

SiP	System in package
SoC	System on a chip
WiGig	802.11ad; very high speed short range Wi-Fi at 60 GHz
WP5D	Working party 5D (ITU)
WRC	World radio conference

12 APPENDIX 1: LIST OF SATELLITE BANDS BY LETTER

Band	Frequency, GHz	Up/down	Typical Use
C	3.6-4.2 5.725-7.075	down up	Telephony, data, VSATs
X	7.25-7.75 7.9-8.4	down up	MoD / NATO Class A[112]
Ku	10.7 – 12.75 12.75-13.25 13.75-14.5	down up up	Direct to Home Broadcast Feeder, VSATs Feeder, VSATs
Ka	17.3-18.4 17.3-17.7 17.7-19.7 19.7-20.2 20.2-21.2 (27.5-27.83; 28.45-28.94; 29.46-30) 30-31	up down down down down up up	Feeder (Broadcast) High Density (HDFSS) Shared with Fixed High Density (HDFSS) MoD / NATO Class A (paired with 30-31, 43.5-45.5) High Density (HDFSS)[113] MoD / NATO Class A (paired with 20.2-21.2)
Q	37.5 – 40.5	down	Proposed for High Throughput Satellites
V	47.2 – 50.2 43.5-45.5	up up	Proposed for High Throughput Satellites MoD / NATO Class A (paired with 20.2-21.2)

[112] See NATO Joint Civil/Military Frequency Agreement (NJFA), 2014. Class A describes a permanent and essential requirement.
[113] See discussion of this range in Section 7.2.3.

13 APPENDIX 2 ANSWERS TO SPECIFIC OFCOM QUESTIONS

Ofcom Question	*Response*
Are there any fundamental/inherent frequency constraints of the 5G technologies currently being investigated in industry, academia and other research bodies?	We have split this question into two parts- 1) fundamental, immutable physical constraints and 2) technology constraints which are subject to evolution. In terms of fundamental constraints, the effects of atmospheric absorption, including water and oxygen peaks and the effects of rain are not an issue at the very short ranges considered for 5G access, such as up to 200m, for frequencies up to at least 100 GHz. The amount of bandwidth available at a given frequency is a fundamental constraint, with higher bandwidth naturally being available at higher frequencies, but this is not a limitation to achieving 1GHz bandwidth at 6 GHz and above. This should not be confused with the separate issue of the lower frequencies being already crowded - which may be subject to change by regulation. In terms of technology constraints, we have shown that device, packaging and antenna technologies will be available in product form over the next five years at frequencies up to at least 100 GHz. Thus technology is not likely to be the key reason for the choice of one band over another below 100 GHz. Beamforming will be an essential technology in order to overcome free space loss. Steerability will also be necessary since propagation will involve multiple reflections in the dense urban area; much as would be the case for optical rays. Blocking/shadowing will be an issue, due to buildings, vehicles, foliage and people. Hence taking dynamic advantage of a variety of reflection paths (by steering) and a variety of base stations (by handover) will be key approaches in combating the blocking problem. Despite the above it may be that QoS will suffer during blocking events, since both users and obstacles can exhibit diverse mobility in the dense urban environment. The operation of directional beams in future 5G scenarios is the least researched aspect of 5G mmW and hence the area of highest technical risk.
Are there any optimal frequencies at which 5G technologies are likely to	There is no narrow 'sweet spot' dictated by physical limits or technology below 100GHz. However, user

operate best?	device proportions may limit useful frequencies to around 30 GHz and above, if antenna arrays are to be small enough to fit within a handset. Considering all aspects together, we have found the range 40.5-71 GHz has yielded the three most likely bands for consideration for 5G mmW access with multi-GHz bandwidths. However, we have also noted that opportunities could exist below 30 GHz. These opportunities would not yield the highest bandwidths but may nonetheless benefit the wider 5G system.
What frequency bands are currently being targeted by the 5G community?	A very wide range of bands from 13 – 86 GHz has been proposed for 5G mmW access. There is also interest closer to 6 GHz, but for more conventional, lower bandwidth systems. Backhaul proponents have expressed interest up to 110 GHz.
What sort of spectrum bandwidth will be needed for 5G?	There is good industry agreement that of the order of 1 GHz will be needed with maybe as low as 500 MHz considered if necessary. This would be a per-operator figure in multi-operator scenarios. The premise is that relatively simple modulation may be used with mmW equipment, so a wide bandwidth is appropriate.
Does this bandwidth need to be in contiguous spectrum blocks?	Channel bonding is seen to add significant complexity at mmW, so contiguous bandwidth is preferred. In a multi-operator environment individual bands would not need to be contiguous with each other, but would ideally need to be close enough so that similar propagation conditions apply. We discuss this specifically with respect to 45.5-48.9 GHz.
Will 5G systems in higher frequency bands need nationwide access to spectrum or will they be limited to smaller coverage areas? And if so what sort of geographic areas will be targeted?	Deployment scenarios are not yet fully developed for future 5G access systems, but to date the industry has assumed that the key applications will be outdoors in the dense urban environment. The geographic target areas would thus be cities and transport hubs. These are localised areas and this might make it possible to geographically share with other services, such as radio astronomy, for example. It would also be possible for sharing to be opportunistic and dynamic, such as under the control of a geo-location database.
Will 5G systems in higher frequency bands need dedicated spectrum or	Simple sharing (e.g. via power-based conditions) with existing services such as fixed and satellite is expected

can they share? And if they can, what other types of services are they likely to be most compatible with?	to be challenging in the same geographical area. Sharing of the spectrum above 6 GHz may be easier than sharing below 6 GHz due to the limited range of the systems and the use of advanced antenna techniques with greater directionality. Detailed compatibility studies would be needed to determine whether co-existence is possible between services in particular bands. Dedicated spectrum is considered preferable if available. It is useful to consider that 5G mmW may share very well with itself most of the time, meaning that self-interference is less likely due to highly focussed steered beams in a dense environment with strong shadowing, although worst case interference will be severe when it occurs. This will lead to efficient spectrum re-use, when backhaul is kept out of band. This suggests collective use would be appropriate. Thus, new mmW collective use bands could be created which 5G mmW might access directly. Importantly, this would not preclude other new unlicensed uses, which may not yet have been discovered, thus encouraging future innovation.

14 APPENDIX 3 QUESTIONS AND ANSWERS ON PRIORITY BANDS

Option 1 66-71 GHz	
Colour in band table	White ('other' spectrum[114])
Who are the incumbents?	Little or no activity, but with primary allocations to mobile, mobile satellite, inter-satellite links (ISL), radio navigation and radio navigation satellite.
What do they use the spectrum for (e.g. services offered, technologies deployed, etc.)?	No applications listed in ECA table. Note reads "Future Civil Systems". ESA will investigate 50-75 GHz for future ISL, and this may result in different, non-RNSS bands being chosen. GSA[115] confirms that it does not currently use this band.
How intensively do they use the spectrum?	No current activity identified. May be investigated for ISL in future.
What is the geographic extent of the services they offer (e.g. national, regional, global, etc.)?	None, potentially space to space in future.
What is their customer base?	None, potentially space to space users in future.
What are the options for them sharing spectrum (based on a high level analysis rather than detailed technical studies)?	No sharing required at present. Sharing any future ISL with terrestrial mobile may be feasible, given that coupling loss would be high due to separation distance and frequency. Mobile must not interfere with space.
What flexibility do they have to move to new frequencies?	No requirement for clearance at present. ESA is considering 50-75 GHz for future ISL use but a non-ISL band may be chosen.
International perspective	This band has a mobile allocation in Europe, China, Japan, South Korea and USA.
Comments	This band is 5GHz wide. Therefore several operators could all use 1 GHz bandwidth here. This band is also adjacent to the current 59-66 GHz licence exempt band where the Wi-Fi Alliance's certified WiGig products are produced at low cost. There is thus an opportunity to realise economies of scale.

[114] 'Other' spectrum is not already in use by fixed, satellite, military or exclusive civil users, see Section 7.2.
[115] European GNSS Agency.

	The band could be opened for collective use, with polite protocols.

Option 2 45.5-48.9 GHz (three sub-bands)	
Colour in band table	White ('other' spectrum)
Who are the incumbents?	Little or no activity, but primary allocations to mobile; mobile-satellite; radio navigation; radio navigation-satellite (45.5-47 GHz) mobile; fixed, fixed satellite (47.2-48.0 GHz and 48.4-48.9 GHz) In between these bands, there is a UK PMSE band which saw no assignments in 2014; and the 6mm Amateur band which is in active use.
What do they use the spectrum for (e.g. services offered, technologies deployed, etc.)?	45.5-47 GHz: no use confirmed by GSA for RNSS and the ECA table note reads 'Not allocated'. 47.2-48.0 and 48.4-48.9 GHz may be used for high throughput satellite feeder links (V-band uplink), with user links in Ka band. Possible future HAPs use.
How intensively do they use the spectrum?	45.5-47 GHz: no use identified 47.2-48.0 and 48.4-48.9 GHz: little use or growth anticipated by satellite industry outside 'niche' applications. No current HAPs use.
What is the geographic extent of the services they offer (e.g. national, regional, global, etc.)?	45.5-47 GHz: no use identified 47.2-48.0 and 48.4-48.9 GHz: likely to be confined to gateways or HAPs in rural areas.
What is their customer base?	45.5-47 GHz: no use identified 47.2-48.0 and 48.4-48.9 GHz: satellite / HAPs operators rather than end users.
What are the options for them sharing spectrum (based on a high level analysis rather than detailed technical studies)?	45.5-47 GHz: no use identified 47.2-48.0 and 48.4-48.9 GHz: geographic sharing may be possible since 5G mmW will typically be used dense urban environments and gateways will not, but it will depend on locations and elevation angles.
What flexibility do they have to move to new frequencies?	45.5-47 GHz: no use identified 47.2-48.0 and 48.4-48.9 GHz: little use anticipated or substitution by lower frequencies.

International perspective	Most of 45.5-48.9 has a mobile allocation in Europe, China, South Korea and USA. In Japan, the mobile allocation stops short at 47 GHz. In China we are aware that 802.11aj, the 'China mmW' version of WiGig has recently claimed part of this band (since there is insufficient spectrum at 60GHz).
Comments	In order to increase the bandwidth available to 5G mmW, and since it had no assignments in this band in 2014, UK PMSE could be a candidate for clearance. We note that Vodafone has suggested the wider range 43-47 GHz could be considered for 5G mmW, but 43.5-45.5 GHz is a harmonised NATO band for satellite uplink in current use, with potential for future mobile use.

Option 3 40-5-43.5 GHz	
Colour in band table	Blue (fixed links spectrum)
Who are the incumbents?	40.5-42.5 GHz was harmonised for Multimedia Wireless System (sterile), but the wider band 40.5-43.5 GHz was recently opened to fixed links, including PMP. 40.5-42.5 GHz is also potentially used for Q band feeder downlinks. This band was auctioned in the UK and is technology neutral.
What do they use the spectrum for (e.g. services offered, technologies deployed, etc.)?	The Multimedia Wireless System was not successful, and now has limited recent use for fixed links and point to multipoint (PMP). Q band satellite use is expected to be niche and be restricted to gateways. UK auctioned band is used for backhaul.
How intensively do they use the spectrum?	Less than 100 links in 2011, in CEPT excluding UK. UK usage initially suffered from a lack of equipment, but this has been solved.
What is the geographic extent of the services they offer (e.g. national, regional, global, etc.)?	National

What is their customer base?	Operators for backhaul, end users for PMP, although PMP has migrated to below 6 GHz in general.
What are the options for them sharing spectrum (based on a high level analysis rather than detailed technical studies)?	Fixed systems are used as backhaul for mobile and thus potentially for 5G mmW access. Operating both access and backhaul in-band is unlikely to be acceptable without some form of co-ordination. This could be geographic separation, band segmentation or it could be self-co-ordination where an operator has exclusive control over a band, e.g. an auctioned band in the UK.
What flexibility do they have to move to new frequencies?	This fixed link band had little use as of 2011, although it was opened only in 2010; if clearance is desired there are opportunities in other licensed fixed link bands. There is no need to clear MWS as it was not exploited anywhere in Europe. In the UK, the band was auctioned.
International perspective	40-5-42.5 GHz has no primary mobile allocation in Europe, although it is at least secondary in Region 1, China, South Korea, Japan and USA. 42.5-43.5 GHz has a mobile allocation in Europe, China and South Korea, although not in Japan or USA.
Comment	Despite 40.5-42.5 GHz having no mobile allocation in Europe, we suggest there is justification for it to be considered for 5G mmW access, since this is in many ways the modern replacement for the Multimedia Wireless Service, which had been harmonised in this band but was not successful in the marketplace.

Option 4 71-76; 81-86 GHz	
Colour in band table	Blue (fixed links spectrum)
Who are the incumbents?	Backhaul and inter-building link providers.
What do the use the spectrum for (e.g. services offered, technologies deployed,	A wide range of services under a light licence regime with partial co-

etc.)?	ordination, achieving Gb/s speeds – the fastest available fixed links. Example uses include mobile operators for backhaul, local authorities, broadcast and utility companies.
How intensively do they use the spectrum?	The popularity of the 'light licensed bands' is increasing due to the lowering cost of components and systems.
What is the geographic extent of the services they offer (e.g. national, regional, global, etc.)?	The key applications are most prevalent in dense urban areas, exactly as 5G mmW access will be.
What is their customer base?	As for licensed links, but with enhanced ease of access for end users.
What are the options for them sharing spectrum (based on a high level analysis rather than detailed technical studies)?	Fixed link users generally demand very good reliability, so in general sharing with a mobile service where a base station or handset is not restricted from interfering with the fixed link path is unlikely to be acceptable. A significant difference in light licensed bands is that there may be more opportunity for self-coordination by the community of licence holders. Recent studies have shown that this is possible, although there are capacity penalties to be paid[116]. Alternatively given that fixed link users want assured performance (viz. the recent management changes in the UK), it may be more appropriate to set aside a segment of the band where access and backhaul links may be operated together under an evolved light licence regime. This might be easiest where fixed and mobile operate under the control of a single entity in an independent band or portion of a band.
What flexibility do they have to move to new frequencies?	The alternative is to use licensed fixed link bands at lower frequencies, but this might be an imperfect substitute specifically resulting in unacceptably lower bandwidth links and generally less

[116] Taori and Sridharan, "Point-to-Multipoint In-Band mmWave Backhaul for 5G Networks", IEEE Communications Magazine, January 2015.

	innovation overall.
International perspective	These bands have a mobile allocation in Europe, China, Japan, South Korea and USA. The light licensing regime is widely applied to these bands.
Comment	There is a wide bandwidth at 70/80 GHz. so band segmentation might be feasible to support extending the self-coordination concept to include mobile. 5G mmW is likely to be TDD which may not match the current usage of these bands.

Option 5	***57-66 GHz***
Colour in band table	Green (licence exempt spectrum)
Who are the incumbents?	Collective use. The band is free to enter for any system which meets the rules, therefore there are no true incumbents – all are subject to change.
What do the use the spectrum for (e.g. services offered, technologies deployed, etc.)?	It is expected that the Wi-Fi Alliance's WiGig certified products will be significant occupants of this band. These products address Gb/s links over short range; fixed or mobile indoor and mobile outdoor.
How intensively do they use the spectrum?	There is a large interest in this band for Gb/s short range links; intensive use is expected to develop.
What is the geographic extent of the services they offer (e.g. national, regional, global, etc.)?	These are short range links, but which may be deployed anywhere.
What is their customer base?	End users.
What are the options for them sharing spectrum (based on a high level analysis rather than detailed technical studies)?	This is a collective use band and sharing is mandatory in accordance with the rules. Operation is on a non-interference and non-protected basis.
What flexibility do they have to move to new frequencies?	There is no alternative licence exempt band which has such wide bandwidth. This band has strongly driven innovation. Attempting to clear a

	collective use band would be highly challenging, not least as there is no record of users.
International perspective	Global harmonisation of much of this band is excellent.
Comment	In any unlicensed band there is the danger of overuse, even where polite protocols are mandated. A better option than to introduce 5G mmW into this band alongside current users would be to open up the 66-71 GHz band to unlicensed use in addition (Option 1 above). This would expand the spectrum available to legacy and new users.