Vodafone Response to Ofcom Call for Input:

Spectrum above 6 GHz for future mobile communications

SUMMARY

Vodafone welcomes the opportunity to comment on Ofcom's call for Input on spectrum above 6 GHz for future mobile communications. This will provide valuable information to inform the development of an agenda item for WRC-19, which will be approved at WRC-15 this coming November. For this agenda item to gain acceptance at WRC-15 and for there to be a successful outcome at WRC-19, Vodafone believes that it will need to focus on a limited number of frequency bands from the outset.

Mobile industry studies on 5G are still at an early stage. There is still much investigation needed on the technical and economic potential of mm-waves to contribute to the vision of 5G (mm-waves are frequencies above around 25-30GHz). However, one thing is already clear: there is much more to 5G than a new mm-wave radio interface. In particular, there will continue to be a need for a 'coverage layer' below 6GHz. It is not yet clear whether this will be an evolution of LTE or a new radio interface, but, particularly for the latter option, there will need for significant extra spectrum below 6GHz to maintain a high quality and consistent user experience beyond the areas served by mm-waves.

In Europe, CEPT will develop the regulatory framework for new 5G frequency bands following WRC-19. They will not be available for use until 2022 at the earliest (if the band is vacant) or perhaps until 2025 if existing users need to be relocated. We therefore envisage that 5G services will initially be offered using lower frequency bands. If further spectrum cannot be released below 6GHz, then the 5925 – 8500MHz band should be seriously considered as an alternative.

For mm-waves to form a successful component of 5G, it is essential that there is a common global implementation in devices. To achieve this, all the bands must be within the frequency range that can be implemented in a single RF subsystem – which is around 30% of centre frequency. There may also be synergy benefits from a common implementation with IEEE 802.11ad. The 43.5 - 47GHz and 51.4 - 52.6 GHz bands meet these criteria, and also appear to be lightly used at present.

Vodafone participates in NGMN and other bodies that are developing visions for 5G. We aim to influence these visions to meeting the needs of mobile operators and their customers in Europe; these needs are sometimes significantly different to the perspectives from other parts of the world. We would be happy to share our insight with Ofcom to assist it in developing its thinking on 5G for WRC-15 and beyond.

SPECTRUM ABOVE 6 GHZ FOR FUTURE MOBILE COMMUNICATIONS

1 INTRODUCTION

This Call for Inputs is looking a decade and more into the future on the potential for higher frequency bands to support mobile services. It covers a very wide range of frequencies, from a lower limit that is only marginally above the 5GHz WiFi band to an upper limit at which there is barely any current commercial use. There is an equally wide range of potential technologies that might be used, and the radio propagation characteristics of the mm-wave mobile environment are not well understood. A key factor in the suitability of particular frequency ranges for 5G is the feasibility of implementing the antenna and RF circuitry in consumer devices.

The short period of this Call for Inputs has not allowed us to fully answer all of the questions. We would be happy to meet with Ofcom to discuss them in more detail.

2 KEY MESSAGES

1 There is much more to 5G than mm-waves, or "bands above 6GHz"

5G needs to deliver more than a new air interface operating in new spectrum. In order to address the emerging business opportunities, 5G is being conceived as an entire end-to-end system built on the principles of network function virtualisation, software defined networking and cloud computing. Whilst 5G is likely to include a new air interface waveform in order to address certain requirements this is only one aspect to consider.

2 To be successful, 5G will also need to be deployed in lower frequency bands

For the new services enabled by 5G to be delivered across a meaningful geographical area on a cost effective basis, 5G will also need to be deployed in lower frequency bands.

3. 5G will encompass new network topologies extending beyond the traditional cellular model

In considering the frequency bands necessary to support 5G, it should be recognised that some important use cases are likely to require direct, short range communication between devices operating in concert with wide area cellular infrastructure.

4. The emergence of WiFi and automotive technology to support mm-wave frequencies should not be ignored

Technology based on Wi-Fi 802.11ad and automotive radar is already emerging and will drive initial volumes in mm-wave ICs several years in advance of 5G being available. The economies of scale from which 5G could benefit may lead to a convergence of standards and an opportunity to minimise the number of frequency bands needed above 6GHz. This would in turn minimise the additional radio frequency components it would otherwise be necessary to incorporate into 5G mobile devices.

5. The propagation characteristics of mm-wave are not yet understood

At this stage, relatively little is known of the propagation characteristics for mm-wave frequencies. There are no industry standard channel models and very few measurement results are available in the literature. For example, the ability of mm-wave frequencies to effectively provide indoor coverage from outdoor cell sites requires a lot more study.

3 THE MM-WAVE LANDSCAPE FOR 5G

A substantial amount of research is currently underway on the potential of mm-waves to deliver mobile services on both technology development and trials. It is difficult to predict the outcome of this research, but this is necessary to make some assumptions in order to meaningfully respond to this CFI. In this section, we describe the assumptions that we have used in developing this response, which combine physical limits, interpretation of studies to date and technology predictions.

Free space path loss as a function of frequency

For free space propagation from an isotropic antenna, the radiated power spreads out equally in all directions. The path loss at a particular distance therefore equals the area of the effective aperture of the receive antenna as a fraction of the surface area of a sphere at that distance.

The aperture of an isotopic antenna is fundamentally related to the wavelength; it is therefore proportional to the inverse square of the operating frequency. The free space path loss therefore increases by 6dB for each doubling in frequency, or by 25 – 34dB between 2GHz and the mm-wave bands considered in the CFI (36GHz to 100GHz).

An antenna has 'gain' if its aperture is larger than an isotopic antenna, which fundamentally means that it is also directional – the higher the gain, the more directional it is (for example, an antenna with a gain of 20dB has a beamwidth of around 10 degrees).

Antenna characteristics of mm-wave terminals

A smartphone is roughly the same size as the aperture of an isotropic antenna at 1GHz. The antenna structure in the phone couples into the metallic structure of the phone, and the radiation is roughly isotropic (the effective aperture will be less, because mobile phone antennas are not perfect radiators).

A mm-wave antenna will almost certainly be an array of patch elements (or similar), which are individually far smaller than the phone. The phone will therefore behave as a ground plane for these elements. They can only capture or emit signals over a relatively narrow angle (roughly, a cone with an angle of ±45 degrees away from the antenna).

It is likely that a device will probably have only one mm-wave antenna structure, on its rear face, for both cost and form-factor reasons For most smartphones, the display occupies the entire front face; if the phone had antennas on its sides, these would have a small aperture, and thus a high free space path loss.

Propagation in a mobile environment at mm-wave frequencies

As well as the free space path loss, there will be additional attenuation due to reflections, scattering, diffraction and absorption though materials like walls and window glass. There is a reasonable amount of data for the current mobile and WiFi bands, which shows a rising trend in the frequency range from 2GHz to 6GHz. The limited data that is available for mm-wave bands suggests that this trend of increasing loss continues to the mm-wave bands.

One new factor will become significant at mm-waves, the special distribution of multipath components. This is not important for the existing mobile bands, because the terminal antennas are largely isotropic and will capture the strongest multipath components, whatever angle they arrive from. However, if the mm-wave antenna in a terminal has a limited angle over which it can capture energy, it will not necessarily capture the strongest components (for example, if the antenna in the phone is pointed away from the base station or a window). This is equivalent to an additional path loss for reliable service.

4 ANSWERS TO QUESTIONS

As the frequency increases and the cell size shrinks, there is an increasing potential for sharing of network elements and spectrum between operators. It is therefore not clear at this time whether mm-wave networks will be dimensioned for peak bit rate, or will be capacity limited. Because of these factors, it is more meaningful to answer these questions for the spectrum needs *per network*, rather than *per operator*.

This applies particularly to questions 3a) and 5d).

Question 1: Are there practical ways of achieving the very high performance that use of wide channels above 6 GHz could offer, for example using carrier aggregation of lower frequency?

This question frames the problem the wrong way round. Wide channels will be needed for the services envisaged for 5G. If there was an unlimited supply of spectrum, then it would be desirable for these wide channels to be at lower frequencies (apart, perhaps, from the perspective of frequency reuse, which is dependent on deployment environment). However, the supply of spectrum is far from unlimited, so it is generally assumed that these channels will need to be at higher frequencies than is technically optimal.

Carrier Aggregation

Carrier aggregation has two distinct purposes:

- To create wider contiguous channels within a single band
- To enable fragmented spectrum to be used more effectively.

The widest bandwidth that Vodafone has in its spectrum holdings in UK is 2 X 20MHz in 2.6GHz band. We expect that wider bandwidths will be needed to efficiently deliver the services that are envisaged for 5G. The 5G technologies developed for existing bands (and for new bands below around 6 GHz) will have wider bandwidths than the maximum of 20MHz for LTE. However, it should be a decision for operators whether to deploy multiple aggregated LTE carriers or a single 5G carrier.

Carrier aggregation of multiple bands is a solution to the spectrum management problem of fragmented mobile bands. It degrades the performance of devices and in many cases increases the cost of the RF components. This limits the number of bands and the combinations that can be supported in a terminal. Some combinations for aggregation of bands are mutually exclusive, so carrier aggregation can compromise the potential for global harmonisation and roaming. Carrier aggregation should therefore not be regarded as an alternative to seeking a small number of wide contiguous bands for future mobile services such as 5G.

Benefits of Lower Frequencies

Mobile networks are becoming progressively more heterogeneous in their architecture, and this trend will continue with 5G. We expect that there will continue to be a need for a wide area coverage layer, to provide ubiquitous coverage and reliable service to high mobility users. Mobile operators currently use the 2GHz band or lower for their coverage layer, and the 800MHz auctions in UK and elsewhere have shown the desirability of spectrum below 1GHz for this purpose. The benefits of lower frequencies for the coverage layer are due to constraints of technology and radio propagation. While the technology constraints will diminish over time, those due to propagation will not. We therefore expect that there will continue to be a need for a coverage layer for 5G, at frequencies well below 6GHz.

It is likely that 5G networks will first be widely deployed in Europe in the early years of the next decade. By this time, the mobile bands currently licensed to MNOs will all be heavily utilised, mostly by LTE. Like previous mobile generations, the 5G service will need to start with a coverage layer. It will not be possible to clear enough spectrum from the existing mobile bands to deploy a 5G carrier with enough bandwidth to provide a good user experience – good enough to encourage customers to adopt 5G. It is therefore fundamental to the success of 5G that sufficient spectrum can be made available for this coverage layer in this timeframe, below 6GHz.

Question 2: What recent or emerging advances in technology may provide effective solutions to the challenges in higher frequency bands? For example can increased propagation losses be mitigated by using the high gains available with massive MIMO?

As discussed under question 4, we expect that the fundamental technology building blocks will be available by around 2020 for mm-wave frequencies up to at least 60GHz.

As the question identifies, a key issue in the feasibility of mm-waves for mobile is increasing the gain of the base station and device antennas, which equates to increasing their effective aperture. A mm-wave antenna would need to contain many hundreds of elements to have a comparable aperture to a typical handheld terminal operating in the current mobile bands. If this antenna employed beam steering, its beamwidth would be less than four degrees, and it could only capture energy arriving from the base station within this angle. MIMO is a technique to enable an antenna array to simultaneously capture a number of components with different angles of arrival.

Massive MIMO is usually considered as a means to enhance capacity, and it is usually assumed that it will have one transmit and receive chain per antenna element. It will not be feasible for a terminal to contain many hundreds of mm-wave transmit and receive chains, so some means will need to be found to reduce the MIMO complexity.

In a mobile environment, the received signal consists of a number of multipath components, due to reflections and diffraction from objects in the region between and around the transmitter and receiver. These have different (and fluctuating) powers and angles of arrival. There is almost no data available on the characteristics of this multipath propagation, in terms of the number of multipath components and the range of angles of arrival.

It is therefore not yet possible to assess what complexity of massive MIMO would be needed in a mm-wave terminal, and how efficiently this could capture the transmitted power – particularly as a single mm-wave antenna array is only likely to have an acceptance angle of around +/- 45 degrees.

Question 3 a): Are there any fundamental/inherent frequency constraints of the 5G technologies currently being investigated with regard to: minimum contiguous bandwidth per operator?

The bandwidth needed per network is the combination of the bandwidth per channel and the number of layers in the network. The bandwidth of a channel is the combination of the bit rate and the spectrum efficiency.

The spectrum efficiency of the LTE radio interface is already very close to the Shannon limit, for a single radio path with particular properties. The improvement in spectrum efficiency for 5G will therefore come from techniques that increase the number of parallel radio paths (e.g. MIMO) or improve the typical properties of a link (e.g. CoMP). However, there are limits in what can be achieved, due to constraints on complexity of base stations and terminals, and on the network architecture.

Vodafone believes that the bit rates for 5G should be defined in terms of what a user will need to obtain a consistent experience for the services that they wish to use (also called the "User Experienced Bit Rate" in ITU and "Sufficient Bit Rate" in some UK discussions). The peak bit rate has only a tenuous connection to user experience, and it can drive the technical solution towards a high requirement for spectrum.

These factors are all subject to uncertainty but, taking all of them into account, Vodafone would concur with the conclusion of NGMN in its White Paper (due to be published shortly):

> "[Higher] frequencies are needed to allow very wide bandwidth channels to support very high data rates and short-range mobile connectivity (e.g. a total of 500 - 1000 MHz of contiguous spectrum per network to support the multitude of services …) Total spectrum requirements should take in to account the potential need to accommodate multiple networks."

Question 3 a): Will the spectrum for multiple operators need to be contiguous (i.e. a single band) or could multiple operators be supported through multiple bands?

As the operating frequency increases, the RF components and the antenna will need to be more closely integrated in order to achieve good performance. The importance of this close integration increases with the number separate RF chains, which also increases with frequency. The mm-wave technologies and antenna structures currently envisaged for 5G probably have a maximum bandwidth of around 30% of centre frequency (in comparison, the maximum bandwidth of an RF chain in current terminals is around 25%, and most terminals have three RF chains and antenna structures).

Therefore, the frequency range of all the bands identified for 5G in the mm-wave region should be within around 30% (in terms of centre frequency), otherwise terminals will need to have multiple mm-wave subsystems in order to support roaming between operators and regions of the world.

Question 3 b): Are there any fundamental/inherent frequency constraints of the 5G technologies currently being investigated with regard to: frequency range over which the technologies are expected to be able to operate, for example due to propagation, availability of electronic components, antenna designs and costs of deployment?

Given the likely scale of 5G product development, we anticipate that the challenges in technologies and components can be addressed for frequencies up to at least 60GHz. As discussed in Section 3 on the mm-wave landscape for 5G, the number of antenna elements needed for a particular antenna aperture increases with the square of the operating frequency. While the number of RF paths will probably not increase as rapidly, it is likely that the overall complexity of the RF circuitry will be higher at higher frequencies. However, as discussed above, there is likely to be a practical limit for number of RF chains.

It is likely that the 5925 – 8500MHz frequency band would have synergy in terminal design with the existing mobile bands, but the RF chains for the mm-wave bands would be completely separate.

It is generally predicted that video will form a large proportion of mobile traffic in the future. People tend to consume video when they are indoors, or while in moving vehicles. Therefore, two key factors in the choice of frequency are the ability to penetrate into buildings from outdoor base stations and to support mobility. Both of these factors favour a frequency closer to 6GHz than 100GHz.

There is unfortunately, very little data on mm-wave propagation into and within buildings – especially houses (university and industrial labs are far better characterised). However, what data there is suggests that the attenuation rises with frequency. This suggests that a cell on a frequency closer to 6GHz would probably be able to take a greater proportion of the mobile traffic, and relieve the pressure on the bands below 6GHz. The data also shows a substantial variation in attenuation with the type of building construction, including aspects that are almost invisible such as whether the windows have heat reflecting glass (which uses a metallic coating). Therefore, trials and demos using a single building or buildings of a single type need to be treated with some caution.

The IEEE has developed a standard for WiFi-like applications that operates in the 60GHz band, 802.11ad. This is already beginning to appear in audio-visual products, and is likely to be in terminals by 2020. There will be synergy benefits if this can share an RF chain with 5G, which means that the 5G band would need to be within 60GHz +/- 30%[1].

Question 4: Will 5G systems in higher frequency bands be deployed, and hence need access to spectrum, on a nationwide basis or will they be limited to smaller coverage areas? And if so, what sort of geographic areas will be targeted?

Given the expected size of mm-wave cells, they are very unlikely to be deployed on a nationwide basis. We expect that the deployment will be targeted at hot spots and high density traffic areas. For an ecosystem to develop for the mm-wave component of 5G, it will need to be something that people use in their daily lives, not only in specific locations. As mentioned in question 3, the majority of 5G traffic is expected to be video, and this is a service that people generally consume indoors. Therefore, it will need to provide reliable indoor service from outdoor base stations.

Question 5 a): To what extent will 5G systems in higher frequency bands need dedicated spectrum on a geographical and/or time basis or can they share?

We expect that 5G systems will offer greater potential for spectrum sharing in higher frequency bands, not only geographically and in time, but also through angular discrimination of antennas.

Geographical sharing

As 5G at mm-waves is likely to be deployed in urban areas, geographic sharing will be possible with services that have complementary geographic deployment.

Time sharing

It is unlikely that the traffic on the mm-wave 5G will predictable enough to provide a worthwhile benefit from scheduled sharing with other services. However it is likely that there will be a statistical benefit.

Angular discrimination

In order to achieve an adequate link budget, the 5G mm-wave system must direct the transmit power towards individual terminals rather than over a wide angle – and this is also a fundamental property of the antennas that are likely to be used.

The directive properties of transmissions in the higher frequency bands will improve the coexistence with other services, most of which will themselves use highly directional antennas. For coexistence with other terrestrial services, the benefit is likely to be statistical. However, for coexistence with satellite services, there will be a guaranteed benefit because the satellite antennas always have a vertical elevation angle.

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[1] This is only the case for TDD or half duplex FDD, because the duplex filter needed for full duplex FDD would limit operation to a single paired band.

Question 5 b): If they can share, what other types of services are they likely to be most compatible with?

Obviously, it will be easiest for 5G to share with services that have complementary geographic coverage and/or low density of usage.

Many services in the mm-wave bands will have directional antennas. This will provide mitigation that may be statistical or guaranteed, depending on the relative orientations of the antennas – see the answer above.

Question 5 c): What technical characteristics and mitigation techniques of 5G technologies could facilitate sharing and compatibility with existing services?

See above.

Question 5 d): Could spectrum channels be technically shared between operators?

The greater potential for spectrum sharing, discussed above, would also apply to spectrum sharing between mobile networks.

Question 6 a): Given the capacity and latency targets currently being discussed for 5G how do you anticipate backhaul will be provided to radio base stations? Are flexible solutions available where the spectrum can be shared between mobile access and wireless backhaul?

The trends already underway for backhaul are expected to continue:

- Replacement of the trunk network with fibre, so that wireless backhaul will be mainly be used for the final hop to base stations.
- Moves to higher frequency bands, where greater capacity is available
- Technologies that enable non-line-of-sight links in urban environments
- ‘Fronthaul’, where a number of remote RF heads are connected via wireless or fibre links to a common baseband processor.

Solutions are already being developed that meet the latency targets being discussed for 5G. Therefore, the main latency constraint on the backhaul will be its physical length, and not the technology used.

We expect that solutions will be developed that enable spectrum to be shared between mobile access and backhaul. However, this is likely to reduce the capacity for access to some extent. Therefore, the feasibility of these solutions will depend on the amount of spectrum that can be made available for 5G and the deployment scenario.

Question 6 b): What, if any, spectrum will be required? What channel sizes will be needed? Will the bands used be similar to those currently used for wireless backhaul?

The growth in demand for mobile traffic will produce a corresponding increase in demand for backhaul. It is unlikely that all of this demand could be satisfied by wireless backhaul, but much of this increase in traffic will be carried by fibre.

Some of the techniques to increase spectrum efficiency of mobile networks require very high data rates between network nodes, which can really only be supported efficiently by dark fibre. Access to dark fibre on an Equivalence of Input basis (particularly from Openreach) will allow mobile operators to deploy these techniques, which will reduce the demand for spectrum for both mobile access and backhaul.

Question 7: Should we expand the scope of bands being reviewed beyond the 6-100 GHz range?

Vodafone believes that further spectrum will be needed at lower frequency bands in order to realise the vision for 5G. This should preferably be below the 5GHz WiFi bands, but the 5925-8500MHz frequency range might be an acceptable substitute.

Vodafone therefore welcomes the belief of Ofcom, as expressed in its "Update on the UK preparations for the World Radiocommunication Conference 2015" that there is merit in further investigating the 3 800 – 4 200 MHz band for mobile broadband and/or IMT identification beyond WRC-15. It is important that any bands that are 'carried forward' from WRC-15 to WRC-19 are considered in a holistic way together with bands above 6GHz in the proposed new agenda item.

Question 8: Do you agree that it is likely to be necessary for bands to have an existing allocation to the mobile service? Does this need to be a primary allocation?

Within the frequency range of 20GHz to 55GHz, 20.55 GHz of the spectrum has a primary allocation to the mobile service. This, taken by itself, suggests that there is no need to consider any other bands in order to find sufficient suitable spectrum for 5G. However, 83% of this spectrum is also allocated to the fixed service, and a substantial part of this is used for mobile backhaul, and the demand for backhaul will rise with the growth in mobile traffic.

43% of the mobile spectrum is also allocated to the Fixed Satellite Service and 15% is also allocated to passive services, and the coexistence of these services with 5G has not yet been studied.

We therefore anticipate that bands with an existing mobile allocation should be investigated first, and we recognise that this will inevitably include bands that are currently used for mobile backhaul. The growth in mobile traffic will inevitably increase the need for backhaul. Therefore, these bands could only be used for 5G if alternatives are available. Ofcom can assist in this by facilitating the availability of dark fibre (see the response to Q6b).

A band does not need to have an existing mobile allocation in order to be considered - other bands should not be ruled out if they are under-utilised or the existing use would have coexistence or synergies with 5G. For example, we note a recent article by Geoff Varrell of RTT proposing the 77-81GHz band on this basis[2].

Question 9: Do you agree with the criteria we have used for our initial filter of bands, and are there other criteria that could also be used?

Yes. These criteria are appropriate for this initial filter.

Question 10: Of the spectrum bands/ranges mentioned in this section, are there any that should be prioritised for further investigation?

As discussed previously, there will be a need for additional spectrum for a wide area coverage layer. If this cannot be found below 6GHz, then the only band with significant potential for this aspect of 5G is the 5925 – 8500MHz. Therefore, this band should be prioritised for further investigation.

In our response to the Ofcom consultation on Preparations for WRC-15, Vodafone suggested further investigation of the 43.5 – 47GHz band, because this is one sizeable band that does not have a co-primary allocation to the fixed or fixed satellite services.

The 51.4 – 52.6GHz band also looks to have potential for 5G. This band is allocated to the fixed and mobile services, but the CFI indicates that this band is not used at all for fixed links in UK. The figure in paragraph A5.51 of the CFI shows space science in this frequency range, but the Footnote 10 of the UK FAT shows that there is no usage of this band by radio astronomy, and there would be no protection if there was usage.

We expect that the 72 – 77GHz and 81 - 86GHz bands will be needed for wireless backhaul. However, there may be potential for also using them for 5G access – provided that this usage is complementary.

Question 11: Are there any bands/ranges not mentioned in this section that should be prioritised for further investigation?

See the comment under Q8 in relation to 77-81GHz.

Question 12: Are there any particular bands/ranges that would not be suitable for use by future mobile services?

We are not aware of any technical factor that makes a part of the 6-100GHz range unsuitable for mobile use. However, lower frequencies are generally more suitable for mobile services, provided that sufficient bandwidth is available.

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[2] Automotive Radar; RTT Technology Topic, February 2015; http://www.rttonline.com/tt/TT2015_002.pdf

For the licence-exempt bands around 60GHz, the current technical conditions would make them less suitable for some of the applications envisaged for 5G.

Question 13: What additional information, beyond that given in Annex 5 would be useful to allow stakeholders to develop their own thinking around spectrum options?

To help Vodafone develop its thinking on spectrum options on the nature, we would appreciate more information on the nature and extent of the existing uses, in order to assess the potential for spectrum sharing.

The CFI document already provides information for fixed links and satellite services, though it would be helpful for Ofcom to provide a breakdown on the proportion of the assignments in urban areas. However, the CFI has less information on other bands, particularly those with public sector use. We appreciate that it may be difficult to provide detailed information on some of these uses, but we would encourage Ofcom to work with the relevant Government departments to make some information available.

It would be helpful for Ofcom to provide more information on the status of the different types of use for each frequency range. For example, in the 51.4 – 52.6GHz band, space science is illustrated equally with the fixed service, but Footnote 10 of the UK FAT shows that there is no usage of this band by radio astronomy, and there would be no protection if there was usage (see the response to Q10).

Question 14: What are the most important criteria for prioritising bands going forward?

Vodafone sees the following criteria as most important:

1) The technical suitability of the band for delivering mobile services (including propagation).

2) Availability of the band, in particular the extent of use by the current services/licensees.

3) Potential for sharing with those services.

4) The bands for public mobile services should be considered in a holistic way, without an artificial boundary at 6GHz, so that the demand for 5G services can be met in rural areas as well as urban.

5) The potential for global harmonisation

6) If more than one higher frequency band is needed to satisfy the predicted future demand for mobile spectrum, the proximity of the bands to allow common implementation in terminals.

Most of the bands with a mobile allocation also have a fixed allocation and are used for mobile backhaul in some or all European countries. Many of the links cannot be easily replaced by fibre. It is therefore important to gain an understanding of the importance of each band for backhaul across Europe and beyond.