Use of C-Band (3400/3600-4200 MHz) for mobile broadband in Hungary, Italy, Sweden and the UK

A report for
Ericsson, Huawei and Qualcomm

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About Plum

Plum offers strategic, policy, regulatory and technical advice on matters relating to the use of spectrum and to the telecommunications, online and audio-visual media sectors. A London-based partnership founded in 2007, it works for governments, regulators, service providers and equipment suppliers around the world. Its advice is based on economic analysis and technical knowledge of radio engineering, which it combines with extensive market knowledge of the communications sectors to provide clear and sound analysis.

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Acknowledgements

This report considers the economic benefit of bringing forward the availability of spectrum in the range 3400/3600-4200 MHz for mobile data services in a number of European countries[1]. To derive the benefits we used data for the incumbent services in the band sourced from the regulator in each of the study countries. Where the data is in the public domain it is reproduced in the report. Where the data is confidential it does not appear here and we only show the results of our analysis. This is the case for Italy where only a part of the data can be published and Sweden where all the frequency data is confidential.

To quantify the amount of spectrum available to the mobile broadband service, certain spectrum sharing approaches are assumed with the incumbent satellite and fixed link services. The actual sharing mechanisms will be specified by the national administrations and may be more refined than those assumed for the purposes of this study. As a result, the estimates of available spectrum are likely to be conservative.

This report makes use of data on C Band satellite and fixed link installations in the UK obtained from Ofcom. All of the calculations utilising this data are Plum's and it should be noted that while Ofcom has provided the data it does not endorse the results or conclusions.

The results for Sweden are based on a sample of mobile network data and an estimate of the limited use of FSS obtained from PTS. The subsequent calculations have been carried out by Plum, and it should be noted that PTS has neither reviewed nor endorsed the methodology, results or conclusions.

Plum would like to acknowledge the assistance of Fondazione Ugo Bordoni (FUB) who undertook the technical analysis for satellite earth stations and fixed links in Italy.

[1] The lower bound of the frequency range (i.e. 3400 MHz or 3600 MHz) depends on whether the administration has already allocated the frequency range 3400-3600 MHz for mobile broadband services

Executive summary

This study commissioned by Ericsson, Huawei and Qualcomm provides an independent assessment of the economic benefits that would arise through use of C-Band spectrum (3400/3600-4200 MHz) for mobile broadband services in Hungary, Italy, Sweden and the UK.

Mobile broadband traffic is forecast to grow rapidly over the next 10-15 years. It is possible that there will be a spectrum shortfall unless sufficient spectrum is made available to avoid operators having to make costly investments in infrastructure to support this traffic growth. The 3400/3600-4200 MHz frequency range could be used to provide additional capacity to address this shortfall. It will reduce the costs of service provision and improve quality of service.

3400/3600-4200 MHz is currently used by several incumbent services including fixed satellite service earth stations (FSS-ES) and the fixed service (FS) – fixed links (point to point and point to multi-point). This report considers the economic benefit arising from the early release of spectrum in the 3400/3600-4200 MHz frequency range for mobile broadband services.

National sharing frameworks and the use of LSA

In order to make 3400/3600-4200 MHz available for mobile services while at the same time protecting incumbent services, administrations need to establish national frameworks for spectrum sharing between Mobile/Fixed Communication Networks (MFCNs) and the existing Fixed Satellite Service (FSS) and Fixed Service (FS). In this report we have applied in particular two spectrum sharing approaches as described below:

- The use of a link performance aware frequency sharing scenario (determines an appropriate margin to mitigate interference from IMT services); and
- An advanced frequency sharing scenario (which makes more efficient use of the accessible bandwidth for the FSS ES).

These sharing mechanisms may be implemented through the Licensed Shared Access (LSA). The LSA system architecture specification including interfaces between the various spectrum sharing functions[2], are being standardized at ETSI. Since LSA requires close cooperation between the incumbent and the LSA licensee, LSA may enable more advanced sharing than what is possible through existing regulatory mechanisms.

Demand for mobile broadband

In a world powered by demand for information, access to the internet has become increasingly important. Advances in access technology have made accessing the internet over a mobile device a reality, resulting in a rapid growth in mobile data traffic. Coverage has been the focus of much network deployment to date but as demand for data increases and user expectations of performance increase there is a need to focus more on capacity provision and quality of service to provide a more consistent user experience.

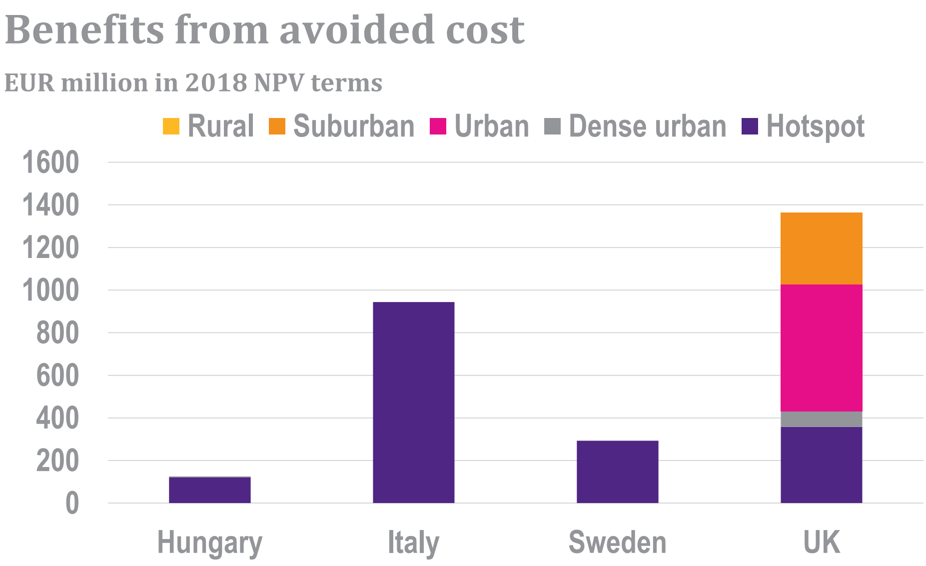
[2] The actual application of LSA in each country would be dependent on the spectrum licensing regime in each country

The traffic demand forecast used for the countries studied was derived by extrapolating the Cisco VNI 2014 short-term (2012-2018) projection to 2028. Where a Cisco forecast was directly available for a study country we used this. Where one was not available we used the forecast for an analogous country and adjusted for population and other effects. The forecasts were then calibrated using historical mobile data volumes where such information was available.

Benefits of use of 3400/3600-4200 MHz for mobile broadband

The output of the technical and economic analysis performed for the study shows that without the additional spectrum made available by the earlier release of 3400/3600-4200 MHz, a spectrum crunch would occur in the period between 2021 and 2025 depending on the country studied. We have quantified the avoided cost benefit of using 3400/3600-4200 MHz spectrum for mobile broadband in these countries. The benefit from avoided costs is computed as the difference in NPV of total radio access network cost between a base case and an alternative case with greater spectrum availability. Our estimates show that use of 3400/3600-4200 MHz frequency range for mobile broadband could generate benefits as shown in Figure 1.

Figure 1: Avoided cost benefits in the study countries



Source: Plum Consulting

The study results also suggest that LSA plays a key role to facilitate sharing arrangements between FSS ES operators and IMT. In the case of the UK where it was possible to model link performance aware and advanced frequency sharing scenarios there is an increase in benefit of up to EUR 468 million in addition to the benefit as shown in Figure 1.

A summary of the benefits is set out below:

- **Hungary:** The benefit comes exclusively from the use of the C-Band in dense urban areas and hotspots. The scale of Figure 1 does not allow the breakdown to be seen – EUR5m comes from dense urban areas and EUR143m from hot spots.

- **Italy:** The benefit comes exclusively from the use of the C-Band in hotspots.
- **Sweden:** The benefit comes exclusively from the use of the C-Band in hotspots.
- **UK:** In the UK the benefit comes from all geotypes, except rural. The application of link budget aware and advanced frequency sharing for satellite services was also modelled in the UK as more detailed satellite usage data was available and the resulting benefit when these techniques are used is:
  - A total of EUR1.7bn for link performance aware (i.e. a EUR300m increment for link performance aware)
  - A total of EUR1.9bn for advanced frequency sharing (i.e. a EUR500m increment for advanced frequency sharing).

The assumptions used to estimate the benefits are inherently conservative. For example our mobile data traffic forecasts could underestimate the actual growth of mobile data, we have assumed that the number of FSS ES remains constant throughout the period whereas in practice we would expect it to decrease, we have excluded benefits from indoor use of the spectrum and assumed a limit of carrier aggregation of three component carriers in the downlink. Benefits derived from technology innovation (i.e. evolution of LTE-A and 5G) that could be triggered by such a large availability of contiguous spectrum have not been taken into account; neither have the benefits from enhanced Quality of Service.

1 Introduction

1.1 Reason for the study

In a world powered by demand for information, access to the internet has become increasingly important. Advances in access technology have made accessing the internet over a mobile device a reality, resulting in a rapid growth in mobile data traffic. Coverage has been the focus of much network deployment to date but as demand for data increases and user expectations of performance increase there is a need to focus more on capacity provision and quality of service to provide a more consistent user experience. This triggers a burgeoning need for investments in network infrastructure as well as a need for an increased amount of spectrum.

The need for more spectrum is recognised, and the European Commission Radio Spectrum Policy Programme (RSPP)[3] has identified a concrete action – "ensuring that at least 1200 MHz spectrum are identified to address increasing demand for wireless data traffic; and assessing the need for additional harmonised spectrum bands".

In many Member States there are measures in place for the release of spectrum. One frequency range that could play a pivotal role in meeting future capacity demands is 3400-4200 MHz and this is the band considered in this report. The frequency range offers the potential for the larger contiguous blocks of spectrum necessary to support the aggregated channels necessary for carrying higher data volumes envisaged in the period between now and the late 2020s.

The 3400-3800 MHz band is the subject of a European Commission Decision harmonising the band for mobile use[4]. RSPG in its opinion on policy objectives for WRC15[5] states that "regarding the band 3.4-3.8 GHz (already harmonised at EU level), a global alignment to the maximum extent possible shall be considered to increase economies of scale for the equipment in this band, taking note of the fact that FSS is extensively deployed in the band 3600 – 4200 MHz in many emerging countries." Further the RSPG notes that the use of 3800-4200 MHz band plays an important role for satellite communications outside of Europe but that this is not the case in Europe. The RSPG also notes that "however, this may limit the possibility of worldwide identification for IMT".[6]

This study focuses on the economic benefits (avoided costs) of releasing spectrum in the 3400/3600-4200 MHz frequency range[7] for mobile broadband in four European countries – Hungary, Italy, Sweden, and the UK. These countries were selected as they present a diverse set of incumbent usage by the Fixed Satellite Service (FSS) and the Fixed Service (fixed links –FL) and allow the options for sharing with mobile broadband to be fully explored.

1.2 IMT Technology Assumptions

This study, as part of its estimation of the avoided costs that accrue from use of 3400/3600-4200 MHz, will take account of macro cell and outdoor small cell deployments. It is becoming increasingly

[3] http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32012D0243

[4] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:144:0077:0081:EN:PDF

[5] http://rspg-spectrum.eu/wp-content/uploads/2013/11/RSPG14-578rev1-Draft_Opinion_WRC-15.pdf

[6] See reference 4, page 6 paragraph 6

[7] Depending on whether 3400-3600 MHz has already been assigned for mobile broadband use in individual countries

apparent that networks based on macro cell sites may require additional network layers based on small cells, either within the coverage area of a macro cell (intra-cell) or in areas between the edges of cells (inter-cell) in order to allow operators to provide mobile broadband capacity at the right level and in the right locations (i.e. a more consistent data performance for mobile broadband users). This type of network comprising coordinated resources in the macro and small cell network layers is often known as a heterogeneous network.

In this study the analysis is restricted to the use of macro sites and small cells in the outdoor environment. Furthermore, it is assumed that in the countries studied that the requirement to build new macro sites beyond 2018 is minimal and that outdoor capacity expansion will be achieved by rolling out the 3400/3600-4200 MHz spectrum on the available macro sites and by the introduction of small cells[8].

Carrier aggregation will become increasingly important in delivery of capacity using small cells as mobile broadband traffic demand increases (both aggregation on a single cell and aggregation between macro and small cell) and use of carrier aggregation is incorporated in the analysis.

The assumptions used in this report are based on LTE technology. However, 5G mobile networks will likely be deployed during the timeframe covered by this report and some of the assumptions, especially for small cell capability, are likely to change. Because of the uncertainty of timing of these developments assumptions related to 5G are not considered in this report.

We do not consider indoor small cells in our analysis

Today indoor mobile data traffic is being overwhelmingly carried over Wi-Fi at very low cost. This means that the bulk of the benefit from indoor use of the 3400/3600-4200 MHz band will not come from avoided cost. Rather the bulk of the benefit of deployment of the band indoors is likely to come from an increase in consumer surplus due to the improvement in quality of service. Consideration of this type of benefit is outside of the estimation of benefits performed for this report. The exclusion of the indoor benefit of C-Band deployment in our analysis will lead to our estimate of the benefit from 3400/3600-4200 MHz being a conservative one.

1.3 Current and future use of 3400-3600 MHz and 3600-4200 MHz

At present the frequency range 3400-4200 MHz is used by several services:

- The fixed satellite service earth stations (FSS ES)
- Fixed links (FL)
- Point to multipoint links (FWA).

Actual usage varies by country and the analysis takes account of the information available for the existing services in the countries considered. In some cases information has been provided on a confidential basis and only the results of the analysis are presented where this is the case. Where information is not confidential it is exposed in the report and its appendices.

In this study it is assumed that IMT will share with the other licensed services currently using the band. Only protection of incumbent users who hold an individual authorisation is considered based on the data received from regulators. Where incumbent users do not hold individual authorization (e.g.

[8] We assume that only a proportion of macro cells will be suitable for C-Band deployment – see Appendix D

VSATs and receive only terminals – it may be possible for these to be registered and thus obtain protection[9]).

Applicable sharing criteria for each of the incumbent services is considered in more detail in this report.

1.3.1 EC Decision on 3400-3800 MHz

The European Commission has harmonised spectrum in the range 3400-3800 MHz for fixed, nomadic, and mobile electronic communication services in the European Union. Decision 2008/411/EC as amended by Decision 2014/276/EC harmonises the technical conditions for 3400-3800 MHz for fixed, nomadic and mobile electronic communication services in the European Union. ECC Decision (11)06 as amended on 14th March 2014[10] sets out harmonised frequency arrangements for mobile/fixed communications networks (MFCN) operating in the bands 3400-3600 MHz and 3600-3800 MHz. Decision 243/2012/EU requires Member States to make available the 3400-3800 MHz frequency band under the terms and conditions of Decision 2008/411/EC subject to market demand and without prejudice to existing service deployments. The Decision indicates a preference for a TDD mode of operation. In this study it is assumed that TDD networks will be deployed in this frequency range.

1.3.2 WRC15 candidate bands

3400-3800 MHz is harmonised for mobile use within the European Union and is supported as a candidate band under Agenda Item 1.1 of WRC15.

In addition, the June 2013 RSPG Opinion on "strategic challenges facing Europe in addressing the growing spectrum demand for wireless broadband" also addresses 3800-4200 MHz and it stated that :

> "… nevertheless, the frequency range 3800-4200 MHz has the potential to play a role in the provision of electronic communications services to ensure that the future capacity needs especially in urban areas, are met. Therefore, studies should be carried out into the possibility of sharing in Europe between the FSS and terrestrial wireless broadband services." [11]., "
>
> "… The Commission should study the possible application of new sharing techniques in Europe between the FSS and terrestrial wireless broadband in this frequency range, while recognizing that the situation within and outside Europe may differ"[12]
>
> , "…Studies should be carried out into the possibility of sharing in Europe between the FSS and terrestrial wireless broadband services including LSA"[13].

In its February 2015 Opinion the RSPG notes that while it is not the case in Europe that the 3400-4200 MHz band is required for reasons of propagation under adverse weather conditions, this may nonetheless limit the possibility of identification of the band for IMT on a worldwide basis[14].

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[9] For example, in the UK where it is possible to register an installation with Recognised Spectrum Access (RSA)

[10] http://www.erodocdb.dk/docs/bdoc98/official/pdf/ECCDec1106.pdf

[11] RSPG13-521 rev 1, Section 9.6 page 22

[12] RSPG13-521 rev 1, Section 11, page 29

[13] RSPG13-521 rev 1, Annex 2 page A2_6

[14] http://rspg-spectrum.eu/wp-content/uploads/2013/11/RSPG14-578rev1-Draft_Opinion_WRC-15.pdf Page 6, Paragraph 6

Work on Agenda Item 1.1 candidate bands continues as part of the preparatory work for WRC15. It should be noted that final positions from administrations and European common positions have yet to be concluded and that the views of RSPG and others reported in this report should be seen as inputs to this process.

1.4 National Sharing Frameworks and the Use of Licensed Shared Access (LSA) option

This study covers the economic benefits of releasing spectrum in the 3400/3600-4200 MHz frequency range for mobile broadband. Mobile broadband services operating in the band will need to share spectrum with the incumbent satellite and fixed link services.

In order to make 3400/3600 – 4200 MHz available, administrations need to establish national frameworks for spectrum sharing between Mobile/Fixed Communication Networks (MFCNs) and the existing Fixed Satellite Service (FSS) and Fixed Service (FS).

National regulatory authorities define criteria for the protection of the incumbent users in the form of maximum permitted interference at the input of the FSS and FS receivers. These limits are then used to calculate the corresponding exclusion zones or maximum permitted EIRPs of MFCN base station sectors (within a restriction zone) so as to avoid harmful interference to the FSS and FS. Administrations have the flexibility to choose the most appropriate approach for defining the technical conditions which the MFCN operators would need to comply with.

It is noted that a work item has recently been established within ECC PT1 on 3600-3800 MHz to draft an ECC Report providing operational guidelines for such spectrum sharing and, where appropriate, the implementation of LSA at a national level. Specifically, document ECC PT1(15)058rev1 outlines a methodology for establishing national frameworks for spectrum sharing between Mobile/Fixed Communication networks (MFCN) and existing FSS/FS services in the 3600–3800 MHz band. The methodology describes a number of sharing mechanisms, ranging from the use of simple frequency-specific exclusions zones, to the application of frequency-specific and location-specific restrictions on the maximum permitted radiated power of individual MFCN base station sectors.

In order to evaluate the economic benefits of the 3400-4200 MHz frequency range, it is necessary to quantify the amount of spectrum that would be available to the mobile broadband service as a result of sharing with the incumbents. While the details of the spectrum sharing mechanisms will be specified by the national administrations (guided by ECC studies), it is nevertheless possible to reasonably quantify lower bounds on the amounts of spectrum that might be available by assuming certain broad sharing approaches.

The above mentioned sharing mechanisms may be implemented via Licensed Shared Access (LSA) which, in turn, standardises the interfaces between the various spectrum sharing functions.

1.4.1 Interference protection criteria

For the purposes of this report two licensed sharing approaches are considered for satellite services to evaluate the amount of spectrum potentially made available to mobile broadband:

- "Link performance aware" – considers specific satellite to ground link performance and how it could be affected by the introduction of certain types of IMT network (beyond the I/N thresholds defined by ITU-R for international satellite coordination)
- "Advanced frequency sharing" – in addition to the above approach, explores the benefits from making use of the spectrum not used by emissions in the accessible bandwidth at an earth station.

The use of licensed sharing to enable the two approaches (which is described in more detail in Section 2.1.1 below) will provide regulatory certainty regarding usage and quality of service for both the incumbent and the sharing IMT services.

In the analysis for this report the techniques are only applied to the FSS ES. They are not considered in the analysis for fixed links as it is not clear that actual implementations of fixed links will have sufficient margin or unused frequency bandwidth to enable their use.

From the perspective of the implementation of spectrum sharing technical rules, LSA is an important option to be adopted to enhance the current sharing frameworks. Under LSA the nature and extent of sharing permitted does not depend on pre-set rules but rather is based on enhancing the effectiveness of spectrum use depending on the balance of economic and social costs and the associated benefits. ETSI is standardising a repository/controller centric architecture for LSA and procedures for establishing and implementing the required technical sharing rules.

1.4.2 Key features of LSA

The key features of LSA are:

- Voluntary: the goal of LSA is to make available additional spectrum resource in specific bands used by incumbent applications through enabling more advanced sharing than what is possible through existing regulatory mechanisms. Sharing through LSA requires close cooperation between the incumbent and the LSA licensee, due to the priority in the spectrum access rights and therefore should be implemented on a voluntary basis.
- Licensed: access to incumbent's spectrum as part of a "sharing framework" that can be understood as a set of sharing rules or sharing conditions that will materialise the change, if any, in the spectrum rights of the incumbent(s) and define the spectrum, with corresponding technical and operational conditions, that can be made available for alternative usage under LSA. The "sharing framework" will be under the responsibility of Administration/NRA that will also be responsible for issuing an individual right of use to the LSA Licensee following a procedure that is compliant with the Authorization Directive
- Exclusivity: The new LSA licensee user is granted an exclusive use of the spectrum resource at a given time and location that is likely to be long term.
- The administration/NRA might manage an LSA repository, containing the relevant information on LSA spectrum that must be protected together with the level of protection provided by the incumbent. The access to the spectrum made available to the LSA licensee based on sharing rules and information on the incumbent's use provided by the LSA repository is managed by the LSA controller. The controller retrieves information about available LSA spectrum from the LSA repository through a secure and reliable communication path.

The incumbent will be incentivised by the fact that spectrum access can be maintained in the longer term and by adequate compensation for sustained sharing in specific bands (the new user is likely to pay a licence fee which could be determined on an administrative basis and/or by auction). LSA licensee motivation will be based on attractive sharing conditions and timely access to spectrum with supportive economies of scale and at a lower cost, such as the absence of coverage obligations

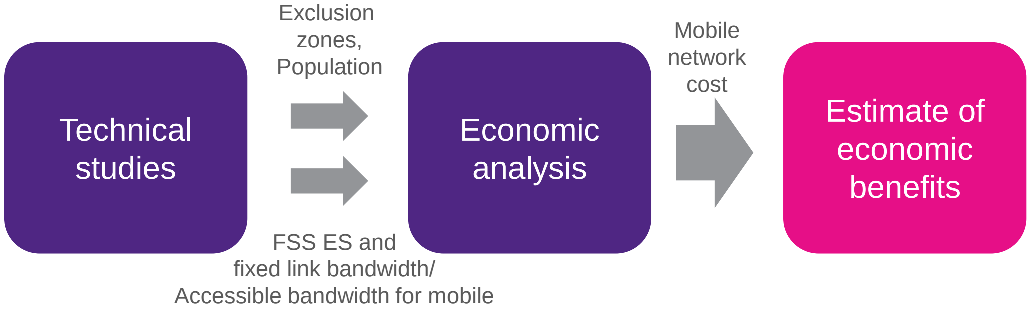
1.5 Study Approach

The key questions addressed by the study are:

- To assess the economic benefit of bringing forward the availability of spectrum at 3400/3600-3800 MHz and 3800-4200 MHz
- To assess the economic benefit arising from the application of LSA to enable the link performance aware and advanced frequency sharing approaches to satellite services. This has been modelled where the detailed data for the incumbent satellite services has been provided.

Figure 1-1 summarises the approach to the analysis.

Figure 1-1: Overview of the approach to economic benefit estimation



Our approach involves the following steps:

- Technical analysis – deriving the size of the areas where potential interference between mobile base stations and satellite earth stations (FSS ES) and mobile base stations and fixed links could occur[15]. Within each of these areas, the study determines the actual amount of spectrum that could be available for IMT based on the spectrum required by satellite and fixed link users. The frequency sharing scenarios are described in Section 2.
- Economic analysis – the economic analysis takes the output of the technical analysis and uses it to determine the total spectrum available for IMT in the study countries[16]. With this spectrum number the total available network capacity is estimated. A number of cases are defined, which are characterised by the frequency sharing scenarios and timing of the C-Band spectrum release. These cases are used to calculate the resulting change in network infrastructure required to handle mobile traffic demand and the cost difference driven by these changes. The total cost associated with the capacity requirement in each case is then computed.

[15] Such areas are referred to as “restriction zones” in the terminology of document ECC PT1(15)058.

[16] That is the C-Band spectrum available plus all other IMT spectrum available

- Economic benefit estimation – the benefit is computed as the cost that mobile operators could avoid as a result of having access to spectrum in the range 3400/3600-4200 MHz. It is computed as the difference in total radio access network cost between a base case (least spectrum/highest cost) and an alternate case (more spectrum/lower cost, as described above) and expressed in 2018 NPV terms. Detailed descriptions of the cases can be found in Section 3.

2 Technical methodology

Prior to undertaking the economic analysis to determine the benefits from avoided costs it is necessary to determine the amount of spectrum that is available for mobile services in any geographic area along with the number of people for which that spectrum is available.

For the purposes of this report it is assumed that the presence of FSS ES and fixed links using some portion of the frequency band prevents mobile use of that portion of the frequency band in certain areas. This effectively identifies frequency-specific exclusion zones in the vicinity of FSS ES and fixed links receivers[17].

To do this it is necessary to combine a model of frequency and geographic areas around fixed links and FSS ES receiving signals in 3400/3600-4200 MHz with a model of population by area obtained for each country.

2.1 FSS ES

The area around a certain FSS receiving earth station can be viewed as a coordination area when considering ITU-R I/N based criteria, tending towards an exclusion area (with reference to the frequencies used by the FSS Earth station) when full account is taken of FSS link performance in terms of C/(N+I). It will be seen later that representative satellite link performance has been taken into account but since this is representative rather than definitive, the term coordination area is used rather than using a mixture of coordination area and exclusion area. Regardless of nomenclature the following considerations ensure the satellite spectrum being used is protected.

2.1.1 Description of the FFS ES frequency sharing scenarios

There are three distinct scenarios that describe different frequency and geographic sharing situations as used for the purposes of this report. These three scenarios depend on:

- The FSS ES interference protection level. The two options are to maintain the very conservative ITU-R criteria which relates to the noise floor or to take account of received signal levels which suggest that margins can accommodate higher levels of interference (i.e. link performance aware approach)
- The amount of spectrum that is actually used by the FSS ES. An FSS ES is licensed to operate over a specified bandwidth, which can be considered the accessible bandwidth, and to use certain emission bandwidths. At one extreme it can be considered that an earth station operator uses the whole of the accessible bandwidth and at the other extreme a single emission bandwidth somewhere within the accessible bandwidth.

In this regard the two options below labelled “link performance aware” and “advanced frequency sharing” provide a range within which the actual situation must reside.

[17] We note that, as described in document ECC PT1(15)058rev1, spectrum sharing can be implemented by (arguably more efficient) mechanisms other than exclusion zones; e.g., the application of frequency-specific and location-specific restrictions on the maximum permitted base station power.

The three scenarios are described below. The link performance aware and advanced frequency sharing scenarios would be implemented using LSA.

"ITU-R criteria" frequency sharing scenario

This scenario assumes that the ITU-R criteria determine the level of interference that can be tolerated by the FSS ES and that the amount of spectrum used by the FSS ES is defined by the accessible bandwidth.

The ITU-R criteria is a safety first method that is suited to identifying 'potential' interference cases and works against the goal of efficient spectrum sharing and high spectral efficiency. It takes a universal I/N threshold and applies this to all satellite services currently offered in C-band (including TV reception as well as the FSS). As the I/N threshold has to cover all services and all deployments it means that if there is only one case where sharing is not possible, all options are closed.

In satellite coordination it has long been acknowledged that I/N thresholds – universally applied – is not an efficient way to manage the regulatory environment for spectrum sharing.

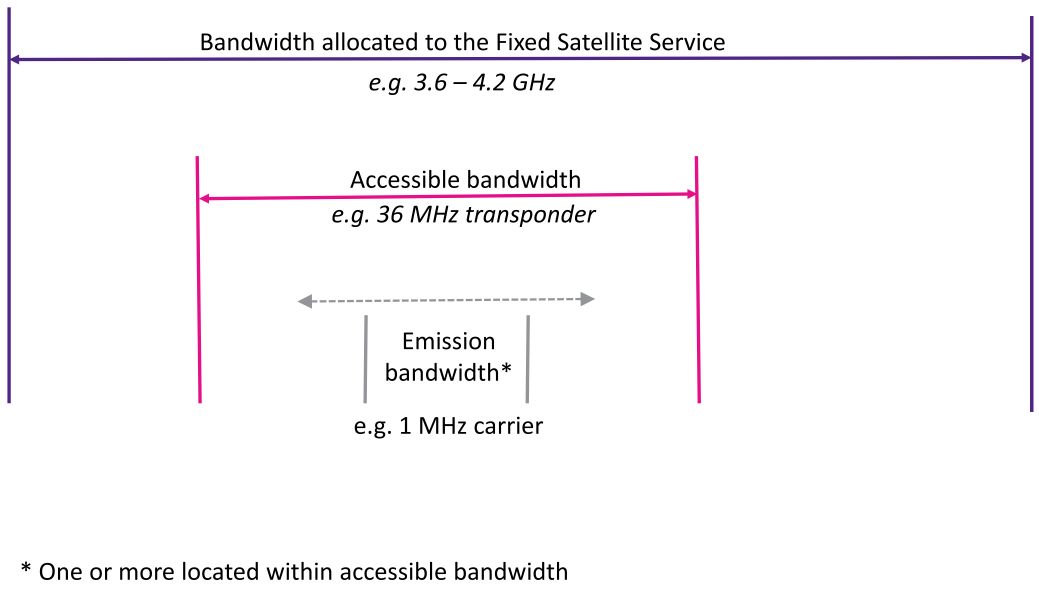
"Link performance aware" frequency sharing scenario

This scenario considers a range of satellite and earth station operating characteristics with a view to determining possible margins that might be available to mitigate interference. As for the ITU-R criteria case above, the amount of spectrum used by the FSS ES is defined by the accessible bandwidth.

"Advanced" frequency sharing scenario

This scenario, as for the link performance aware case above, considers a range of satellite and earth station operating characteristics with a view to determining possible margins that might be available to mitigate interference. In this case the amount of spectrum used by the FSS ES is defined by the emission bandwidth. The relationship between different types of bandwidth is summarised in Figure 2-1.

Figure 2-1: Relationship between different types of bandwidth



2.2 Fixed links

In principle the analysis of area and frequency used by a fixed link is very similar to the method that has been used for the FSS ES. However, there are some points of difference to note as follows:

- A point-to-point fixed link effectively uses a zero or near zero degrees elevation angle so the main lobe of the antenna has a greater intersection with the ground and therefore the potential to create an exclusion area that looks more like an ellipse than a circle although diffraction loss will significantly reduce this effect.
- A point-to-point fixed link generates two exclusion zones, one relating to the transmit end of the link (interference into IMT) and the other relating to the receive end of the link (interference from IMT). For this exercise which concerns the protection of existing systems, only the receive characteristics of fixed links are taken into account.
- Unlike the analysis for satellite systems a margin is not assumed. Where Automatic Transmit Power Control (ATPC) is employed on fixed links significant margins will not exist. Where ATPC is not employed margins will exist but these are to absorb multipath fading on the link.

In addition to point-to-point fixed links ECC Report 173 also identifies point-to-multipoint base stations. From an exclusion area point of view this means that the base station coverage area plus isolation margin determines the first layer of exclusion but this should then be further extended by another exclusion distance to protect the user terminals.

For the fixed link analysis only the ITU-R criteria is used to determine the level of interference that can be tolerated by the fixed link. The absence of or unpredictability of a margin prevents the use of link performance aware and advanced frequency sharing with fixed links.

2.3 Technical modelling results

The technical modelling is a two-step process:

i. The first step determines the amount of spectrum that is precluded from mobile use and over what area
ii. The second step maps the precluded spectrum/areas onto population data

The output from this modelling, namely the areas where differing amounts of spectrum are not available to a certain number of people for mobile use, is then subtracted from the whole frequency band to give the spectrum that is available by area and number of people. The population and spectrum availability data is then input to the economic analysis. Outputs are provided for both macro and outdoor small cell IMT base stations.

Figure 2-2 shows an example taken from the UK of the output of the technical modelling. In this case there are both Fixed Satellite Service Earth Stations and Fixed Links present.

Fixed Satellite Service Earth Stations

The area around a Fixed Satellite Service Earth Station or Fixed Link within which a particular piece of spectrum would not be available to mobile services is determined by a large number of factors including the surrounding terrain and the Earth Station or Fixed Link antenna pattern in the horizontal plane which in turn is determined by the elevation angle at which the antenna is operated.

For simplicity it has been assumed that the area around an Earth Station is described by a circle of a particular radius. That radius has been determined by an extensive Huawei study (reported in JTG contributions[18] and further developed since then) which takes account of:

- The types of location in which the Satellite Earth Station and the macro and small cells are located
- The aggregation of potential interference from multiple macro / small cell transmitters
- A propagation model (based on long term interference because aggregation effects are being considered) with a small obstacle mid-path. Note that this approach gives rise to similar separation distances to those that are obtained through the specific modelling of actual earth station sites (i.e. taking account of actual terrain)
- An earth station elevation angle of 5 degrees. This is a very conservative assumption as many of the earth station antennas are known to operate at elevation angles greater than 5 degrees. Operation at higher elevation angles gives rise to a reduced earth station antenna gain in the horizontal plane and consequently smaller coordination areas

The coordination area radius is also determined by the criterion defining an acceptable level of interference at the Satellite Earth Station. The starting position is the traditional ITU-R criteria which is defined relative to the noise floor of the FSS ES receiver (I/N = -13 dB). However, consideration is also given to the situation where a margin exists on the satellite link such that a higher level of interference can be tolerated. Examination of satellite and earth station characteristics suggests that such margins might support an I/N of 10 dB or more. It is noted that a detailed end-to-end link performance (i.e. uplink and downlink combined) would determine the actual margins available. However, such information is not generally available in the public domain so the downlink characteristics have been considered in isolation.

Fixed Links

In the case of a Fixed Link the procedure is similar but, as noted earlier, a point-to-point fixed link effectively uses a zero or near zero degrees elevation angle so the main lobe of the antenna has a greater intersection with the ground and therefore the potential to create an exclusion area that looks more like an ellipse than a circle although diffraction loss will significantly reduce this effect.

Furthermore, unlike the analysis for satellite systems a margin is not assumed to be available to absorb interference. Where Automatic Transmit Power Control (ATPC) is employed on fixed links significant margins will not exist. Where ATPC is not employed margins will exist but these are to absorb multipath fading on the link. For the fixed link analysis only the ITU-R criteria is used to determine the level of interference that can be tolerated by the fixed link. The absence of or unpredictability of a margin prevents the use of link performance aware and advanced frequency sharing with fixed links.

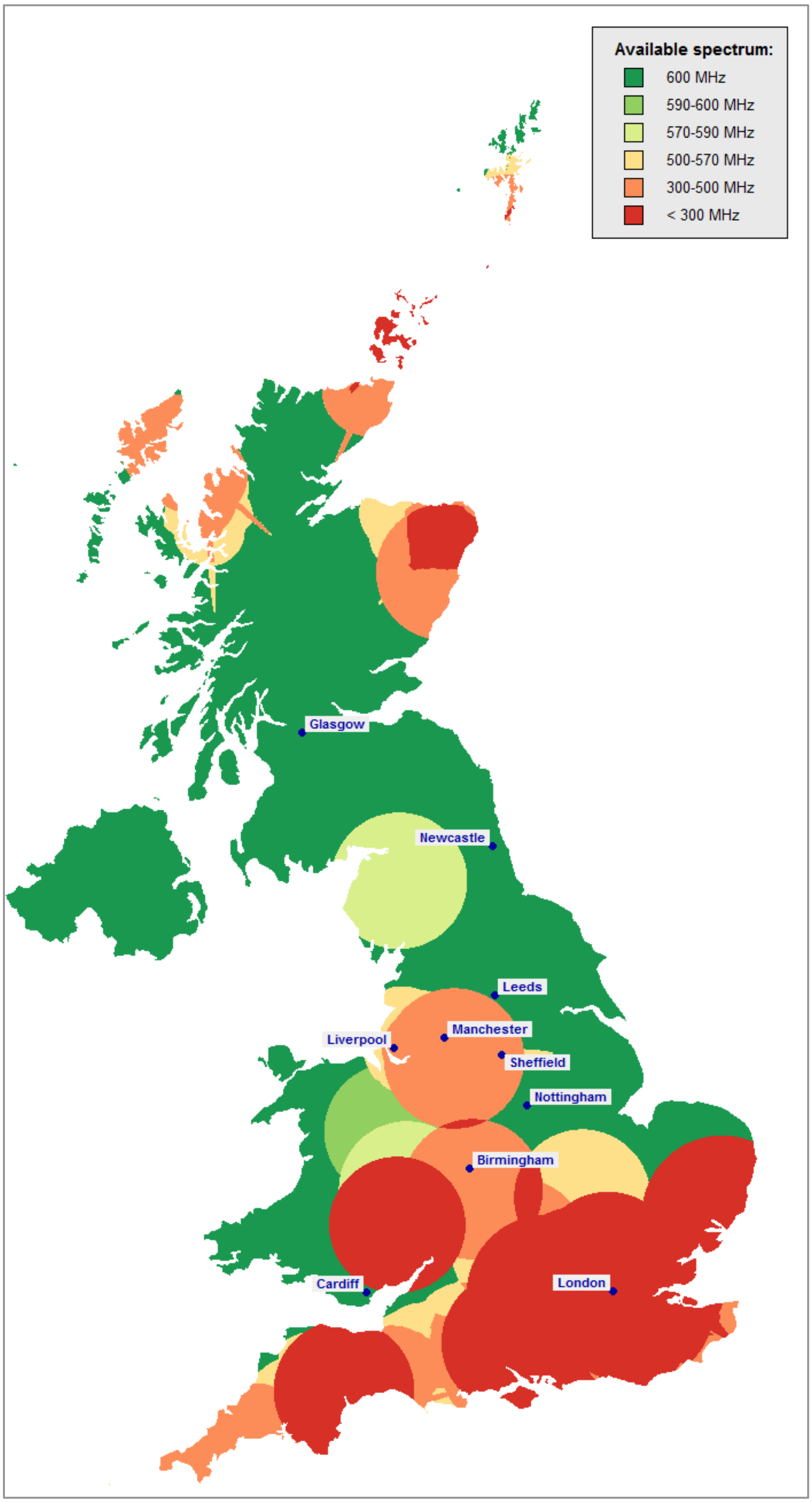
[18] CPG-PTD(14)057_Report on sharing between terrestrial IMT and FSS systems operating in the 3800-4200 MHz frequency range

Aggregate effect

The impact of Fixed Satellite Service Earth Stations and Fixed Links are then aggregated to show the areas where differing amounts of spectrum are not available to a certain number of people for mobile use. This is then subtracted from the whole frequency band to give the spectrum that is available by area and number of people.

In Figure 2-2 the areas shaded green represent land masses where no Fixed Satellite Service Earth Stations or Fixed Links require protection, so that all of the C-Band is available for IMT. These are areas outside of the coordination areas for macro cells.

Figure 2-2: Amount of spectrum (within the 3600 – 4200 MHz range) that could be available for IMT macro-cell use within the coordination areas around earth station and fixed link receivers combined based on ITU-R criteria (Example for the UK)



3 Economic methodology

The economic benefit is estimated as the potential change in cost that operators could experience from having access to larger amounts of spectrum compared to a base case. In the base case the core assumption is that the frequencies in the spectrum range 3600-3800 MHz and the spectrum range 3800-4200 MHz will be released between 2020 and 2025 and between 2025 and 2030 respectively[19]. Table 3-1 shows the assumptions for release of spectrum in each of the study countries. The sharing scenario with incumbent services required for the use of these frequency ranges in the base case is assumed to be one based on the ITU-R criteria for both FSS ES and fixed links.

Table 3-1: Timing of assumed release dates for all study countries

Country	Expected release dates		Assumed early release dates	
	3600-3800 MHz	3800-4200 MHz	3600-3800 MHz	3800-4200 MHz
Hungary	2025	No plans to release	2020	2025
Italy	2025	2028	2020	2025
Sweden	2025	2028	2020	2025
UK	2022	2028	2018	2020

Having access to more spectrum at any given point in time will in general allow operators to roll out fewer base station sites to support the same volume of mobile data. This leads to a lower network cost. Therefore, the total benefits in the modelled scenarios come from the operators having:

- The same amount of spectrum as in the base case but at an earlier point in time and/or
- Where applicable, a larger amount of spectrum in the C-Band compared to the base case (as a result of less stringent criteria than the ITU-R criteria)

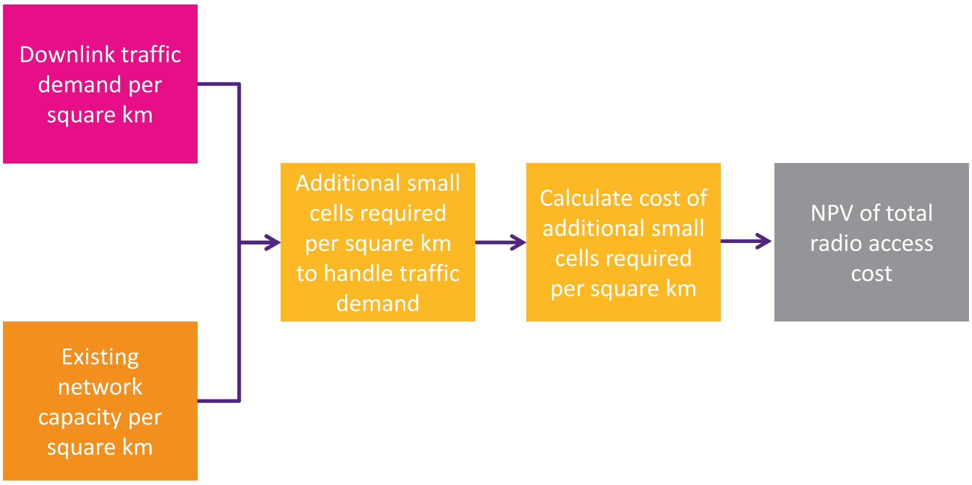
The type of benefit described above is known as avoided cost. We restrict our estimation of benefit to the avoided cost from the use of C-Band spectrum for macro and small cells in the outdoor environment. As noted in Section 1.2 we have not included indoor small cells in our analysis.

3.1 Deriving the avoided costs

Figure 3-1 provides a high level overview of the steps used to derive the costs that form the input to the calculation of the avoided costs. The process for deriving the benefit is described in detail in Appendix C. The appendix also contains a discussion of the key assumptions that are implicit in the network costing function of the model.

[19] Where applicable 3400-3600 MHz is also included in the analysis

Figure 3-1: High level overview of the steps to calculate radio access network cost for all areas and for all bands including C-Band (in the 2018-2027 time frame)



The function of the model is as follows:

- Using population data and a mobile data traffic demand forecast the downlink traffic demand per square kilometre is calculated.
- Using the available spectrum (output from the technical analysis) the network capacity per square kilometre is calculated.
- The outputs of the previous two steps are compared to calculate the incremental number of small cells per square kilometre required to meet the downlink traffic demand (if demand exceeds capacity). From this the additional network cost to meet demand is calculated.
- The above steps are carried out over the time duration of the model and the net present value of the additional radio access costs is calculated.

The steps described above are carried out for a number of scenarios to calculate the final avoided cost. There are up to 3 frequency sharing scenarios and for each of these frequency sharing scenarios up to 3 types of area to consider (coordination areas for macro cells and small cells and the areas outside of these coordination areas). This results in a total of 9 combinations of spectrum availability and area types to consider before the change in the timing of C-Band release is accounted for. A more detailed description of the model is at Appendix C.

The benefit from avoided costs is computed as the difference in NPV of total radio access network cost between a base case and an alternative case with greater spectrum availability – i.e. Benefit equals (Base Case's cost NPV) minus (Alternative Case cost NPV)[20].

Table 3-2, summarises the key characteristics of the base case and the 3 alternate cases that are modelled. These characteristics are the timing of the release of the 3600-3800 MHz and 3800-4200 MHz ranges and the sharing criteria that are assumed for each case.

[20] Note that we assume no change to market structure when performing the analysis. That is no new entry or the exit of an existing operator from the market. The base cost relates to the cost of the existing operators in the market.

Table 3-2: Definition of Base Case and Alternate Cases by C-Band release dates, frequency sharing scenario and IMT rollout scenario

Modelling scenario	Release date of 3600-3800 MHz	Release date of 3800-4200 MHz	Frequency sharing scenario FSS ES	Frequency sharing scenario for fixed links	IMT rollout scenario
Base Case	2022	After 2028	ITU-R criteria	ITU-R criteria	Macro Cell + outdoor Small Cell
Alternate Case 1	See Table 3-1	See Table 3-1	ITU-R criteria	ITU-R criteria	Macro Cell + Outdoor Small Cell
Alternate Case 2	See Table 3-1	See Table 3-1	Link performance aware	ITU-R criteria	Macro Cell + Outdoor Small Cell
Alternate Case 3	See Table 3-1	See Table 3-1	Advanced frequency sharing	ITU-R criteria	Macro Cell + Outdoor Small Cell

It should be noted that link performance aware and advanced frequency sharing are only applied where the data is available to enable the scenario to be modelled.

Geotypes are used to ensure that the variation in subscribers and site density in different areas across countries is captured. There are 5 geotypes, which are defined by population density thresholds: hot spot, dense urban, urban, suburban and rural areas. The definitions of the geotypes as well as the population/subscriber and network parameters associated with them can be found in Appendix D.

The concept of heterogeneous networks is incorporated into the analysis by making the assumption that all new cells will be small cells subsequent to 2014 in the UK and 2015 or 2016 in the other study countries. Small cells will only be rolled out when all available bands (including C-band when available) have been deployed on existing macro-cell sites and there is still capacity shortfall[21]. This means that mobile operators are assumed to prefer adding new bands to macro-cells as opposed to installing new small cells straight away. Where small cells are rolled out, it is assumed that only bands at or above 2600MHz will be used on them.

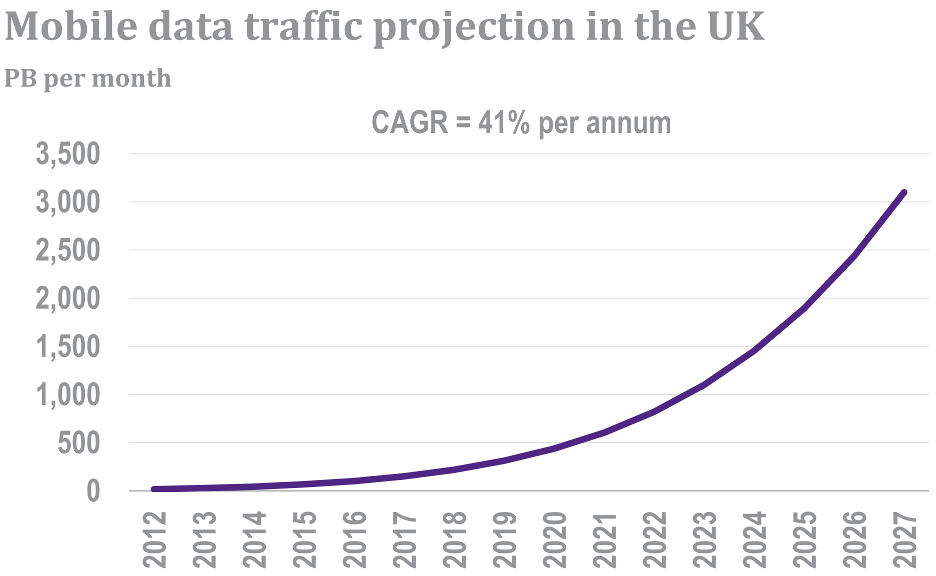
3.2 Traffic demand forecast

The key demand-side input is the amount of traffic that operators will need to support. The traffic demand forecast is derived by extrapolating the relevant country Cisco VNI 2014 short-term (2012-2018) projection to 2028 using a Gompertz curve. Where appropriate the Cisco-extrapolated forecast is scaled using historic mobile data volume information from regulators. In situations where a Cisco country forecast is not available an adjusted version of the forecast for an analogous country is used.

Figure 3-2 shows an example traffic forecast. Detailed traffic projections for each study country are shown at Appendix A.

[21] It should be noted here that not all macro cell sites will be suitable for C-band deployment. We assume that only a proportion of macro cell sites in each geotype will be upgraded with C-band frequencies.

Figure 3-2: Example of mobile traffic demand forecast



Source: Ofcom, Cisco VNI, Plum Consulting

Long-term projections of mobile data traffic demand are inherently uncertain. Usage behaviour beyond the next few years will depend on both the availability of devices and applications, the quality of the service that can be delivered and the associated supply side cost. The latter will also determine the extent of mobile device data offload to Wi-Fi and residential indoor small-cells.

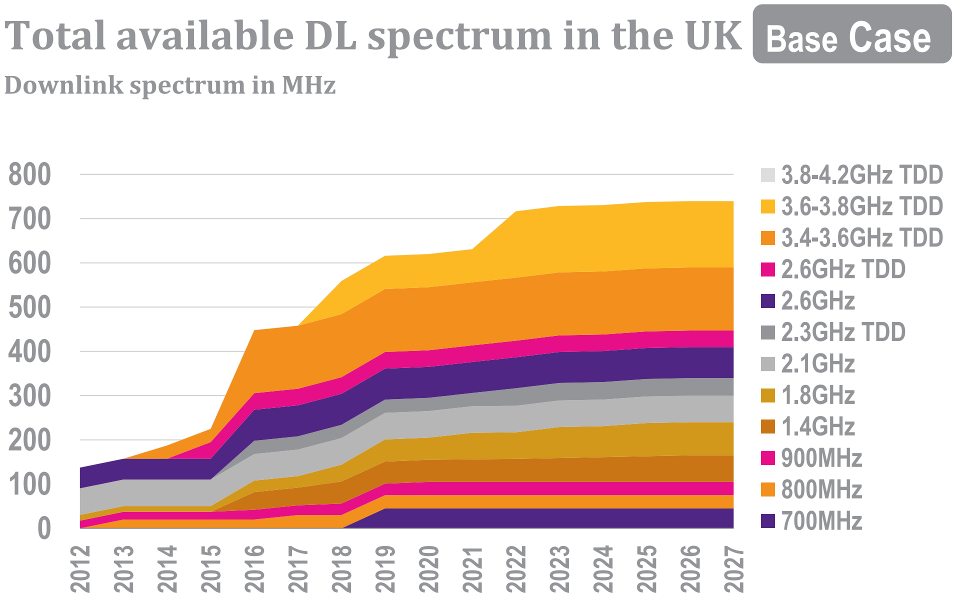
3.3 In-band backhaul use

The analysis also considers the use of C-Band for in-band backhaul. The use of C-band or 2600MHz TDD spectrum for backhaul is assumed to apply only for outdoor small cells. We assume that microwave and fixed connections will continue to be used for backhaul on macro cell sites (and some small cell sites). The use of in-band backhaul for small cells means that not all of the spectrum available can be used for radio access. To ensure that backhaul capacity is guaranteed for small cells, half of available spectrum for IMT in the C-Band is assumed to be reserved for backhaul. Implicit in this assumption is that operators do not incur annual spectrum fees on backhaul for small cells.

3.4 Spectrum supply in the Base Case

Spectrum is an important supply-side input. It determines the level of existing capacity for comparison with demand. Figure 3-3 shows an example of the base case portfolio of downlink spectrum assumed to be available to operators outside of coordination areas during the modelling period. The amount of available downlink spectrum across all frequency bands in each of the countries studied can be found in Appendix A. Note that the profile of available downlink spectrum will change moving from the Base Case to Alternate Case 3.

Figure 3-3: Example of downlink spectrum availability – Base Case



Source: Plum Consulting

3.5 Other key considerations

The number existing mobile base station sites per square kilometre is required to set the base line for infrastructure cost calculations. This information is derived from data released into the public domain, government or information obtained directly from communications operators[22].

For the purpose of determining the total radio network infrastructure requirement, it is assumed that outdoor small cells can support a total of 60MHz during the modelling period (i.e. an outdoor small cell will have capacity to transmit on three 20MHz carriers, which could be in the same or different bands)[23]. As 3GPP is specifying the aggregation of three C-Band component carriers in the downlink in Release 12, this assumption may be a conservative one looking forward to the end of the modelling period where aggregation of five carriers (or more longer term) could be achieved as well as the use of wider channel bandwidths (beyond 20 MHz) This is being activity discussed for future 3GPP releases.

5G mobile networks will likely be deployed from 2020, starting with some leading markets of the world (e.g. Japan and Korea). The availability of the 3600-4200 MHz in the 2020 timeframe will represent an important candidate frequency band to support the introduction of 5G. The benefits associated with the contribution that the 3600-4200 MHz range would give to the innovation of mobile broadband networks and in particular to the establishment of 5G have not been quantified in this report.

[22] The data for Hungary is a Plum estimate based on information in the public domain.

[23] Based on discussion with industry stakeholders and vendors on the evolution of carrier aggregation in small cells and the current specifications of microcells. At present, an outdoor microcell can only support a maximum of 2 bands and 1 carrier in each band.

4 Results

In this section the results of the modelling of avoided network costs in the four countries studied are set out. The situation of each country studied is different in terms of land area and population. This is summarised in Table 4-1.

Table 4-1: Population, land area and geotypes

Parameter	Hungary	Italy	Sweden	UK
Geotype area size (sqkm):				
Hot spots	16	79	34	56
Dense urban	11	99	25	105
Urban	138	1,861	223	2,238
Suburban	7,238	32,636	5,453	36,608
Rural	86,016	275,046	444,175	204,316
2014 Population (million people)	9.9	60.8	9.7	63.2
Total land area (sqkm)	93,419	309,721	450,024	243,322
Population density (persons per sqkm)	105	196	22	263

The deployment of incumbent services in the frequency range 3400-4200 MHz also varies between the countries studied and this is summarised in Table 4-2.

Table 4-2: Deployment of incumbent services

	Hungary	Italy	Sweden	UK
FSS ES ITU-R	No	Yes[24]	Yes	Yes
No of ES locations / assignments	N/A	1 location	This information is confidential	27 locations and 1076 assignments
FSS ES link budget aware and advanced frequency sharing	N/A	N/A	No – detailed assignment information not available	Yes
Fixed links	Yes	Yes	No	Yes
No of FL receive assignments	706[25]	This information is confidential	N/A	18826

[24] There is one C-Band satellite earth station at Fucino in Italy. it is located in the crater of an extinct volcano, which provides effective shielding. It has not therefore been taken into account in our model.

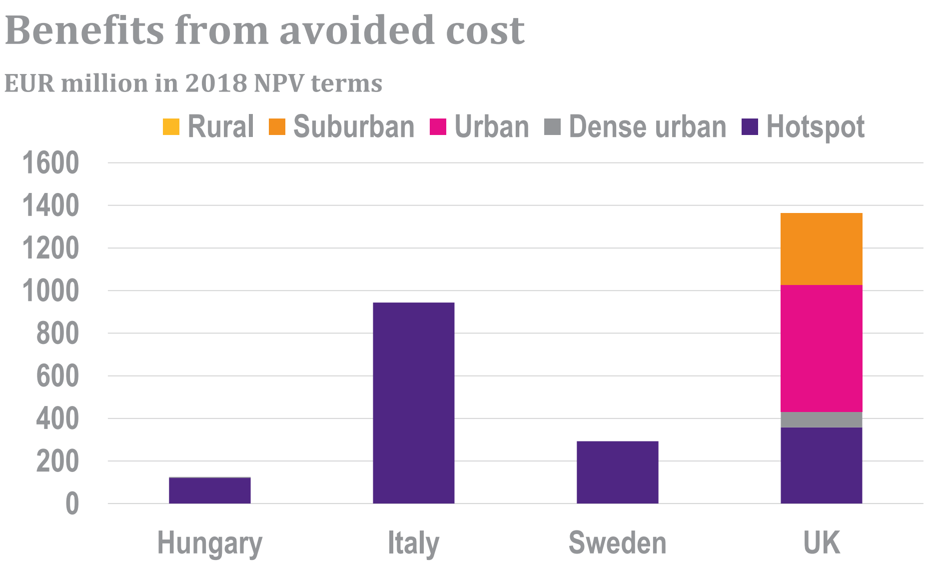
[25] In Hungary there are 672 assignments at 3400-3600 MHz (point to multipoint) and 34 assignments at 3600-3800 MHz

The diversity of demographic factors, incumbent service deployment and traffic density leads to quite a wide variation of benefit across countries. It has however allowed the examination of different situations with countries having only fixed links (e.g. Hungary), countries with only satellite services (e.g. Sweden) and countries with both (e.g. the UK).

4.1 Positive economic benefit from bringing forward availability of 3400-4200 MHz spectrum

There is a positive economic benefit in all cases modelled. Benefit stated here is avoided network cost as a result of having more spectrum available to serve mobile data traffic. Figure 4-1 shows the benefit for each country.

Figure 4-1: Avoided cost benefit from 3400/3600-4200 MHz spectrum



Source: Plum Consulting

Factors driving the benefit are as follows:

- **Hungary:** The benefit comes exclusively from the use of the C-Band in dense urban areas and hotspots to serve growing mobile data demand when the spectrum is released early. The scale of Figure 4-1 does not allow the breakdown to be seen – EUR4m comes from dense urban areas and EUR121m from hot spots.
- **Italy:** The benefit comes exclusively from the use of the C-Band in hotspots to serve growing mobile data demand when the spectrum is released early. Note that the result is based on

[26] The data from Ofcom shows 188 assignments.8 are shown as dual polarisation and our model has used 196 assignments to take the additional 8 entries into account.

analysis of a partial set of fixed link data and that the benefit shown here is likely to be an upper bound.

- **Sweden:** The benefit comes exclusively from the use of the C-Band in hotspots to serve growing mobile data demand when the spectrum is released early.
- **UK:** The benefit from avoided cost totals EUR1.4bn in 2018 NPV terms. The application of link budget aware and advanced frequency sharing was also modelled in the UK for satellite services and the resulting benefit when these techniques are used is EUR1.7bn and EUR1.9bn respectively. In the UK the benefit comes from all geotypes except rural.

4.2 Conclusion

The early availability of 3400/3600-3800 MHz and 3800-4200 MHz spectrum for IMT is expected to yield significant net benefit. This spectrum potentially offers the large contiguous blocks that will be required for mobile broadband use as mobile data traffic grows. In all of the study countries the early release of C-Band spectrum and, where applicable, the application of link performance aware and advanced frequency sharing delivered a benefit in terms of avoided cost. The actual magnitude of the benefit is dependent on a number of factors including demographics, the density of incumbent services and projected traffic growth.

The additional spectrum at 3400/3600-4200 MHz is required to provide capacity to meet mobile data traffic demand as mobile data traffic grows. The analysis suggests that a spectrum crunch occurs between 2021 and 2025 depending on the country in the absence of the earlier availability of this spectrum. This result is based on the relatively conservative mobile data traffic demand forecasts used for modelling the avoided costs. If mobile traffic demand were to grow more aggressively the spectrum crunch would occur earlier.

It should be noted that some of the other assumptions used to model the benefit are conservative and as a result the avoided cost is likely to be underestimated. Also, only outdoor deployments have been considered in the model and no benefits (consumer surplus) are included from use of the spectrum for indoor small cells.

The results of the study suggest that consideration should be given to the early release of spectrum at 3400/3600-3800 MHz. Also, release of spectrum at 3800-4200 MHz should be considered as a medium term measure. The likelihood of a spectrum crunch in the early 2020s indicates that action is required in the short term to deliver sufficient predictability and regulatory certainty for potential users of the band.

The study results also suggest that LSA plays a key role to facilitate sharing arrangements between FSS ES operators and IMT. In the case of the UK where it was possible to model link performance aware and advanced frequency sharing scenarios there is an increase in benefit of up to EUR 468 million in addition to the benefit shown in Figure 4-1.

Appendix A: Country data and results

A.1 Hungary

A.1.1 Technical analysis

A.1.1.1 C-Band FSS ES

There are no known C-Band FSS earth stations.

A.1.1.2 Fixed links

Technical data on the fixed links using the 4 GHz part of C-band has been provided by the Administration. Band utilisation falls in three parts:

- 3400 – 3600 MHz: Large number of P-MP base stations
- 3600 – 3800 MHz: Not used
- 3800 – 4200 MHz: Small number of trunk network links

Protection of these links has been based on the I/N criterion specified in ITU-R Recommendation 758 but taking account of the system noise figure and losses. A conservative assumption has been made regarding the system noise figure and losses in order to provide sufficient protection to the fixed links.

A.1.1.3 Mobile transmitters

Two cases are considered:

Macro cell (outdoor) EIRP = 61 dBm in 20 MHz

Small cell (outdoor) EIRP = 29 dBm in 20 MHz

A.1.2 Spectrum availability

Based on parameter values summarised in the preceding section and provided in more detail in Section A1.5, spectrum availability is summarised for the two sub-bands 3400 – 3600 MHz and 3800 – 4200 MHz, noting that 3600 – 3800 MHz is currently unused.

Results for the two sub-bands that are currently used are presented with respect to both LTE macro cell transmitters and small cell transmitters.

Figure A-1: Amount of spectrum (within the 3400-3600 MHz range) that could be available for IMT macro-cell use within the coordination areas around fixed link receivers (P-MP base stations) based on ITU-R criteria

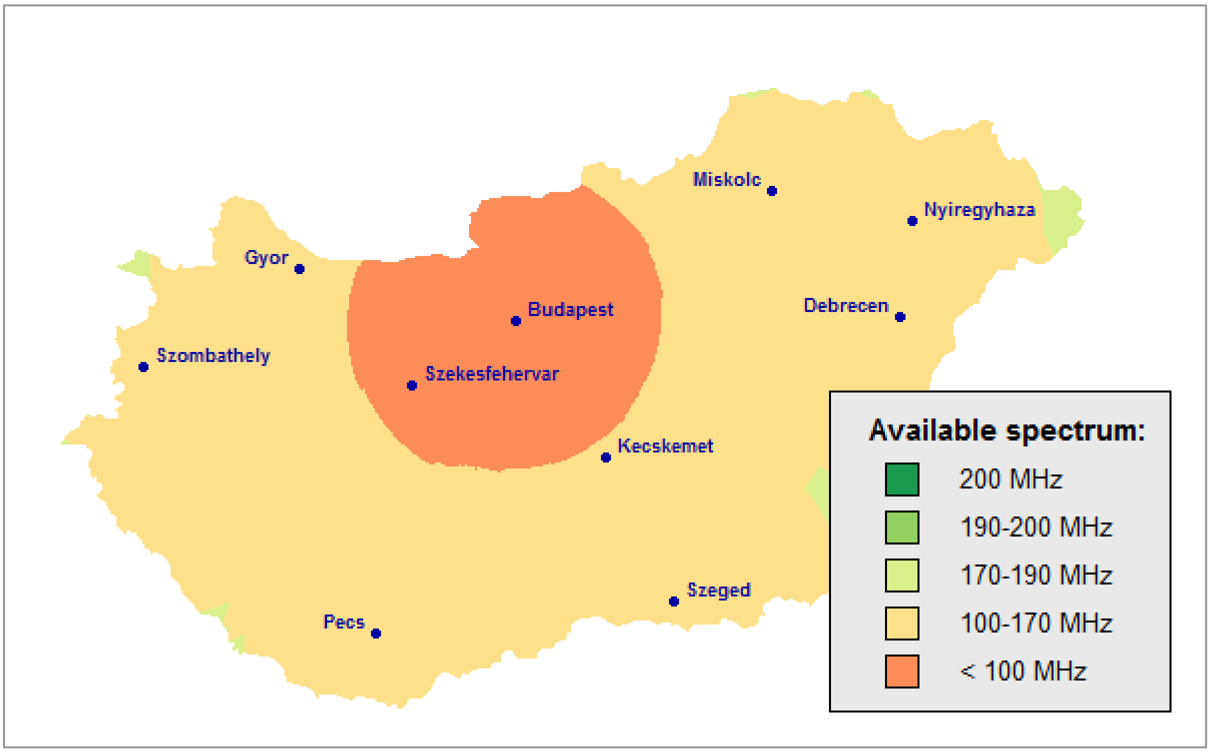


Figure A-2: Amount of spectrum (within the 3400 – 3600 MHz range) that could be available for IMT small cell use within the coordination areas around fixed link receivers (P-MP base stations) based on ITU-R criteria

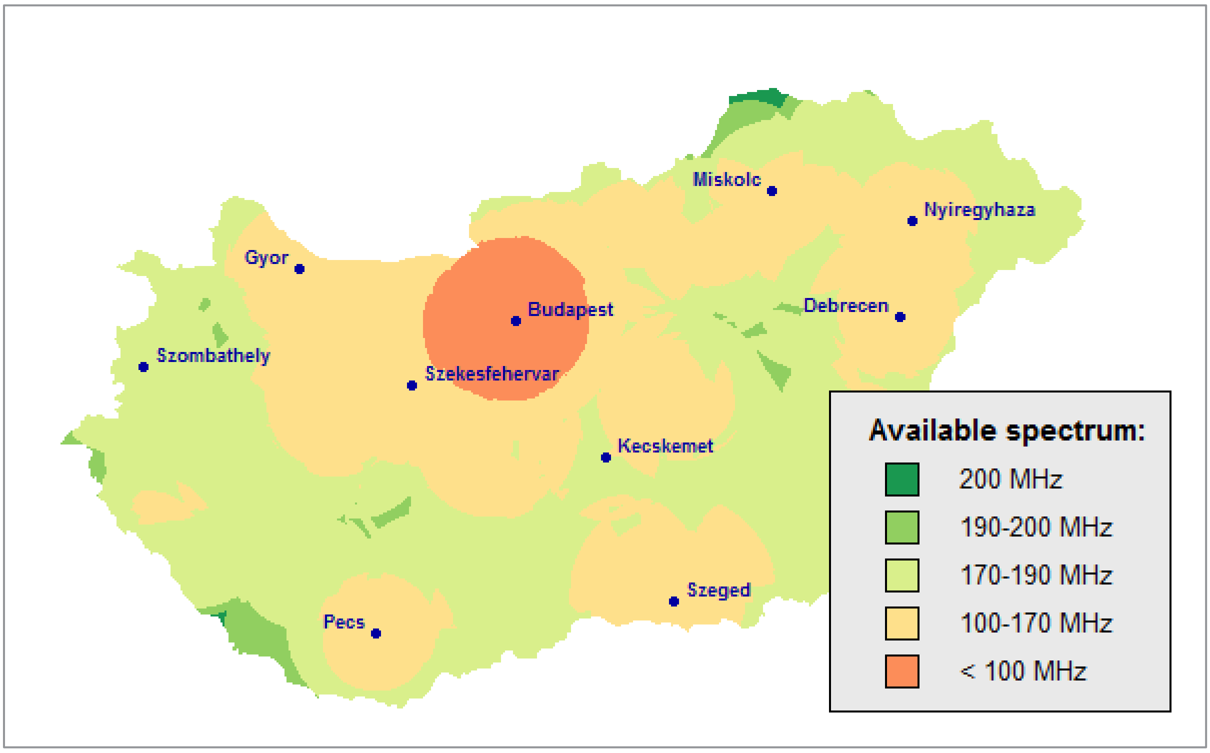


Figure A-3: Amount of spectrum (within the 3800 – 4200 MHz range) that could be available for IMT macro-cell use within the coordination areas around P-P fixed link receivers based on ITU-R criteria

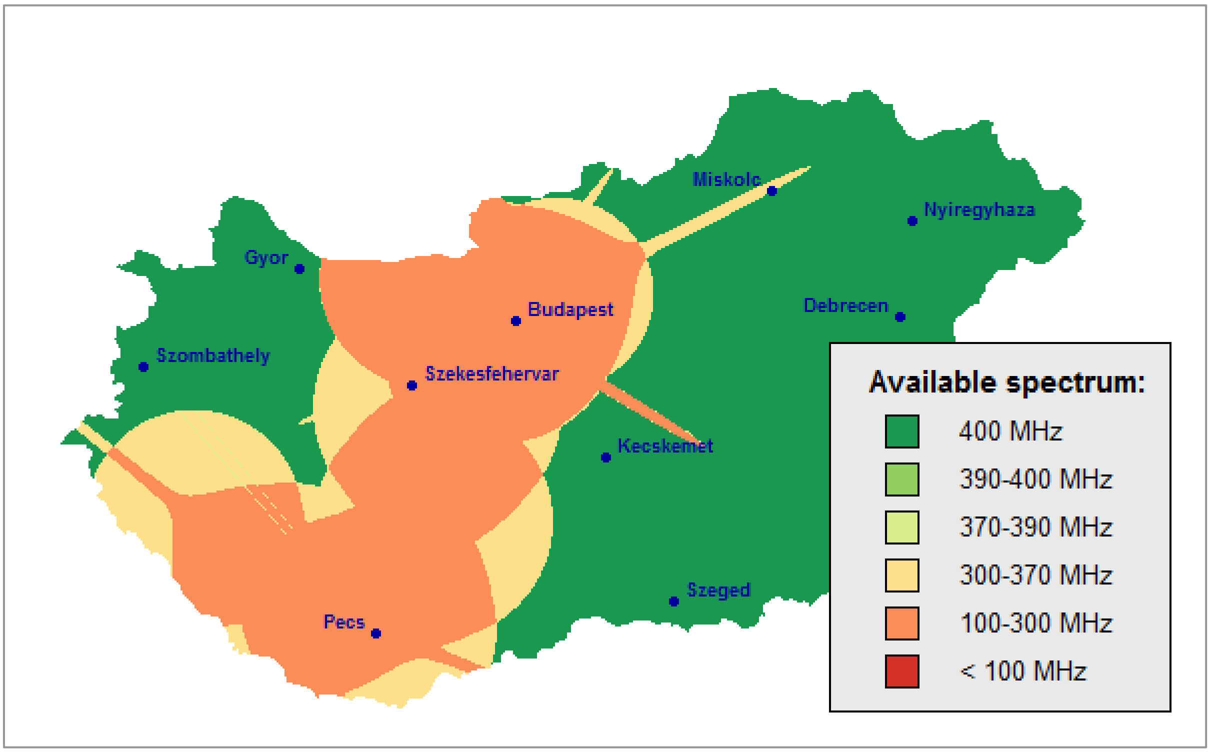


Figure A-4: Amount of spectrum (within the 3800 – 4200 MHz range) that could be available for IMT small cell use within the coordination areas around P-P fixed link receivers based on ITU-R criteria

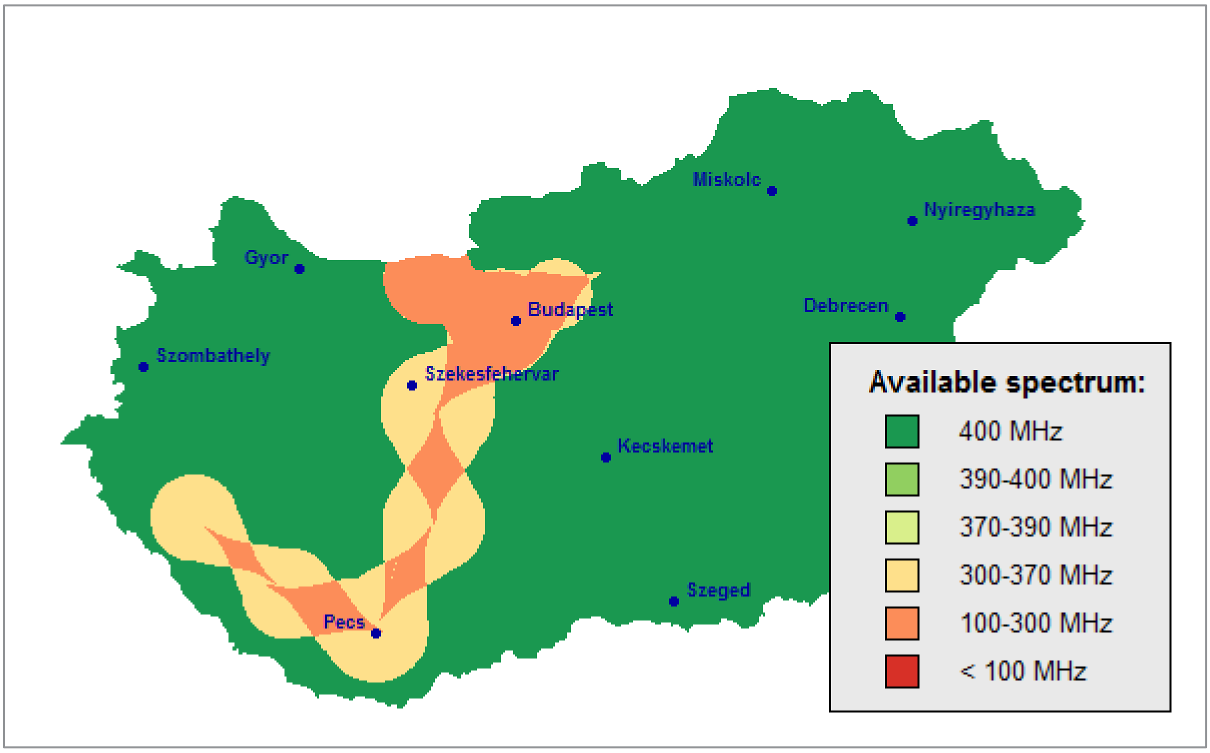


Table A-1 shows the total bandwidth available for the Macro cell and Small cell coordination zones. The total here refers to the average amount of bandwidth available across each geotype, which has been calculated based on more granular outputs from the technical studies.

- No spectrum has been considered to be available in the range **3400–3600 MH**z as this is populated by a very large number P-MP narrow band systems. Analysis shows that this leads to very fragmented spectrum being available for LTE use.
- The band **3600–3800 MHz** is vacant and has therefore been considered to be wholly available for LTE use.

The band **3800 – 4200 MHz** is used by a relatively small number of wide band point-to-point fixed links. The presence of these links reduces the amount of spectrum available for LTE use in different parts of the country. See Table A-2.

Table A-1: Spectrum availability for 3600-3800 MHz under ITU-R criteria frequency sharing scenario in Hungary

Geotype	3600-3800 MHz availability (MHz) in Macro cell coordination areas[27]	3600-3800 MHz availability (MHz) in Small cell coordination areas
Hot spot	200	200
Dense urban	200	200
Urban	200	200
Suburban	200	200
Rural	200	200

Table A-2: Spectrum availability for 3800-4200 MHz under ITU-R criteria frequency sharing scenario in Hungary

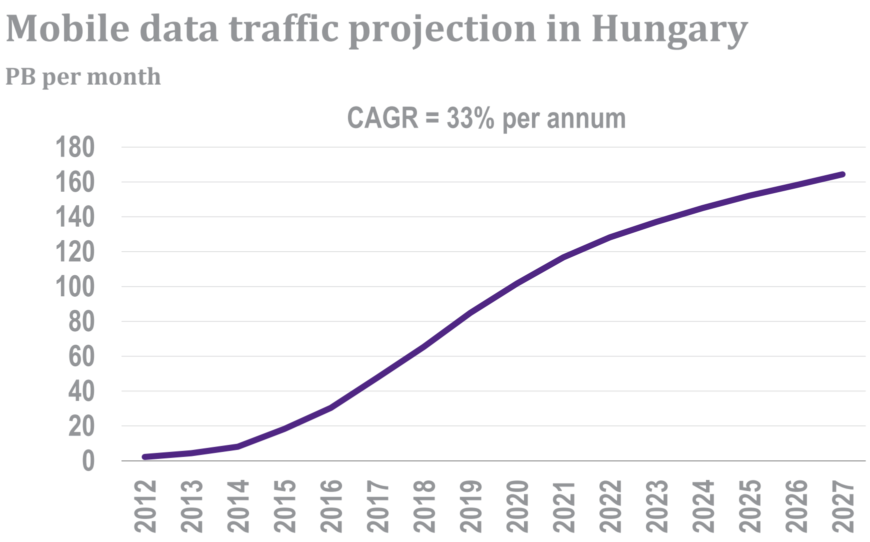
Geotype	3800-4200 MHz availability (MHz) In Macro cell coordination areas	3800-4200 MHz availability (MHz) In Small cell coordination areas
Hot spot	111	200
Dense urban	111	200
Urban	126	208
Suburban	191	261
Rural	264	309

A.1.3 Traffic demand forecast

Figure A-5 shows the mobile traffic data for Hungary used in the economic model.

[27] The coordination zones are superimposed on maps with set geotypes. Each coordination zone may straddle across affects a different distribution of geotypes: this implies each geotype has a different amount of spectrum that is available for use. We then calculate an average amount of spectrum per unit area for each geotype by sharing scenario. This applies to both 3600-3800MHz and 3800-4200MHz ranges.

Figure A-5: Hungary traffic demand forecast



Source: Cisco VNI, Plum Consulting

A.1.4 Avoided cost benefit

The benefit from avoided cost totals **EUR125m** in 2018 NPV terms. This benefit comes predominantly from the use of the C-Band in dense urban areas and hotspots to serve growing mobile data demand when the spectrum is released early

A.1.5 Country assumptions

A.1.5.1 Technical assumptions

Fixed Service systems operate in the bands 3400 – 3600 MHz and 3800 – 4200 MHz. It is understood that there are no FS operations in the 3600 – 3800 MHz band.

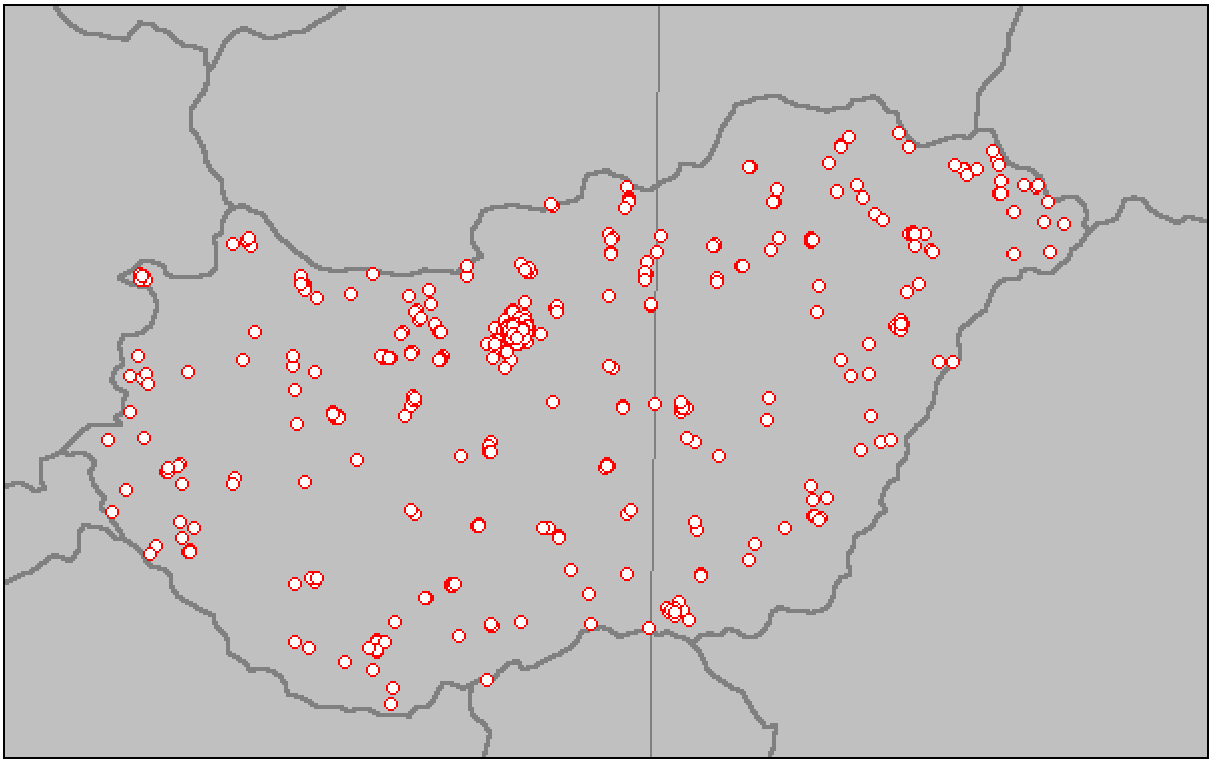
There are no Fixed Satellite Service (FSS) or other operations in the band 3400 – 4200 MHz.

3400 – 3600 MHz

There are 672 receive records (see Figure A-6) representing a mix of 1.75 MHz and 3.5 MHz channels. It is understood from ECC Report 173[28] that spectrum is made available in blocks on an unlicensed basis for Point-to-Multipoint systems in accordance with ECC Decision (07)02. It is assumed that the 672 receive records represent the base stations.

[28] ECC Report 173 - Fixed Service in Europe: Current use and future trends post 2011, including band-by-band analysis. March 2012.

Figure A-6: Base station locations



The data indicates FDD operation largely in line with CEPT Recommendation 14-03[29] with the extent of the two halves being:

3409.125 – 3494.875 MHz (85.75 MHz bandwidth)

3494.875 – 3509.125 MHz (14.25 MHz centre gap around 3500 MHz)

3509.125 – 3594.875 MHz (85.75 MHz bandwidth)

Two entries indicate use of relatively high gain antennas of 35 dBi and the remainder fall in the range 8 to 20 dBi which are probably a mix of omnidirectional and sector antennas in azimuth and having a constrained beamwidth in the elevation plane. In the absence of antenna patterns it has been assumed that antennas are omnidirectional in the horizontal plane with gain provided by directionality in the vertical plane.

The combined receive noise figure and feed loss values fall in the range 0 dB to 16.3 dB with most being 6 dB or 9 dB. A conservative assumption has been made to protect links on the basis of the most stringent value, namely 0 dB. This means that the propagation loss required with respect to the two types of IMT cell is:

Macro cell loss required = 175 + $G_{FL}(\theta)$ dB

Small cell loss required = 143 + $G_{FL}(\theta)$ dB

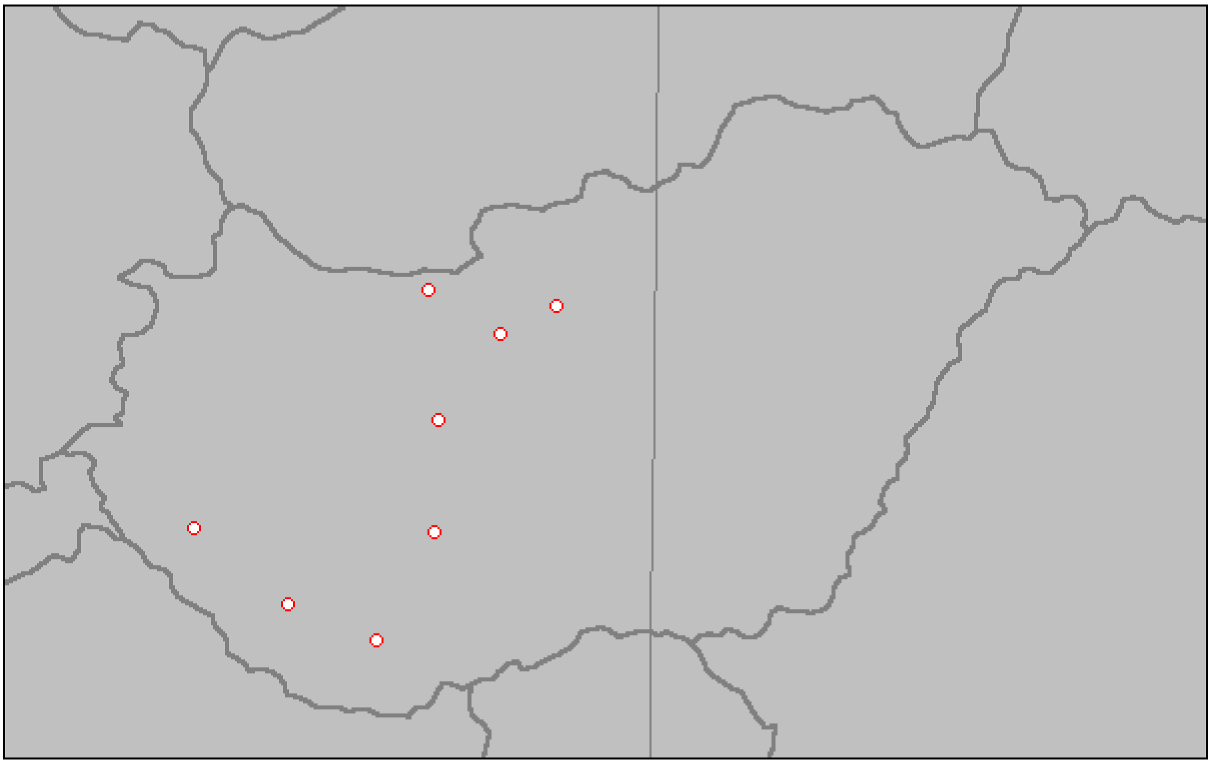
It has been assumed that the registered locations are the Base Stations and no record is held of the user terminals. Calculations have been undertaken on the basis of protecting the Base Stations.

[29] CEPT/ERC/Recommendation 14-03 – Harmonised radio frequency channel arrangements and block allocations for low and medium capacity systems in the band 3400 MHz to 3600 MHz. Turku 1996, Podebrady 1997.

3800 – 4200 MHz

There are 34 receive records (see Figure A-7) of 24 MHz and 29 MHz channels. The latter are in the majority and it is thought that the quoted narrower bandwidth channels may represent the occupied bandwidth rather that the larger channel bandwidth. ECC Report indicates that this band is for point-to-point fixed links assigned on a link by links basis in line with CEPT Recommendation 12-08[30].

Figure A-7: Point to point sites



The data indicates that operations are largely in line with CEPT Recommendation 12-08 (6 channels in the lower half of the band {3800 – 4000 MHz} and similarly 6 channels in the upper half of the band {4000 – 4200 MHz}) but with some interleaved channels. These interleaved channels skew usage slightly such that the extent of the two halves is:

3795.5 – 3984.0 MHz (188.5 MHz bandwidth)

3984.0 – 4008.5 MHz (24.5 MHz centre gap around 3996.25 MHz)

4008.5 – 4197.0 MHz (188.5 MHz bandwidth)

High gain antennas of 38.8 dBi or 41.3 dBi are used, likely 3 m and 4 m parabolics. The appropriate ITU-R Recommendation 699 antenna pattern has been assumed pending clarification of the actual antenna performance.

The combined receive noise figure and feed loss values fall in the range 3.16 dB to 5.56 dB dB. A conservative assumption has been made to protect links on the basis of the most stringent value,

[30] CEPT/ERC/Recommendation 12-08 – Harmonised radio frequency channel arrangements and block allocations for low, medium and high capacity systems in the band 3600 MHz to 4200 MHz. Podebrady 1997, Saariselka 1998.

namely 3 dB. This means that the propagation loss required with respect to the two types of IMT cell is:

Macro cell loss required = 172 + $G_{FL}(\theta)$ dB

Small cell loss required = 140 + $G_{FL}(\theta)$ dB

A.1.5.2 Demographic assumptions

Table A-3: Hungary demographic assumptions

Parameter	Value used	Source
Area size by geotype ('000 sqkm)		Plum's calculations based on population data from ESRI
Hotspot	0.02	
Dense urban	0.01	
Urban	0.14	
Suburban	7.24	
Rural	86.02	

A.1.5.3 Market and network assumptions

Table A-4: Hungary market and network assumptions

Parameter	Value used	Source
Number of operators	3	Plum based on publicly available data from national regulators' websites
Monthly data consumption (PB/month)		Plum's projection based on regulators' historical data and CISCO VNI projections
2012	2	
2015	18	
2020	102	
2025	152	
2030	185	
Averate total sites[31] per sqkm in 2014:		Plum's estimates based on site density estimates from national regulators and their websites or total base station statistics released into the public domain by operators
Hotspot	50	
Dense urban	12	
Urban	6	
Suburban	1	
Rural	0.1	

[31] A site that is shared by multiple operators is counted as multiple sites.

A.1.5.4 Spectrum assumptions

Shows the total amount of downlink spectrum assumed to be available and in use in the different bands for the entire market (MHz) outside of the restriction areas that are the output of the technical studies.

Table A-5: Total downlink spectrum available outside of restriction zones

Band	2014	2016	2018	2020	2022	2024	2026	2028	2030
700MHz[32]	0	0	0	0	0	0	30	30	30
800MHz	20	20	30	30	30	30	30	30	30
900MHz	17	22	26	30	30	30	30	30	30
1.4GHz[33]	0	30	40	50	52	56	60	60	60
1.8GHz	13	26	38	50	60	70	70	70	70
2.1GHz	45	45	45	45	45	45	45	45	45
2.3GHz TDD	0	0	0	45	45	45	50	50	50
2.6GHz TDD	0	19	19	19	19	19	19	19	19
2.6GHz	47	70	70	70	70	70	70	70	70
3.4-3.6GHz TDD	0	21	63	105	105	150	150	150	150
3.6-3.8GHz TDD	0	0	0	0	0	0	150	150	150
3.8-4.2GHz TDD	0	0	0	0	0	0	0	300	300

The following points should be noted:

- For all TDD spectrum bands, it is assumed that 3/4 of all the timeslots are used for downlink transmission in order to support a downlink to uplink ratio of 3:1. Therefore, for simplicity, we assume that a bandwidth equivalent to 3/4 of the total bandwidth is used for downlink transmission.
- Linear interpolation is used to estimate the bandwidth in the years between 2012, 2015, 2020, 2025 and 2030. This gives rise to bandwidth sizes that are rounded to the nearest whole rather than the nearest 10.
- In the case of 3400-3600 MHz it is expected that it will become available for MFCN systems beyond 2016
- In the case 0f 3600-3800 MHz it is expected that the spectrum will become available for use earlier than shown in Table A-5 but that practical exploitation may lag some time behind spectrum availability
- In the case of 3800-4200 MHz there are no current plans for release

[32] The release of 700 MHz could occur earlier if regulatory developments permit

[33] 1452-1492 will be made available in accordance with EC Decision EU2015/750. Other parts of the band in the range 1375-1400 MHz and 1427-1452 MHz will be released as conditions allow

- In the case of 2.3GHz, it is assumed a total of 70 MHz will be released by 2025 based on a previous Plum's study on the use of the band for Qualcomm for mobile[34].

[34] http://www.plumconsulting.co.uk/pdfs/Plum_Dec2013_Economic_benefits_of_LSA_2.3_GHz_in_Europe.pdf

A.2 Italy

A.2.1 Technical analysis

A.2.1.1 C-Band FSS ES

The Earth Station site that has been confirmed to use C-band frequencies is situated at Fucino which is 90 km east of Rome. The site is intentionally located in an extinct volcano crater which provides effective screening in all directions. Analysis indicates that the LTE exclusion area around the site extends little further that the crater itself and therefore any impact is limited to the population within the crater which is 70,000. The impact of such a number on the economic analysis is negligible and has been ignored.

A.2.1.2 Fixed links

This data is confidential.

A.2.1.3 Mobile transmitters

Two cases are considered:

Macro cell (outdoor) EIRP = 63 dBm in 30 MHz

Small cell (outdoor) EIRP = 30.8 dBm in 30 MHz.

A.2.2 Spectrum availability

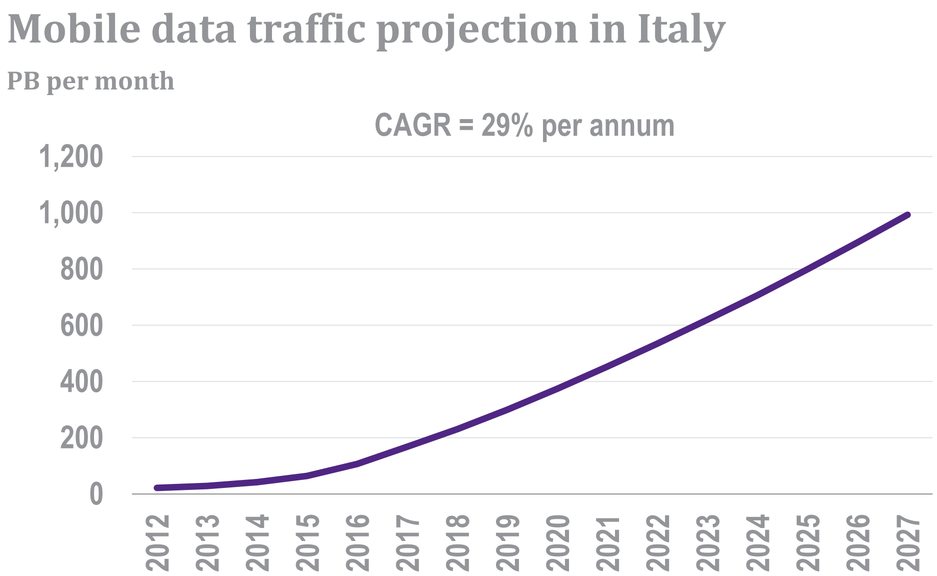
Table A-6 shows the total bandwidth available for the Macro cell and Small cell coordination zones. The total here refers to the average amount of bandwidth available across each geotype, which has been calculated based on more granular outputs from the technical studies.

Table A-6: Spectrum availability for 3800-4200 MHz under ITU-R criteria frequency sharing scenario in Italy

Geotype	3600-4200 MHz availability (MHz) In Macro cell coordination areas	3600-4200 MHz availability (MHz) In Small cell coordination areas
Hot spot	431	506
Dense urban	443	505
Urban	449	496
Suburban	465	513
Rural	468	518

A.2.3 Traffic demand forecast

Figure A-8: Italy traffic demand forecast



Source: PTS, Cisco VNI, Plum Consulting

A.2.4 Avoided cost benefit

The benefit from avoided cost totals **EUR940m** in 2018 NPV terms. This benefit comes exclusively from the use of the C-Band in hotspots to serve growing mobile data demand when the spectrum is released early. This is due to the fact that the high population density of hotspots will drive mobile data traffic growth beyond the capacity of existing and forecast radio network infrastructure. In other geotypes, the existing level of infrastructure supply will be sufficient to cope with future traffic demand throughout the modelling period.

A.2.5 Country assumptions

Fondazione Ugo Bordoni (FUB) have access to the confidential data for fixed links and have undertaken the necessary analysis to determine what spectrum would be available for LTE and to what parts of the population in different geotypes. Some of their technical assumptions are shown in Section 2.5.1 below[35].

A.2.5.1 Technical assumptions

The interference from a single IMT base station seen from the FS receiver station under a discrete set of azimuth angles has been computed to determine the minimum reuse distances along each specific direction. The result is presented as a plot of required minimum reuse distance between the FS

[35] Note that the study is based on a partial set of fixed link data and the the spectrum availability results represent an upper bound for the spectrum likely to be available for mobile data services

receiver station and the IMT base station. Therefore, a contour may be drawn around the FS receiver station that delimits the exclusion zone outside which interference protection requirements are met, as a function of the IMT BS EIRP. Macro cellular layout obviously corresponds to larger exclusion zones.

Figure A-9 shows the separation distance between FS receiver and IMT base station for macro cell and small cell layouts, under the assumptions in Table A-7.

The co-channel separation distance is between 44 km and 93 km for macro cell layout and between 2 km and 58 km for small cell layout.

Figure A-9: FS receiver vs IMT transmitter exclusion zones

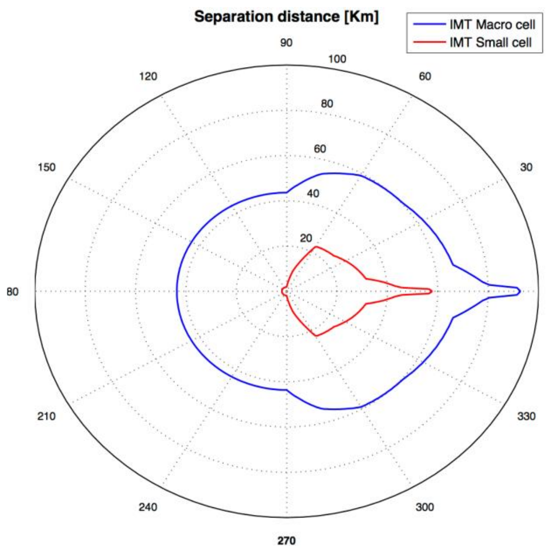


Table A-7: IMT base station characteristics

Parameter	Macro cell	Small cell
EIRP	63 dBm/30 MHz 48.2 dBm/MHz	30.8 dBm/30 MHz 16 dBm/MHz
Height	30m	6m
Pattern	Omni directional	Omni directional

Figure A-10 depicts an example of exclusion zones for the different values of BS EIRP in a hypothetical location of a FS receiver station. Figure A-11 shows the exclusion zones for both end-points of the considered FS link. In this latter figure, the overlapping area of the two exclusion zones determined for each of the end-point of the FS link delimits a region where the usage of both 30 MHz channels in the lower and upper half of the 3.6-4.2 GHz band is not allowed.

Figure A-10: FS receiver vs IMT transmitter exclusion zones

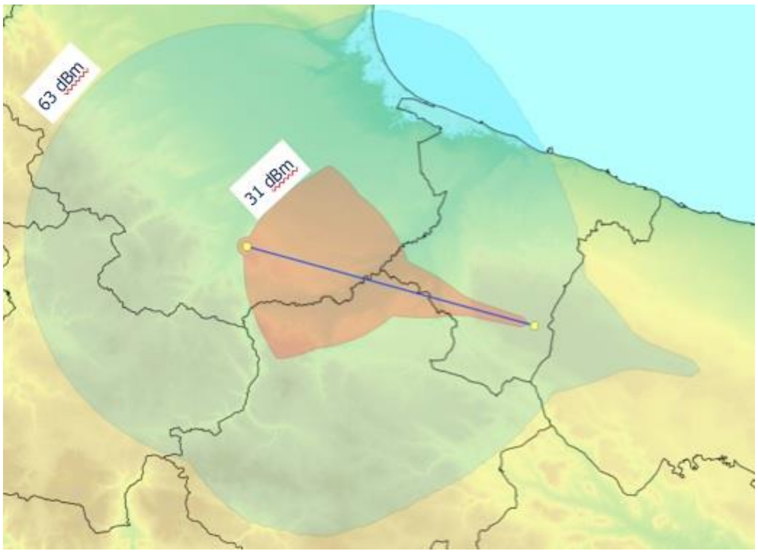
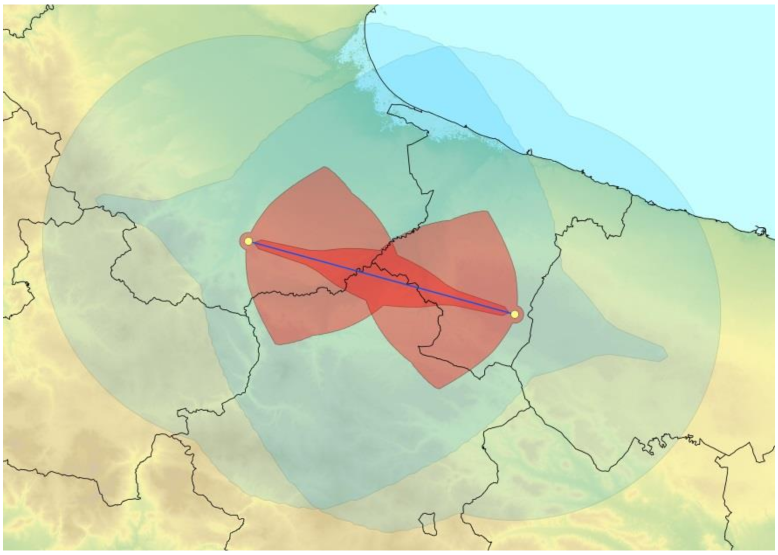


Figure A-11: FS link vs IMT transmitter exclusion zones



A.2.5.2 Demographic assumptions

Table A-8: Italy demographic assumptions

Parameter	Value used	Source
Area size by geotype ('000 sqkm)		
Hotspot	0.08	Plum's calculations based on population data from ESRI
Dense urban	0.10	
Urban	1.86	
Suburban	32.64	
Rural	275.05	

A.2.5.3 Market and network assumptions

Table A-9: Italy market and network assumptions

Parameter	Value used	Source
Number of operators	4	Plum based on publicly available data from national regulators' websites
Monthly data consumption (PB/month)		Plum's projection based on regulators' historical data and CISCO VNI projections
2012	22	
2015	64	
2020	374	
2025	798	
2030	1,285	
Averate total sites[36] per sqkm in 2014:		Plum's estimates based on site density estimates from national regulators and their websites or total base station statistics released into the public domain by operators
Hotspot	37	
Dense urban	15	
Urban	7	
Suburban	1.2	
Rural	0.1	

A.2.5.4 Spectrum assumptions

Table A-10 shows the total amount of downlink spectrum assumed to be available and in use in the different bands for the entire market (MHz) outside of the restriction areas that are the output of the technical studies.

Table A-10: Total downlink spectrum available outside of restriction zones

Band	2014	2016	2018	2020	2022	2024	2026	2028	2030
700MHz	0	0	0	0	0	0	30	30	30
800MHz	20	20	30	30	30	30	30	30	30
900MHz	17	22	26	30	30	30	30	30	30
1.4GHz	0	40	50	50	52	56	60	60	60
1.8GHz	13	26	38	50	60	70	70	70	70
2.1GHz	60	60	60	60	60	60	60	60	60
2.3GHz TDD	0	0	0	45	45	45	60	60	60
2.6GHz TDD	0	23	23	23	23	23	23	23	23
2.6GHz	47	70	70	70	70	70	70	70	70

[36] A site that is shared by multiple operators is counted as multiple sites.

Band	2014	2016	2018	2020	2022	2024	2026	2028	2030
3.4-3.6GHz TDD	0	24	71	95	95	150	150	150	150
3.6-3.8GHz TDD	0	0	0	0	0	0	150	150	150
3.8-4.2GHz TDD	0	0	0	0	0	0	0	300	300

The following points should be noted:

- For all TDD spectrum bands, it is assumed that 3/4 of all the timeslots are used for downlink transmission in order to support a downlink to uplink ratio of 3:1. Therefore, for simplicity, we assume that a bandwidth equivalent to 3/4 of the total bandwidth is used for downlink transmission.
- Linear interpolation is used to estimate the bandwidth in the years between 2012, 2015, 2020, 2025 and 2030. This gives rise to bandwidth sizes that are rounded to the nearest whole rather than the nearest 10.
- In the case of 2.3GHz, it is assumed a total of 80 MHz will be released by 2025 based on a previous Plum's study on the use of the band for Qualcomm for mobile[37].

[37] http://www.plumconsulting.co.uk/pdfs/Plum_Dec2013_Economic_benefits_of_LSA_2.3_GHz_in_Europe.pdf

A.3 Sweden

A.3.1 Technical analysis

Based on a current situation snap-shot of confidential data held by the Swedish administration, a total of 100 MHz needs to be protected across the whole country for FSS use.

A.3.2 Spectrum available

Table A-11 shows the total bandwidth available for the Macro cell and Small cell coordination zones.

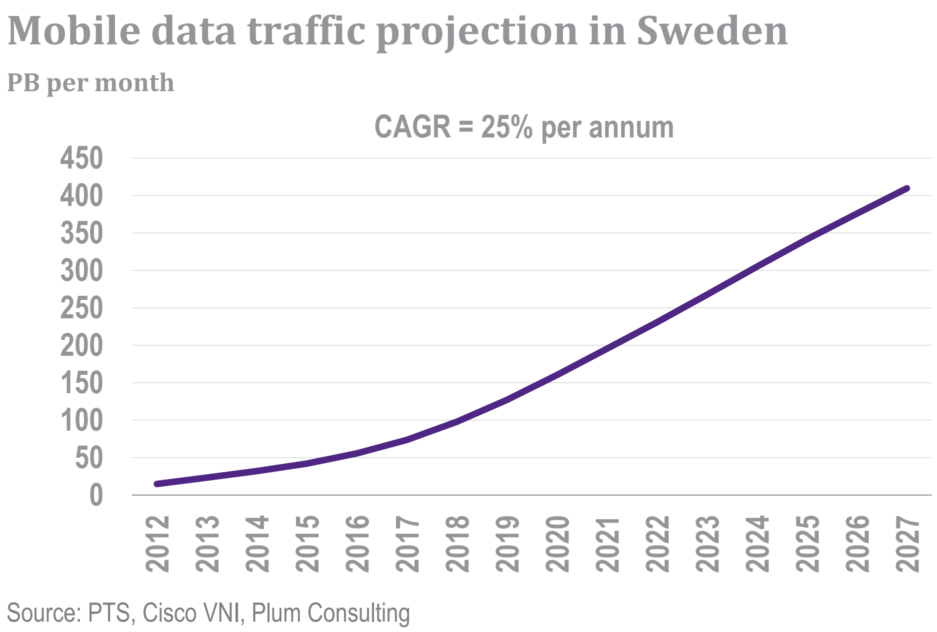
Table A-11: Spectrum availability for 3800-4200 MHz under ITU-R criteria frequency sharing scenario in Italy

Geotype	3600-4200 MHz availability (MHz) In Macro cell coordination areas	3600-4200 MHz availability (MHz) In Small cell coordination areas
Hot spot	500	500
Dense urban	500	500
Urban	500	500
Suburban	500	500
Rural	500	500

A.3.3 Traffic data

Figure A-12 shows the mobile traffic data for Sweden used in the economic model. The total here refers to the average amount of bandwidth available across each geotype, which has been calculated based on more granular outputs from the technical studies.

Figure A-12: Sweden mobile traffic data forecast



A.3.4 Avoided cost benefit

The benefit from avoided cost totals **EUR293m** in 2018 NPV terms. The benefit comes exclusively from the use of the C-Band in hotspots to serve growing mobile data demand when the spectrum is released early. This is due to the fact that the high population density of hotspots will drive mobile data traffic growth beyond the capacity of existing and forecast radio network infrastructure. In other geotypes, the existing level of infrastructure supply will be sufficient to cope with future traffic demand throughout the modelling period.

A.3.5 Country assumptions

A.3.5.1 Technical assumptions

Information regarding the deployment of systems in the band is regarded as confidential by the Administration. It is however known that the band is only used for Fixed Satellite Service earth stations which are spread across the country. It has been agreed that 100 MHz of the band will not be available in order to protect existing FSS operations. Further, it is known that the remaining spectrum that could be available for LTE use is not detrimentally fragmented. The spectrum being used by the FSS is in three relatively evenly spread portions across the band leaving four portions, each of significant size, for use by LTE.

A.3.5.2 Demographic assumptions

Table A-12: Sweden demographic assumptions

Parameter	Value used	Source
Area size by geotype ('000 sqkm)		Plum's calculations based on population data from ESRI
Hotspot	0.03	
Dense urban	0.03	
Urban	0.22	
Suburban	5.45	
Rural	444.18	

A.3.5.3 Market and network assumptions

Table A-13: Sweden market andnetwork assumptions

Parameter	Value used	Source
Number of operators	4	Plum based on publicly available data from national regulators' websites
Monthly data consumption (PB/month)		Plum's projection based on regulators' historical data and CISCO VNI projections
2012	13	
2015	43	
2020	142	
2025	270	
2030	380	
Averate total sites per sqkm in 2014:		Plum's estimates based on site density estimates from national regulators and their websites or total base station statistics released into the public domain by operators
Hotspot	50	
Dense urban	50	
Urban	30	
Suburban	1.3	
Rural	0.03	

A.3.5.4 Spectrum assumptions

Table A-14 shows the total amount of downlink spectrum assumed to be available and in use in the different bands for the entire market (MHz) outside of the restriction areas that are the output of the technical studies.

Table A-14: Total downlink spectrum available outside of restriction zones

Band	2014	2016	2018	2020	2022	2024	2026	2028	2030
700MHz	0	0	30	30	30	30	30	30	30
800MHz	20	20	30	30	30	30	30	30	30

Band	2014	2016	2018	2020	2022	2024	2026	2028	2030
900MHz	17	22	26	30	30	30	30	30	30
1.4GHz	0	0	40	40	52	56	60	60	60
1.8GHz	13	26	38	50	60	70	70	70	70
2.1GHz	60	60	60	60	60	60	60	60	60
2.3GHz TDD	0	0	0	45	45	45	60	60	60
2.6GHz TDD	0	38	38	38	38	38	38	38	38
2.6GHz	47	70	70	70	70	70	70	70	70
3.4-3.6GHz TDD	0	84	84	150	150	150	150	150	150
3.6-3.8GHz TDD	0	0	0	0	0	0	124	124	124
3.8-4.2GHz TDD	0	0	0	0	0	0	0	251	251

The following points should be noted:

- For all TDD spectrum bands, it is assumed that 3/4 of all the timeslots are used for downlink transmission in order to support a downlink to uplink ratio of 3:1. Therefore, for simplicity, we assume that a bandwidth equivalent to 3/4 of the total bandwidth is used for downlink transmission.
- Linear interpolation is used to estimate the bandwidth in the years between 2012, 2015, 2020, 2025 and 2030. This gives rise to bandwidth sizes that are rounded to the nearest whole rather than the nearest 10.
- In the case of 2.3GHz, it is assumed a total of 80 MHz will be released by 2025 based on a previous Plum's study on the use of the band for Qualcomm for mobile[38].

[38] http://www.plumconsulting.co.uk/pdfs/Plum_Dec2013_Economic_benefits_of_LSA_2.3_GHz_in_Europe.pdf

A.4 UK Country results and data

A.4.1 Technical analysis

A.4.1.1 C-Band FSS ES

The input data for the C-Band FSS ES is the same as that used in Plum's previous study[39].

A.4.1.2 Fixed link receivers

Ofcom has provided technical data on the fixed links using the 4 GHz part of C-band – see Table A-21 for a summary.

There are nearly 200 fixed link carriers being received across the UK. They are located across the South of England, near Manchester and Aberdeen, and across to the Western Isles, Orkney and the Shetland islands. All carriers conform to the Ofcom 30 MHz channel plan specified in OfW446[40] and which is based on ITU-R Recommendation 635.

Protection of these links (see Table A-21 and the text below the table) has been based on the I/N criterion specified in ITU-R Recommendation 758 but taking account of the system noise figure and losses applied by Ofcom in the OfW446 planning process.

A.4.1.3 Mobile transmitters

As before two cases are considered:

Macro cell (outdoor) EIRP = 61 dBm in 20 MHz

Small cell (outdoor) EIRP = 29 dBm in 20 MHz

A.4.2 Spectrum available

Based on parameter values summarised in the preceding section and provided in more detail in Section A4.5.1, spectrum availability is summarised for six cases:

- With respect to macro cell transmitters and:
  - Earth station receivers (from previous work) - Figure A-13
  - Fixed link receivers - Figure A-14
- Earth station and fixed link receivers combined - Figure A-15
- With respect to small cell transmitters and:
  - Earth station receivers (from previous work) - Figure A-16

[39] Section 2 and Appendix A of http://plumconsulting.co.uk/pdfs/Plum_Oct2014_Economic_benefits_from_C_band_use_for_mobile_broadband_in_UK.pdf

[40] http://stakeholders.ofcom.org.uk/binaries/spectrum/spectrum-policy-area/spectrum-management/research-guidelines-tech-info/tfac/ofw446.pdf

- Fixed link receivers - Figure A-17
- Earth station and fixed link receivers combined - Figure A-18

Table A-15 to Table A-20 show the total bandwidth available for the two types of coordination zones and the three different frequency sharing scenarios in the UK. The total here refers to the average amount of bandwidth available across each geotype, which has been calculated based on more granular outputs from the technical studies.

Table A-15: Spectrum availability for 3600-3800 MHz under ITU-R criteria frequency sharing scenario in the UK

Geotype	3600-3800 MHz availability (MHz) in Macro cell coordination areas	3600-3800 MHz availability (MHz) in Small cell coordination areas
Hot spot	95	106
Dense urban	103	116
Urban	133	147
Suburban	155	178
Rural	161	186

Table A-16: Spectrum availability for 3800-4200 MHz under ITU-R criteria frequency sharing scenario in the UK

Geotype	3800-4200 MHz availability (MHz) In Macro cell coordination areas	3800-4200 MHz availability (MHz) In Small cell coordination areas
Hot spot	0	156
Dense urban	6	197
Urban	84	243
Suburban	124	299
Rural	165	328

Table A-17: Spectrum availability for 3600-3800 MHz under link performance aware frequency sharing scenario in the UK

Geotype	3600-3800 MHz availability (MHz) In Macro cell coordination areas	3600-3800 MHz availability (MHz) In Small cell coordination areas
Hot spot	95	106
Dense urban	104	116
Urban	131	147
Suburban	151	179
Rural	166	186

Table A-18: Spectrum availability for 3800-4200 MHz under link performance aware frequency sharing scenario in the UK

Geotype	3800-4200 MHz availability (MHz) In Macro cell coordination areas	3800-4200 MHz availability (MHz) In Small cell coordination areas
Hot spot	10	190
Dense urban	36	208
Urban	114	250
Suburban	176	311
Rural	227	334

Table A-19: Spectrum availability for 3600-3800 MHz under advanced frequency sharing scenario in the UK

Geotype	3600-3800 MHz availability (MHz) In Macro cell coordination areas	3600-380 MHz availability (MHz) In Small cell coordination areas
Hot spot	95	106
Dense urban	104	116
Urban	134	147
Suburban	156	180
Rural	172	186

Table A-20: Spectrum availability for 3800-4200 MHz under advanced frequency sharing criteria in the UK

Geotype	3800-4200 MHz availability (MHz) In Macro cell coordination areas	3800-4200 MHz availability (MHz) In Small cell coordination areas
Hot spot	103	190
Dense urban	130	208
Urban	189	251
Suburban	217	311
Rural	251	334

Figure A-13: Amount of spectrum (within the 3600 – 4200 MHz range) that could be available for IMT macro-cell use within the coordination areas around earth station receivers based on ITU-R criteria

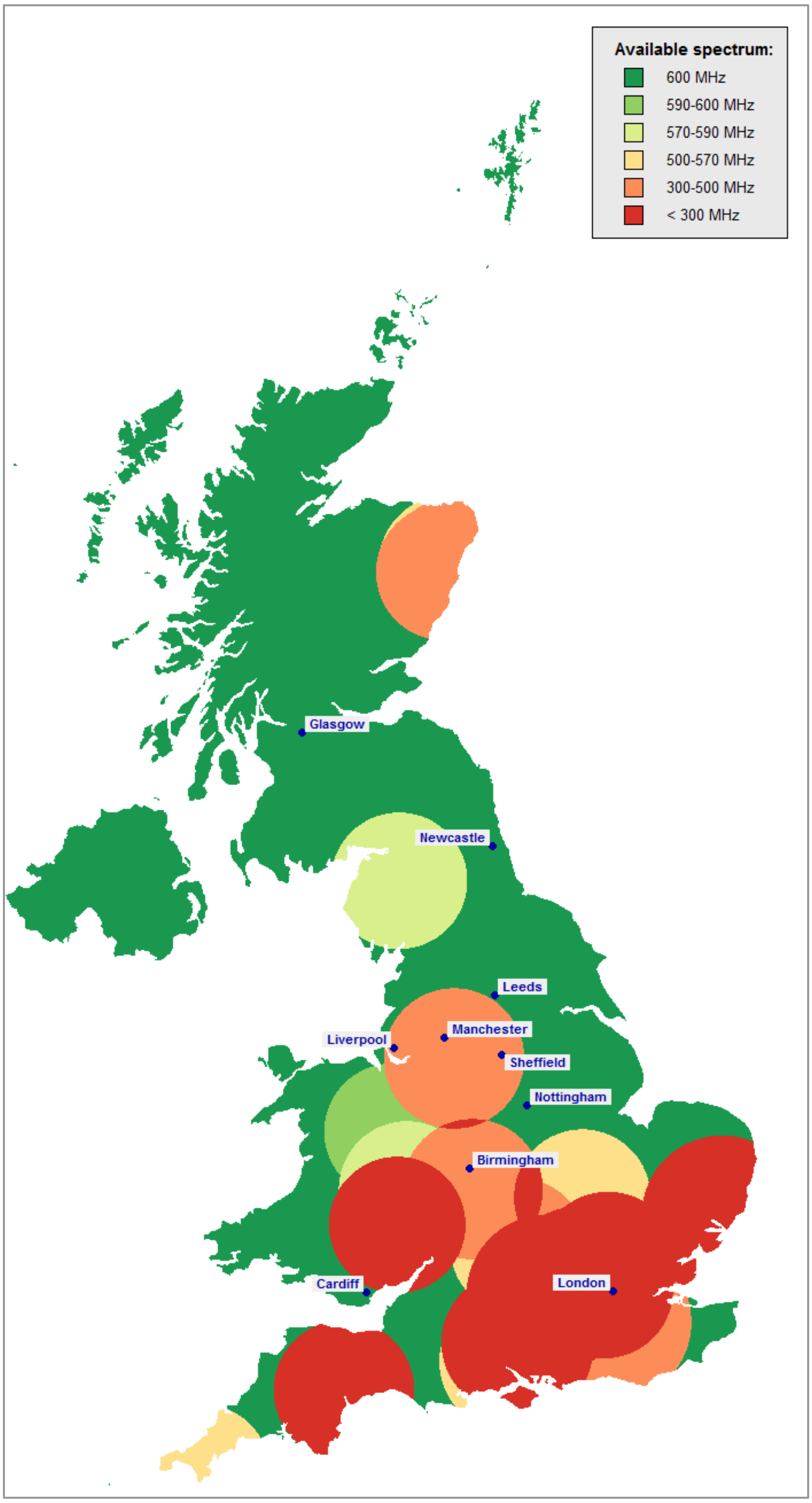


Figure A-14: Amount of spectrum (within the 3600 – 4200 MHz range) that could be available for IMT macro-cell use within the coordination areas around fixed link receivers based on ITU-R criteria

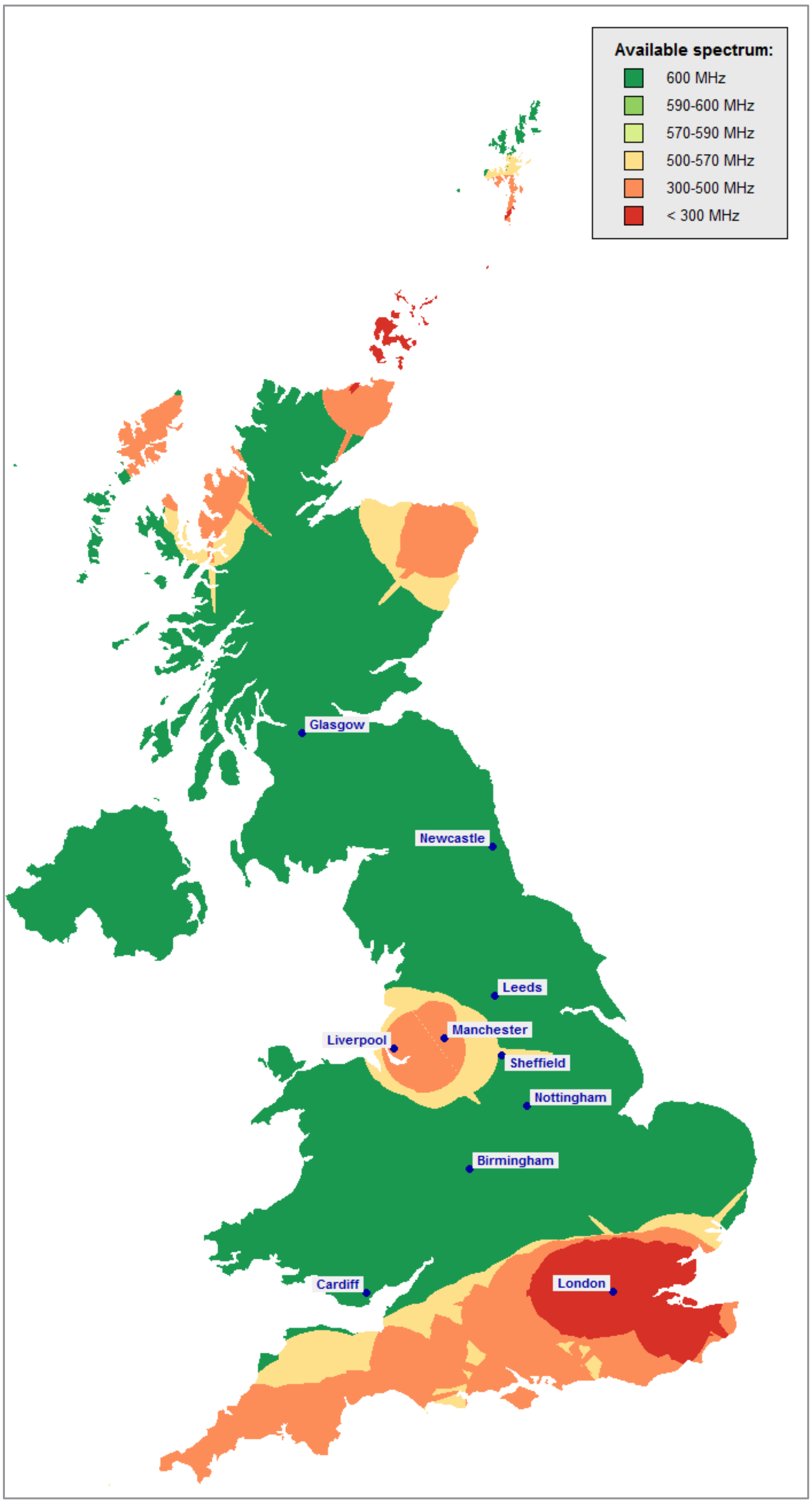


Figure A-15: Amount of spectrum (within the 3600 – 4200 MHz range) that could be available for IMT macro-cell use within the coordination areas around earth station and fixed link receivers combined based on ITU-R criteria

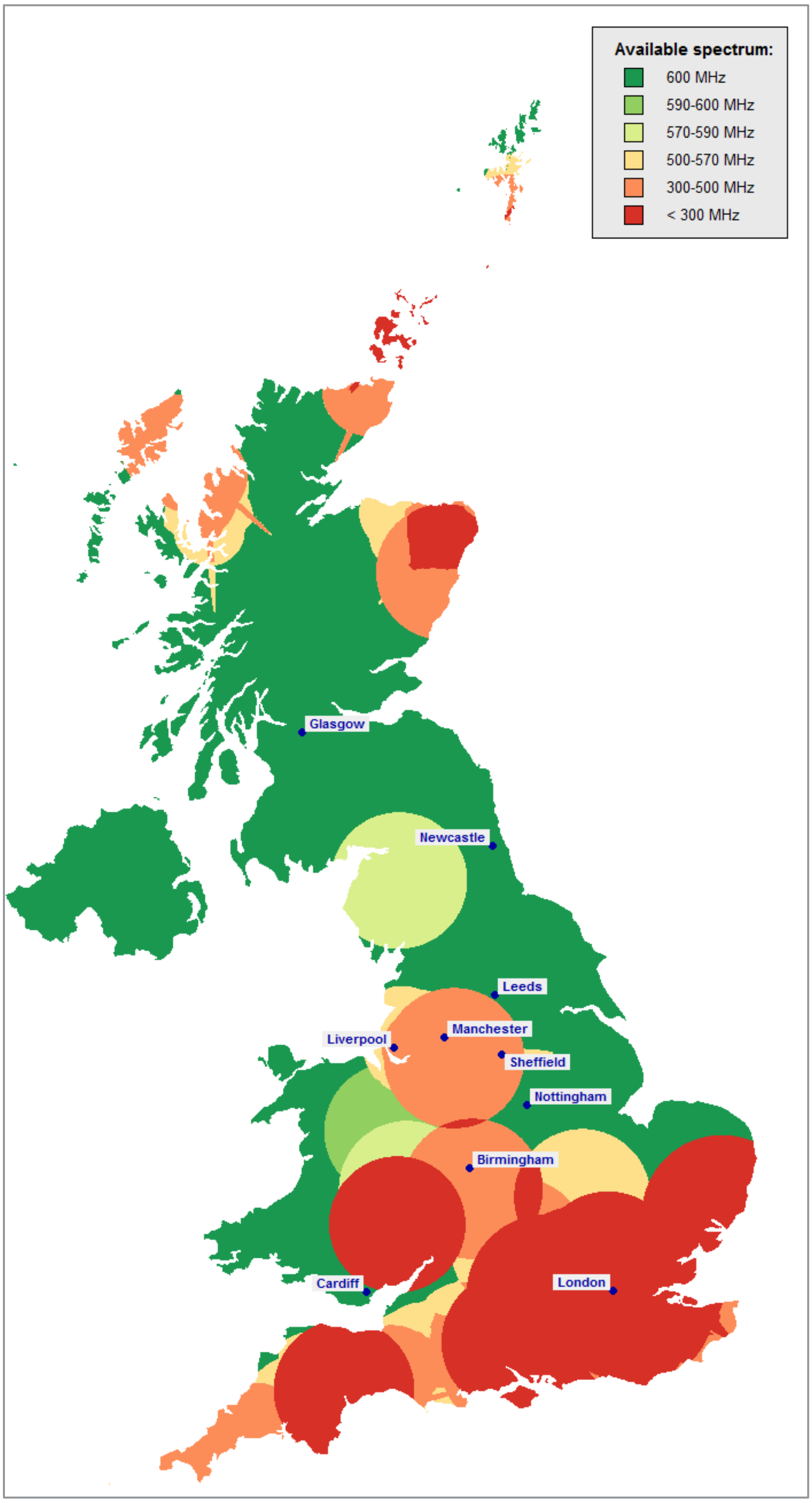


Figure A-16: Amount of spectrum (within the 3600 – 4200 MHz range) that could be available for IMT small cell use outdoors within the coordination areas around earth station receivers based on ITU-R criteria

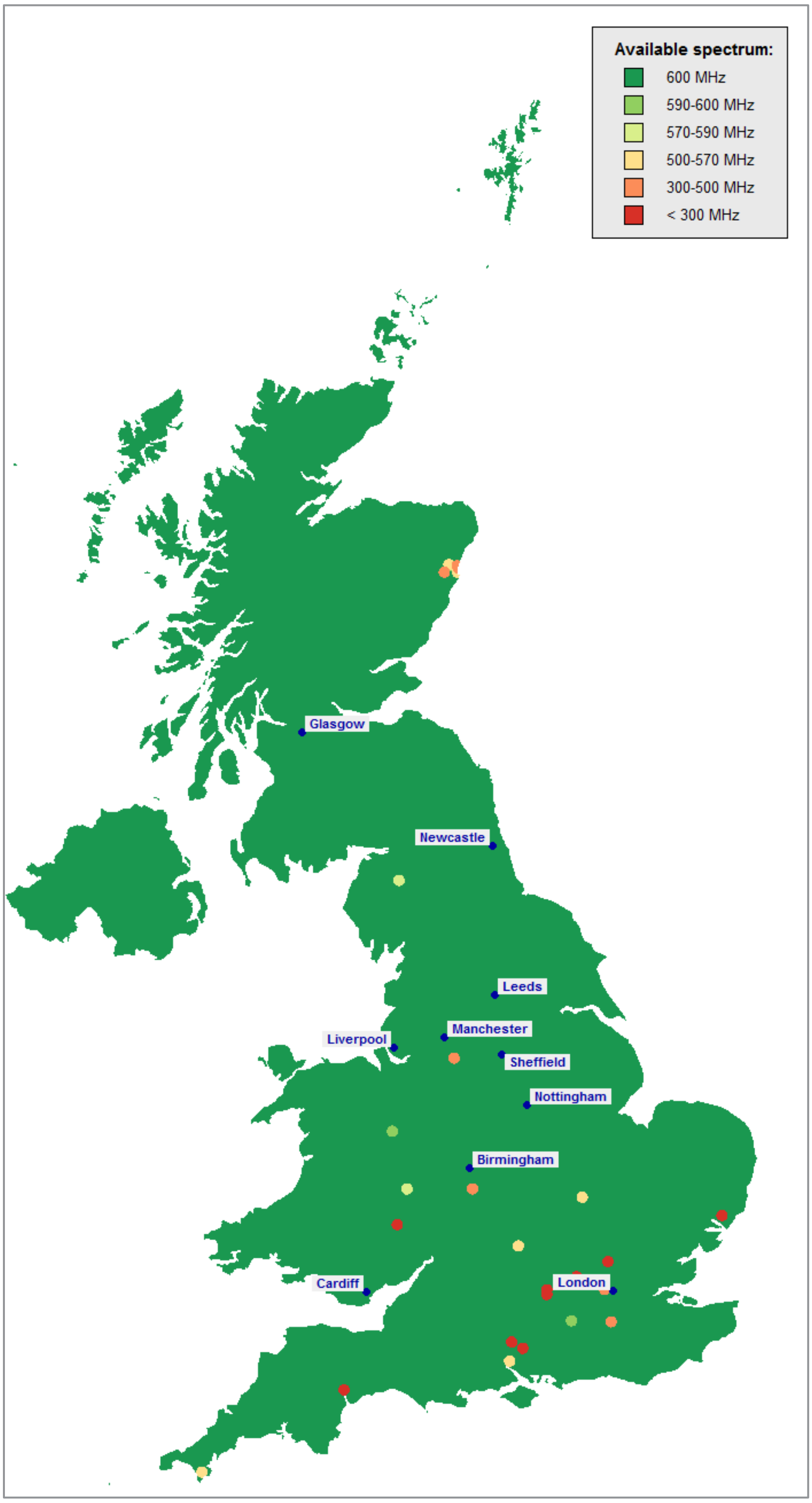


Figure A-17: Amount of spectrum (within the 3600 – 4200 MHz range) that could be available for IMT small cell use outdoors within the coordination areas around fixed link receivers based on ITU-R criteria

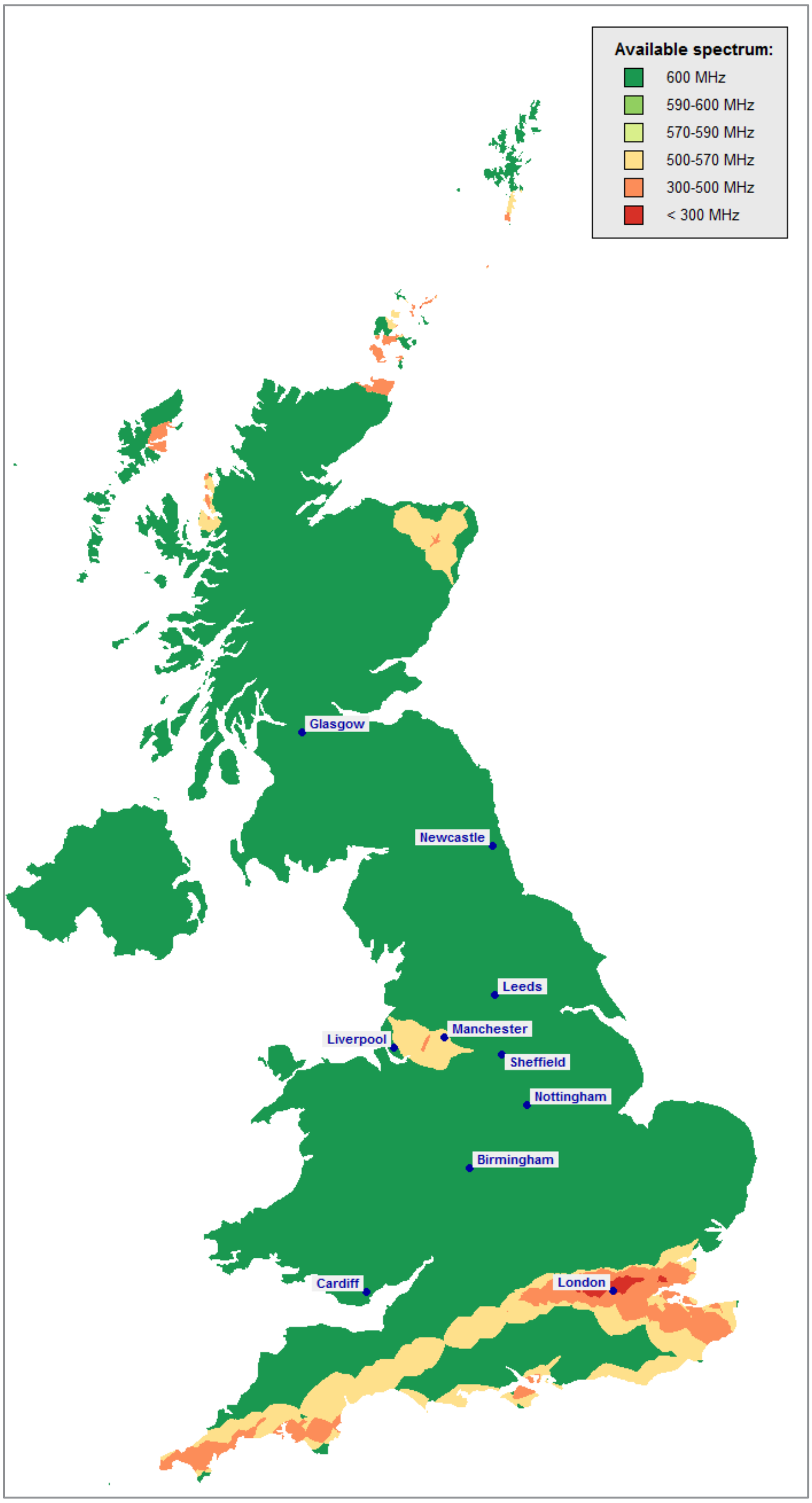
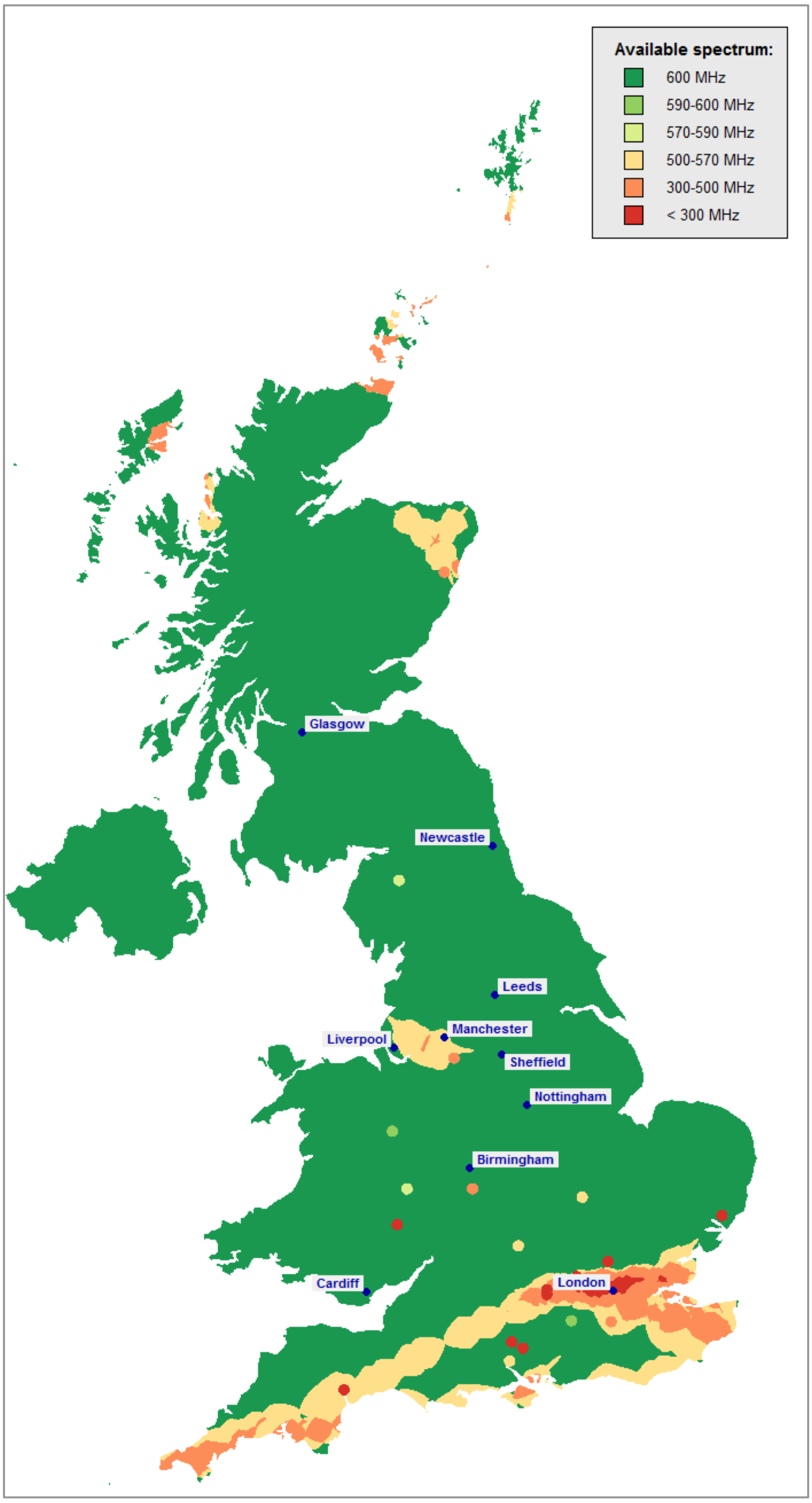
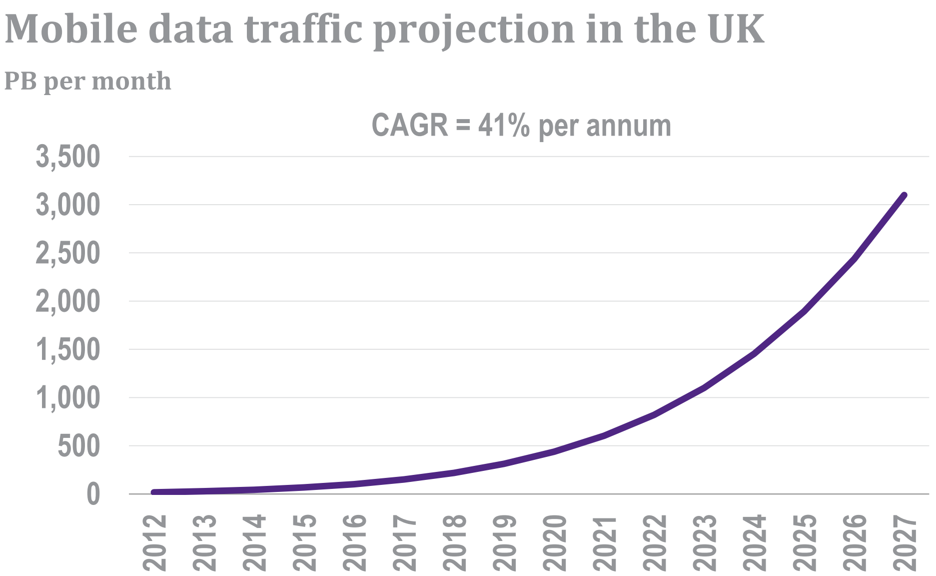


Figure A-18: Amount of spectrum (within the 3600 – 4200 MHz range) that could be available for IMT small cell use outdoors within the coordination areas around earth station and fixed link receivers combined based on ITU-R criteria



A.4.3 Traffic demand forecast

Figure A-19: UK mobile data traffic forecast

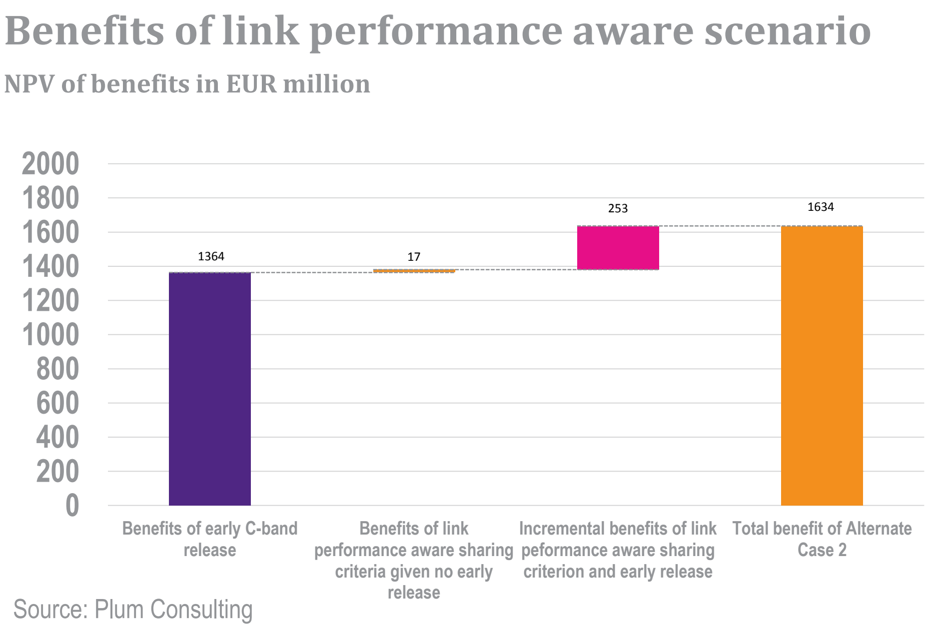


Source: Ofcom, Cisco VNI, Plum Consulting

A.4.4 Avoided cost benefit

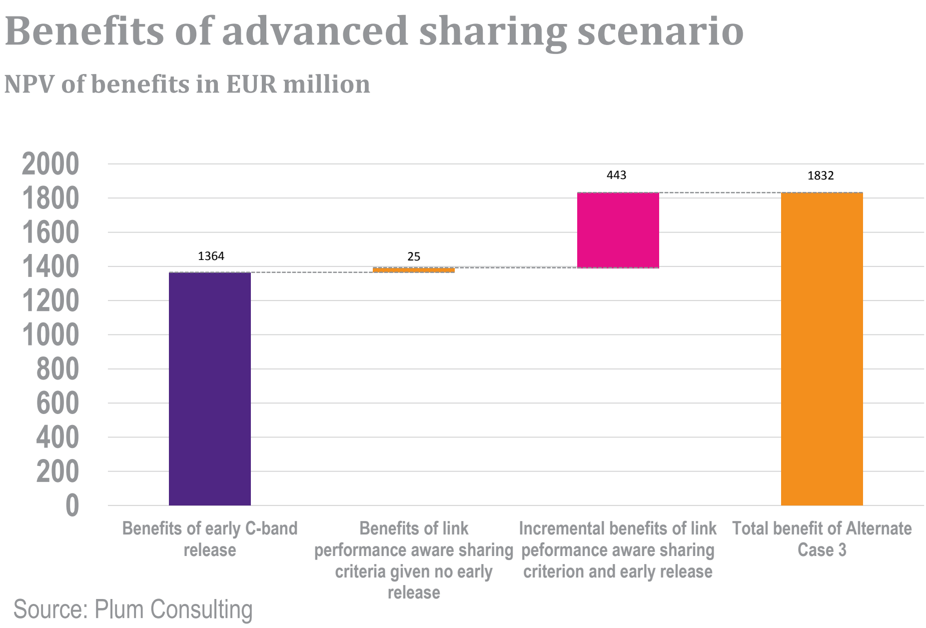
The benefit from avoided cost totals **EUR1.4bn** in 2018 NPV terms. The application of link performance aware and advanced frequency sharing for satellite services was also modelled in the UK and the resulting benefit when these techniques are used is EUR1.6bn and EUR1.8bn respectively. The breakdown of the incremental benefits from early release and the use of more advanced sharing techniques are shown in Figure A-20 and Figure A-21 respectively. It is also worth noting that in the UK the benefit comes from all geotypes except rural, due to large increases in expected traffic demand towards the end of the modelling period across all geotypes.

Figure A-20: UK link performance aware



Source: Plum Consulting

Figure A-21: UK advanced frequency sharing



Source: Plum Consulting

A.4.5 Country assumptions

A.4.5.1 Technical assumptions

Table A-21: UK technical assumptions

Fixed link parameter	Value	Comment
Location	See Figure A-22	
Pointing	See Figure A-22	
Height (above ground level)	15 m – 200 m	50 m most common
Antenna gain	30.8 dBi – 42.7 dBi	Parabolic 1.2 m – 4.6 m diameter D/λ = 16 – 61.3
Antenna pattern	See Figure A-23	
Feed loss	Not specified	See derivation of criterion for implicit assumption regarding feed loss.
Receive system noise level	Not specified	See derivation of criterion for implicit assumption regarding system noise level.
Polarisation	V & H mix. Some Dual.	
Centre frequency and bandwidth used	Channel centre frequencies specified. 6 go and 6 return 30 MHz channels.	OfW446 specifies channel plan based on ITU-R Rec 635. Lower channels in line with OfW446 but upper channels shifted upwards by 90 MHz.
Bit rate / modulation	155 Mbps / 64QAM or 128 state	ETSI Spectral Efficiency Class 5B
Receiver sensitivity level	-97.0 dBW	
ATPC	No	

Criterion

Based on ITU-R Recommendation 758-5 (Table 14)

Feed loss = 0 dB

Noise Figure = 3 dB

Noise power density = -141 dBW/MHz

Based on Ofcom assignment process (OfW446)

Noise = -121.7 dBW in 30 MHz = -136.5 dBW/MHz or -106.5 dBm/MHz

This level reflects the system noise figure and system losses (i.e. it is representative of a reference point just behind the antenna and before the feed loss.

By implication, and for comparison with the ITU-R values above, a combined feed loss + noise figure of 7.5 dB gives a noise value of -136.5 dBW/MHz just behind the antenna (kTB = -144 dBW/MHz).

I/N = -13 dB (includes -3 dB for apportionment)

$I_{LTE} - N_{FixedLink} = -13$ dB

$I_{LTE} = EIRP_{LTE} - \text{Propagation loss} + G_{FixedLink}(\theta)$

Propagation loss required (as a positive value)

$= EIRP_{LTE} + G_{FixedLink}(\theta) - N_{FL} + 13$

Macro cell (outdoor)

$EIRP_{LTE}$ = 61 dBm in 20 MHz = 48 dBm/MHz

N_{FL} = -106.5 dBm/MHz

Propagation loss required = 48 + $G_{FixedLink}(\theta)$ - -106.5 + 13 = 167.5 dB + $G_{FixedLink}(\theta)$

Small cell (outdoor)

$EIRP_{LTE}$ = 29 dBm in 20 MHz = 16 dBm/MHz

N_{FL} = -106.5 dBm/MHz

Propagation loss required = 16 + $G_{FixedLink}(\theta)$ - -106.5 + 13 = 135.5 dB + $G_{FixedLink}(\theta)$

Figure A-22: Fixed link locations

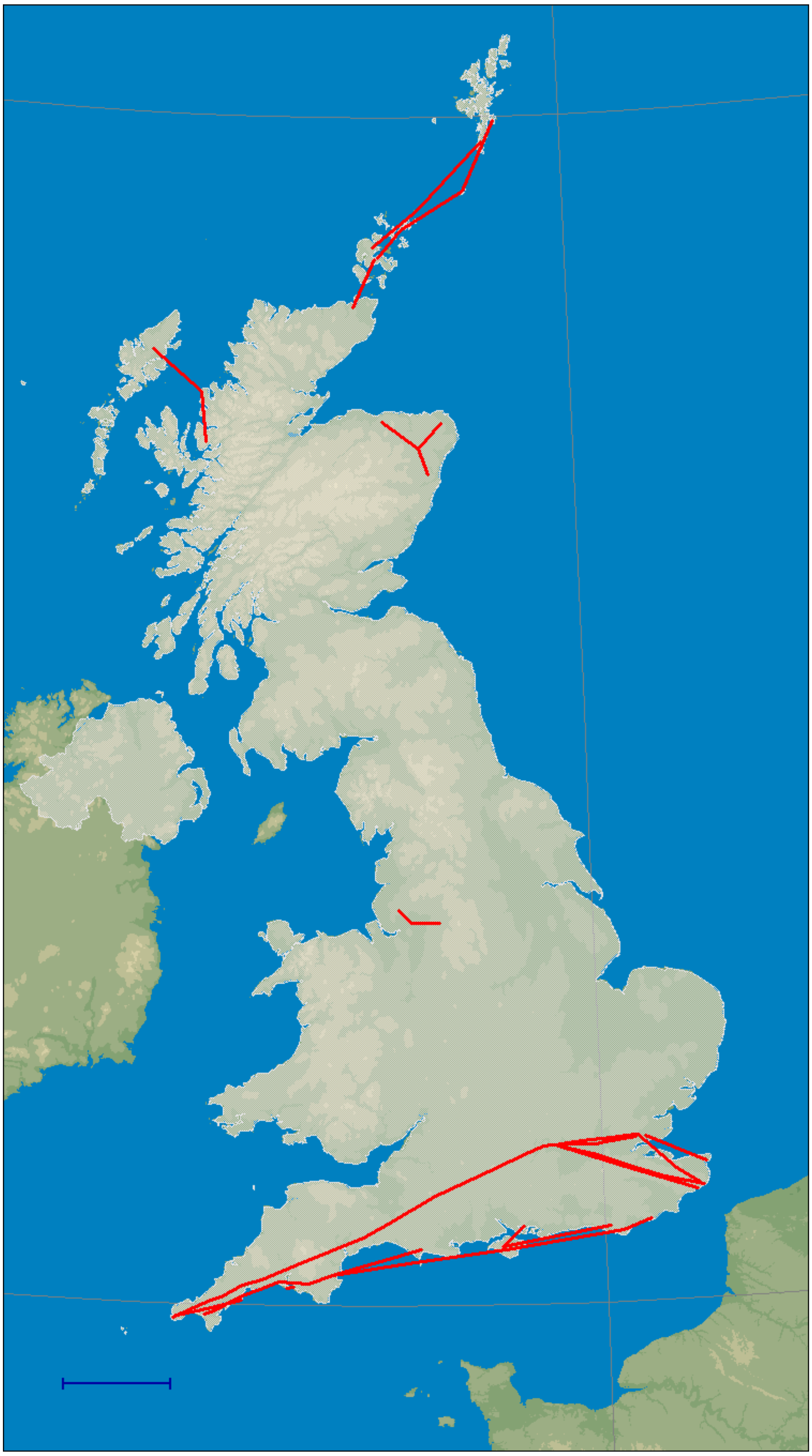
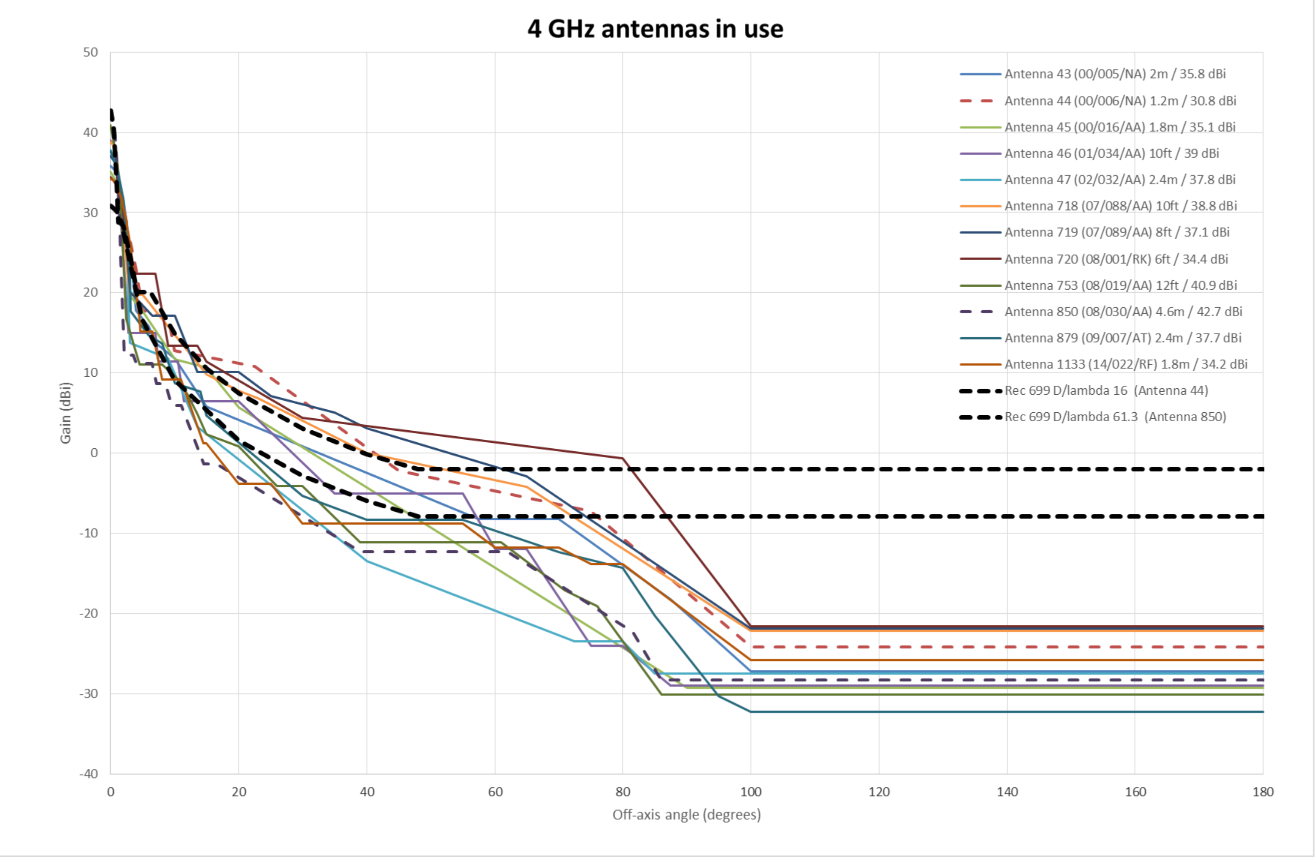


Figure A-23: Fixed link antenna patterns



A.4.5.2 Demographic assumptions

Table A-22: UK demographic assumptions

Parameter	Value used	Source
Area size by geotype ('000 sqkm)		Plum's calculations based on population data from ESRI
Hotspot	0.06	
Dense urban	0.11	
Urban	2.24	
Suburban	34.61	
Rural	204.32	

A.4.5.3 Market and network assumptions

Table A-23: UK market and network assumptions

Parameter	Value used	Source
Number of operators	4	Plum based on publicly available data from national regulators' websites

Parameter	Value used	Source
Monthly data consumption (PB/month)		Plum's projection based on regulators' historical data and CISCO VNI projections
2012	17	
2015	68	
2020	437	
2025	1,893	
2030	5,963	
Average total sites[41] per sqkm in 2014:		Plum's estimate based on OFCOM's Sitefinder database and 2011 data from Qualcomm
Hotspot	85	
Dense urban	20	
Urban	6	
Suburban	0.6	
Rural	0.1	

A.4.5.4 Spectrum assumptions

shows the total amount of downlink spectrum assumed to be available and in use in the different bands for the entire market (MHz) outside of the coordination areas that are the output of the technical studies.

Table A-24: Total downlink spectrum available outside of restriction zones

Band	2014	2016	2018	2020	2022	2024	2026	2028	2030
700MHz	0	0	0	45	45	45	45	45	45
800MHz	20	20	30	30	30	30	30	30	30
900MHz	17	22	26	30	30	30	30	30	30
1.4GHz	0	40	50	50	52	56	60	60	60
1.8GHz	13	26	38	50	60	70	75	75	75
2.1GHz	60	60	60	60	60	60	60	60	60
2.3GHz TDD	0	30	30	30	40	40	40	40	40
2.6GHz TDD	0	38	38	38	38	38	38	38	38
2.6GHz	47	70	70	70	70	70	70	70	70
3.4-3.6GHz TDD	30	143	143	143	143	143	143	143	143
3.6-3.8GHz TDD	0	0	0	0	150	150	150	150	150
3.8-4.2GHz TDD	0	0	0	0	0	0	0	300	300

The following points should be noted:

[41] A site that is shared by multiple operators is counted as multiple sites.

- For all TDD spectrum bands, it is assumed that 3/4 of all the timeslots are used for downlink transmission in order to support a downlink to uplink ratio of 3:1. Therefore, for simplicity, we assume that a bandwidth equivalent to 3/4 of the total bandwidth is used for downlink transmission.
- Linear interpolation is used to estimate the bandwidth in the years between 2012, 2015, 2020, 2025 and 2030. This gives rise to bandwidth sizes that are rounded to the nearest whole rather than the nearest 10.
- In the case of 2.3GHz, it is assumed that only 40MHz of spectrum will be released in 2015 and no additional spectrum will be released until 2022. In 2022, 20MHz of additional spectrum is assumed to be released on a shared basis. Because this bandwidth does not cover the entire population and is not available 100% of the time, the effective bandwidth released is only 12.8MHz (assuming 100% population coverage). Therefore, from 2022, the equivalent downlink bandwidth for the band rises to 40MHz.

Note that for all TDD spectrum bands, it is assumed that 3/4 of all the timeslots are used for downlink transmission in order to support a downlink to uplink ratio of 3:1. Therefore, for simplicity, we assume that a bandwidth equivalent to 3/4 of the total bandwidth is used for downlink transmission.

Appendix B: Generic technical assumptions

B.1.1 Fixed Satellite Service

The area around a Fixed Satellite Service Earth Station within which a particular piece of spectrum would not be available to mobile services is determined by a large number of factors including the surrounding terrain and the earth station antenna pattern in the horizontal plane which in turn is determined by the elevation angle at which the antenna is operated. For simplicity it has been assumed that the area around the earth station is described by a circle of a particular radius. That radius has been determined by an extensive Huawei study (reported in JTG contributions[42] and further developed since then) which takes account of:

- The types of location in which the Satellite Earth Station and the macro and small cells are located
- The aggregation of potential interference from multiple macro / small cell transmitters
- A propagation model (based on long term interference because aggregation effects are being considered) with a small obstacle mid-path. Note that this approach gives rise to similar separation distances to those that are obtained through the specific modelling of actual earth station sites (i.e. taking account of actual terrain)
- An earth station elevation angle of 5 degrees. This is a very conservative assumption as many of the earth station antennas are known to operate at elevation angles greater than 5 degrees. Operation at higher elevation angles gives rise to a reduced earth station antenna gain in the horizontal plane and consequently slightly smaller coordination areas

The coordination area radius is also determined by the criterion defining an acceptable level of interference at the Satellite Earth Station. The starting position is the traditional ITU-R criteria which is defined relative to the noise floor of the FSS ES receiver (I/N = -13 dB). However, consideration is also given to the situation where a margin exists on the satellite link such that a higher level of interference can be tolerated. Examination of satellite and earth station characteristics suggests that such margins might support an I/N of 10 dB or more. It is noted that a detailed end-to-end link performance (i.e. uplink and downlink combined) would determine the actual margins available. However, such information is not generally available in the public domain so the downlink characteristics have been considered in isolation.

On the basis of the above considerations, the radii of the coordination areas around the FSS ES sites under different frequency sharing scenarios (e.g. ITU-R criteria, link performance aware, advanced frequency sharing), mobile network rollout scenarios (macro cell, outdoor small cell), and geotypes (urban, suburban, rural) are as follows:

[42] CPG-PTD(14)057_Report on sharing between terrestrial IMT and FSS systems operating in the 3800-4200 MHz frequency range

Table B-1: Sharing scenarios

Ref	Frequency sharing scenario	Sharing	Criterion	Cell type	Cell geotype	ES Rural (km)	ES Suburban (km)	ES Urban (km)
1	ITU-R	No sharing within accessible bandwidth	ITU-R I/N = -13 dB	Macro	Urban / suburban mean	59.5	61.25	70
2	ITU-R	No sharing within accessible bandwidth	ITU-R I/N = -13 dB	Small cell (outdoor)	Urban	5	5	5
3	Link performance aware	No sharing within accessible bandwidth	Margin I/N = +10 dB	Macro	Urban / suburban mean	27.5	29.5	38.25
4	Link performance aware	No sharing within accessible bandwidth	Margin I/N = +10 dB	Small cell (outdoor)	Urban	0.3	0.3	0.3
5	Advanced frequency sharing	Sharing within accessible bandwidth (LSA)	Margin I/N = +10 dB	Macro	Urban / suburban mean	27.5	29.5	38.25
6	Advanced frequency sharing	Sharing within accessible bandwidth (LSA)	Margin I/N = +10 dB	Small cell (outdoor)	Urban	0.3	0.3	0.3

B.1.2 Fixed Service

The approach used for terrestrial fixed links is in most respects similar to that used for earth stations. The main difference is that the elevation angle of the fixed links is zero or near zero degrees which gives rise to a more elongated area around a fixed link receiver where IMT use is precluded. Further, a more general use of high performance antennas with suppressed rear lobe performance reduces the precluded area behind a fixed link receiver which distorts the area even more when compared to the near circular shape around an earth station.

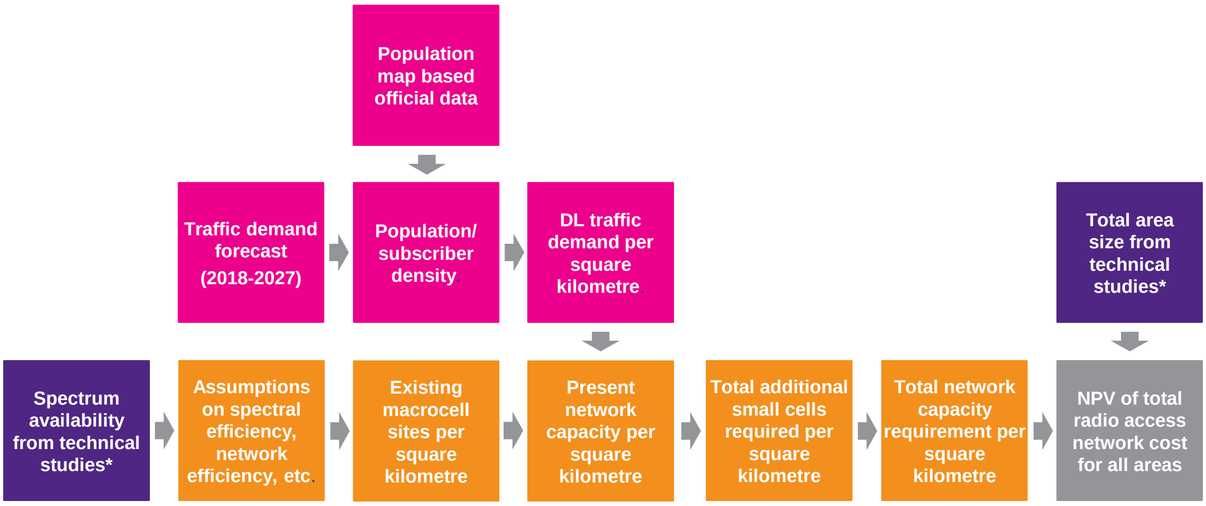
Unlike the analysis for satellite systems a margin on the fixed link is not assumed. Where Automatic Transmit Power Control (ATPC) is employed on fixed links significant margins will not exist. Where ATPC is not employed margins will exist but these are to absorb multipath fading on the link. The ITU-R criterion of I/N = -13 dB is therefore used to determine the level of interference that can be tolerated by the fixed link.

Determining the level of interference that can be tolerated is determined by the noise floor and the point in the fixed link receive chain at which the I/N is calculated (i.e. before or after the feed loss if this is specified).

Appendix C: Economic model structure

The economic analysis is confined to traffic transmitted over macro cells and outdoor small cells. Network costing, which forms the basis for the avoided-cost benefit calculation, is summarised in the flow diagram in Figure C-1.

Figure C-1: Structure of the network costing process



*There are up to 3 frequency sharing scenarios and for each scenario up to 3 types of areas – i.e. macro cell and small cell coordination zones plus the area outside of these coordination zones. This means in total there are 9 combinations of spectrum availability and total area size to consider before change in the timing of C-Band release is accounted for.

The rest of this appendix discusses the steps undertaken and the key assumptions made in the processes of:

- Treatment of the technical analysis output for use in the economic analysis
- Mobile traffic demand determination
- Infrastructure and capacity supply determination
- Infrastructure costing and benefit calculation

C.1 Technical study output processing

The model determines the extent of the coordination areas, where the coexistence of FSS ES, FL and IMT means there is only partial spectrum availability for IMT.

- This is done for macro cells and outdoor small cells, where the radii of the coordination areas with the ES at their centres will be larger for macro cells than for small cells.
- Within the coordination areas for macro cells, the entire C-Band frequency range can be deployed on small cells except in the coordination areas for small cells (nested within the macro cells'

coordination areas). Within the small cells coordination areas, there is a restriction on spectrum usage due to potential interference with the FSS ES.

While the shape of the coordination area for FL is not a circle similar considerations apply.

The coordination areas are superimposed onto a gridded map of the country population density (2km x 2km squares), which is in turn divided up into 5 geotypes based on population density. The geotypes are:

- Hotspots (13,910< persons per sqkm)
- Dense urban (between 10,910 and 13,910 persons per sqkm)
- Urban (between 4,290 and 10,910 persons per sqkm)
- Suburban (between 202 and 4,290 persons per sqkm)
- Rural (between 0 and 202 persons per sqkm)

The amount of spectrum needed for the FSS ES is then determined and hence the quantum available for IMT in each of the coordination areas for macro cells and small cells. The effective amount of spectrum can then be computed for the areas belonging to the 5 geotypes within these coordination areas. The effective amount of spectrum available is calculated as the average amount in MHz across each geotype in the coordination areas for macro cells and small cells.

C.2 Traffic demand forecast

The short-term mobile traffic projection from Cisco VNI 2014 is extrapolated to 2028 using a best-fit Gompertz curve. If a Cisco forecast is not available for a study country a suitable country analogy is used. Where historical mobile data traffic statistics are available these are used as points of reference for the traffic forecast.

The subscriber distribution is used as the basis on which traffic is allocated across the geotypes and grids.

During the busy hour, the traffic volume transmitted is assumed to be 8%[43] of the total traffic during the day.

C.3 Infrastructure and capacity supply

The number of sites per square kilometre for the 5 geotypes is estimated from available sources. As a simplification, it is assumed that all sites are macro cell sites, on which up to 12 different spectrum bands can be deployed.

It is assumed that not all macro cell sites that have been built will be suitable for C-Band deployment due to their locations as well as the more limited propagation distance of the C-Band spectrum.

The totality of sites erected up until 2018 gives operators an inherent capacity given the amount of spectrum available. Future capacity shortfall, when mobile traffic demand exceeds supply, will be supported by outdoor small cells. However, small cells will only be rolled out when all available bands

[43] http://dspace.mit.edu/bitstream/handle/1721.1/62579/MIT-CSAIL-TR-2011-028.pdf?sequence=1

(including C-band when available) have been deployed on existing macro-cells and there is still capacity shortfall. This means that where possible operators are assumed to prefer adding new bands to macro-cells to installing new small cells straight away. When small cells are rolled out, it is assumed that only bands above 2.6GHz will be used on them.

The total available amount of spectrum for different cell types depends on the cell types (i.e. macro and small) in the coordination areas. Outside of these zones, all spectrum is assumed to be available for IMT.

A total of 60MHz per small cell is assumed based on discussion with Huawei and other industry stakeholders. This could mean the use of three 20MHz carriers in one band or the use of 3 bands, each supporting one carrier. At present, outdoor microcells support up to 2 bands and up to 1 carrier per band, giving a maximum of 40MHz of spectrum[44]. Given the fact that 3GPP is specifying the aggregation of three component carriers in the downlink in Release 12, this assumption is expected to be a conservative one

The use of C-band or 2.6GHz TDD spectrum for wireless backhaul is assumed to only be made for outdoor small cells. We assume that microwave and fixed connections continue to be used for traffic backhaul on macro cell sites.

The use of in-band backhaul for small cells means that not all of the spectrum available in the C-Band can be used for radio access – i.e. to serve mobile users' traffic. To ensure that backhaul capacity is guaranteed for small cells, half of all available spectrum for IMT in the C-Band is assumed to be reserved for backhaul.

C.4 Infrastructure costing and benefit calculation

A comparison is made of mobile data traffic demand with capacity supply between 2012 and 2027. Where demand exceeds supply, new infrastructure is required, operators will deploy additional bands on existing suitable macro cell sites until these bands are exhausted, at which point they will begin to roll out outdoor small cells to meet traffic demand. Bands that are used on outdoor small cells are 2.6GHz (both TDD and FDD), 3.4-3.6GHz, 3.6-3.8GHz and 3.8-4.2GHz. This determines the total infrastructure requirement under different frequency sharing and spectrum release scenarios

The annualised cost for each site type is calculated based on the CAPEX and OPEX parameters detailed in Appendix D.

The total annualised cost of radio network infrastructure for the different modelling scenarios is computed for each year up to 2027.

A 2018 NPV of the total radio network infrastructure cost is calculated based on a discount rate of 8% for each modelling scenario

The benefit is calculated as the avoided cost – i.e. the reduction in cost that operators can enjoy as a result of having more spectrum compared to a base case. Therefore, the benefit is calculated as the difference in NPV of the total network cost between a modelled scenario and the Base Case. This means that the benefit that accrues to an alternate Case 1 is:

Benefit of Case 1 = Cost NPV of Base Case – Cost NPV of Case 1

[44] http://www.thedasforum.org/wp-content/uploads/2013/02/DAS-And-Small-Cell-Technologies-Distinguished-2_4_13.pdf

Appendix D: Generic economic model assumptions

D.1 Geotype and demographic assumptions

Table D-1: Geotype assumptions

Parameter	Value used	Source	Comments
Population density threshold for geotype (persons per sqkm) Hotspot Dense urban Urban Suburban Rural	. 13,910 10,910 4290 202 0	Plum and Qualcomm	
Average subscriber density for geotype (subscribers per sqkm) Hotspot Dense urban Urban Suburban Rural	300,000 50,000 16,000 1,200 30	Plum and Qualcomm	This is used for apportioning total traffic to different geotypes
Population annual growth rate	2%	Plum's estimate based on UN data	

D.2 Network assumptions

Table D-2: Network assumptions

Parameter	Value used	Source	Comments
Percentage of traffic in busy hour	8%	Estimated based on traffic profile graphic for European countries in Heikkinen and Berger[45]	
Percentage of traffic in the downlink 2013 2015 2020 2025 2030	 86% 89% 90% 90% 90%	Plum 2011 study for Ericsson and Qualcomm	

[45] http://dspace.mit.edu/bitstream/handle/1721.1/62579/MIT-CSAIL-TR-2011-028.pdf?sequence=1

Parameter	Value used	Source	Comments
Percentage of network capacity that is usable accounting for mismatch of supply and demand in some locations	80%	Plum's estimate	
Sectors per BTS by cell type macro cell outdoor small cell	 3 1		
Number of bands that can be supported by cell type macro cell outdoor small cell	.. . multiple multiple	Cost models in the public domain including WIK, a paper published by DAS Forum and Huawei[46]	
Number of carrier per band by cell type macro cell outdoor small cell	 multiple up to 3	Cost models in the public domain including WIK and a paper published by DAS Forum and Huawei[47]	
Spectrum efficiency[48](bps/Hz/cell) 2013 2030	 0.45 1.6	Plum's estimate based on vendors' view	
Average target user speed (Mbps) 2013 2030	 1 Mbps 18 Mbps	Plum's estimate based on discussion with vendors	These throughput rates are assumed to ensure there is reasonable growth in expected speed over the modelling period. The model then channelizes to the total available bandwidth at these throughput rates (using the assumed GoS), whereas under real operating conditions data packets are multiplexed statistically.
Required Grade of Service (maximum blocking rate for data transmission)	1%	Plum's estimates based on international benchmarks	
TDD downlink-to-uplink subframe ratio	3:1	Huawei	

[46] http://www.thedasforum.org/wp-content/uploads/2013/02/DAS-And-Small-Cell-Technologies-Distinguished-2_4_13.pdf

[47] http://www.thedasforum.org/wp-content/uploads/2013/02/DAS-And-Small-Cell-Technologies-Distinguished-2_4_13.pdf

[48] This refers to the average spectral efficiency across a cell taking into consideration site loading.

Parameter	Value used	Source	Comments
Percentage of macro cells that are suitable for C-band deployment by geotype Hotspot Dense urban Urban Suburban Rural	.. … 60% 40% 40% 20% 0%	Plum's estimates	

D.3 Infrastructure cost assumptions

Table D-3 below shows the values that have been used in the models for the input variables relating to infrastructure cost.

Table D-3: Infrastructure cost assumptions

Network cost type	Value used	Source	Comments
Discount rate (commercial discount rate)	8%	National regulators	Average rate used for MTR model
CAPEX per band for macro cell - cost of each set of antennas and RF (EUR '000)	12	Estimates from NSN49	These are costs for macro cell sites.
Base station CAPEX for macro cell (EUR '000)	25		
Site establishment cost for macro cell (EUR '000) Civil works Installation and commissioning	. 70 9	Estimates from NSN50	
Backhaul for macro cell Urban (fibre-based product) Suburban/rural (microwave)	 18 15	Analysys Mason, Plum's estimates based on conversations with vendors	
CAPEX for integrated outdoor small cell unit ('000)	8	Plum's estimate based on Huawei's numbers	
OPEX as % of CAPEX Non-backhaul Backhaul Urban Suburban/rural	 5% 30% 15%	Analysys Mason, Plum's estimates based on conversations with vendors	These are both for macro cells and outdoor small cells

[49] These numbers are cross-checked with figures published by Analysys Mason in Opportunity cost of the spectrum used by digital terrestrial TV and digital audio broadcasting, Analysys Mason, Aegis Systems, 2013: http://stakeholders.ofcom.org.uk/binaries/consultations/aip13/annexes/report.pdf.

[50] Opportunity cost of the spectrum used by digital terrestrial TV and digital audio broadcasting, Analysys Mason, Aegis Systems, 2013: http://stakeholders.ofcom.org.uk/binaries/consultations/aip13/annexes/report.pdf.

Network cost type	Value used	Source	Comments
Site rental per year (EUR ‘000) Urban Suburban/rural	 25 5	Plum’s estimate	