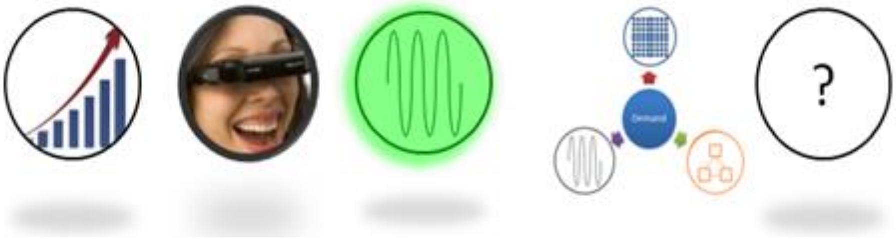
# Study on the future UK spectrum demand for terrestrial mobile broadband applications

## *Final report*



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realwireless

independent wireless experts

# About Real Wireless

Real Wireless is a leading independent wireless consultancy, based in the U.K. and working internationally for enterprises, vendors, operators and regulators – indeed any organization which is serious about getting the best from wireless to the benefit of their business.

We seek to demystify wireless and help our customers get the best from it, by understanding their business needs and using our deep knowledge of wireless to create an effective wireless strategy, implementation plan and management process.

We are experts in radio propagation, international spectrum regulation, wireless infrastructures, and much more besides. We have experience working at senior levels in vendors, operators, regulators and academia.

We have specific experience in LTE, UMTS, HSPA, Wi-Fi, WiMAX, DAB, DTT, GSM, TETRA – and many more.


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# Executive summary

**Study background**

The next ITU-R World Radiocommunication Conference is scheduled to take place in November 2015. Agenda item 1.1 scheduled for this meeting will consider additional spectrum allocations for mobile services. The rationale for this agenda item is to address demand for additional terrestrial wireless broadband spectrum. The agenda item is forward looking, considering spectrum that could be suitable for a new mobile allocation and/or identification for International Mobile Telecommunications (IMT) networks to meet demand in the next decade and beyond (e.g. 2020 onwards).

Ofcom has commissioned this study to inform the UK's input on the spectrum estimate work being carried out in ITU-R WP5D as part of the preparatory work for WRC-15 Agenda Item 1.1.

To achieve this Ofcom asked Real Wireless to deliver the following:

1. An estimate of UK mobile data traffic demand for the period from 2015 to 2030 based on evidence from market trend data.
2. Using this traffic demand and other relevant information, identify and justify appropriate input parameters to be used in the spectrum estimation methodology developed by the ITU-R as defined in the latest version of Recommendation ITU-R M.1768-1 [7].
3. An estimate of the UK spectrum requirement for IMT networks based on the ITU-R methodology, including:
    - The total spectrum needed for coverage, for capacity and for performance (including the corresponding frequency ranges);
    - How the spectrum requirement varies for the cases of low and high demand (e.g. different market settings as was done in Report ITU-R M.2078);
    - The level of asymmetry between downlink and uplink for traffic and the impact on spectrum requirements.
4. Adapt as necessary the ITU-R methodology to also estimate the spectrum requirement for traffic to be carried over Wi-Fi networks and produce a corresponding spectrum estimate.
5. Identify the key sensitivities that will affect the spectrum estimation and produce a matrix of results that takes account of such sensitivity analyses.
6. Identify any deficiencies in the methodology that might affect the spectrum estimation and propose how these could be addressed and quantified.

Alongside this study Ofcom has issued a Call for Input (CFI) to allow stakeholders an opportunity to express their views on issues related to the future spectrum demand for terrestrial mobile broadband applications and the pros and cons of specific frequency bands as potential candidates to help fulfil that demand. We have taken into consideration the responses from this Call for Input process when determining suitable input parameters for the ITU-R spectrum estimation model used for this study.

**Our spectrum estimates are based on baseline model settings which challenge ITU recommended model settings**

In the course of this project we have reviewed all inputs to the model defined in Recommendation ITU-R M.1768-1. Our starting point for model settings has been the input values recommended by ITU-R working party 5D in their work in progress response to JTG 4-5-6-7 in response to WRC-15 agenda item 1.1. However, we have recommended updates to these ITU recommended model settings in our analysis to make these up to date with current mobile broadband service requirements, in line with practical mobile broadband network capabilities and in line with UK mobile broadband network deployments. The main areas where we have suggested revisions which are likely to have the biggest impact on overall spectrum requirements are:

- Maximum allowable mean IP packet delay
- Mean IP packet size
- Application rates
- Spectrum efficiency
- Coverage levels

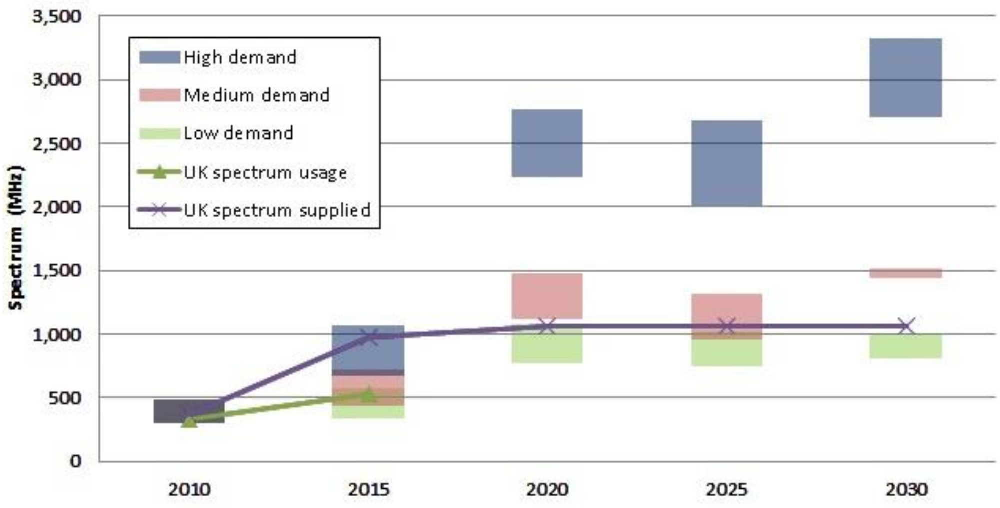
**Our spectrum estimates for licensed spectrum show the existing plan of spectrum releases could become insufficient from 2020 onwards**

Within this study we have generated estimates of spectrum requirements for wireless broadband services from 2010 to 2030 using the model defined in Recommendation ITU-R M.1768-1. Figure 1 shows our results for licensed spectrum requirements in our low, medium and high demand scenario using our recommended baseline settings for the ITU-R model.

The blue, pink and green blocks in this figure give a range for our spectrum requirements estimates for each of our high, medium and low demand scenarios respectively. For each of these cases we provide:

- A dedicated spectrum result (upper end of the coloured blocks) where macrocells, microcells, picocells and hotspots for each Radio Access Technology Group (RATG)[1] all require a dedicated spectrum layer. Note that this is slightly different to the ITU definition of dedicated spectrum which allows for some sharing between layers. However, our revised definition of dedicated spectrum estimates presents an upper bound limit on spectrum requirements for the scenario being considered.
- A shared spectrum result (lower end of the coloured blocks) where all cell types for a given RATG share spectrum. This aligns with the ITU's definition of shared spectrum estimates and gives a lower bound on spectrum requirements for the scenario being considered.

[1] Note that RATGs are defined within the ITU-R to group classes of air interfaces together. RATG1 includes GSM, UMTS and LTE, RATG2 includes LTE-A onwards and RATG3 covers local area wireless technologies such as Wi-Fi.




| Spectrum(MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| High demand | Shared | 295 | 665 | 2,230 | 2,010 | 2,710 |
| | Dedicated | 490 | 1,070 | 2,770 | 2,675 | 3,325 |
| Mid demand | Shared | 295 | 440 | 1,120 | 950 | 1,445 |
| | Dedicated | 490 | 720 | 1,475 | 1,315 | 1,515 |
| Low demand | Shared | 295 | 340 | 775 | 740 | 805 |
| | Dedicated | 490 | 575 | 1,080 | 1,015 | 995 |

**Figure 1: Our low, medium and high demand baseline licensed spectrum estimate results (MHz) against UK spectrum usage in 2010 and 2015 and anticipated UK spectrum supply over time without future allocations of mobile broadband spectrum at WRC-15**

In practice some sharing of spectrum across cell types is achieved in cellular networks and therefore a spectrum requirement between the dedicated and shared result is likely to be the most realistic. The position of the most realistic spectrum requirement value between this shared and dedicated spectrum estimate will vary over time depending on operator approaches to frequency reuse in their networks, enhancements in technologies to reduce interference between network layers sharing spectrum, the location of deployments of small cells and whether they are isolated from wider area cells in indoor environments etc.

In Figure 1 we compare these spectrum estimates for different market settings against our estimate of the volume of mobile broadband spectrum either already awarded or likely to be awarded over our timeline to 2030. This is shown by the purple line in Figure 1. The frequency bands that we consider and their availability over time in the estimate of spectrum availability is summarised in Figure 2. Note that all frequency bands considered here already have a mobile service allocation in the ITU-R Table of Allocations.

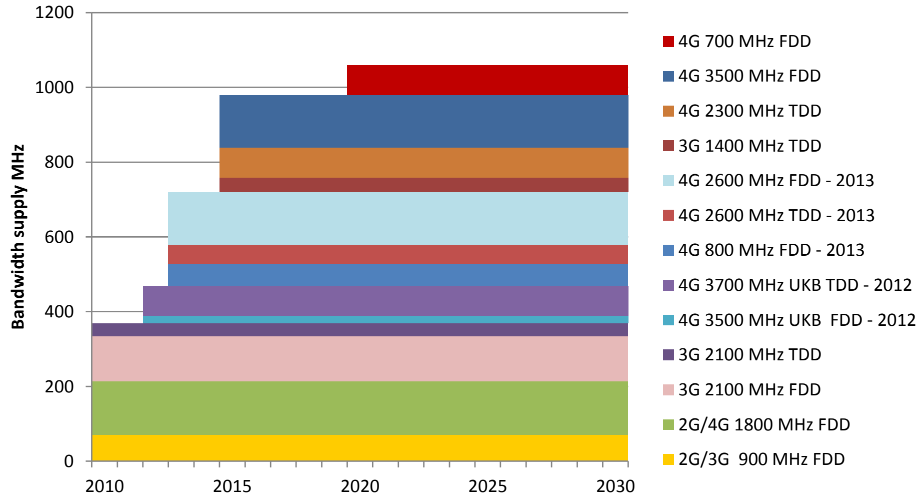



**Figure 2: Our assumed availability of UK mobile broadband spectrum out to 2030, in the absence of new allocations at WRC-15**

Comparing our spectrum estimates against this anticipated spectrum availability for the UK in Figure 1 we conclude that:

- By 2020 currently awarded and planned awards of mobile broadband spectrum in the UK may not be sufficient to keep pace with demand if our medium and high estimates of UK mobile broadband demand and baseline model settings are realised in practice.
- Only if UK mobile broadband demand follows our low demand forecasts and baseline model settings will the current planned level of UK spectrum awards be potentially enough to keep pace with increases in demand out to 2030.
- In the high demand case mobile broadband spectrum requirements up to and including 2015 are commensurate with current UK spectrum availability and future release plans but rely on all awarded spectrum becoming fully utilised. Given that this includes a number of TDD bands and that UK cellular networks are currently deployed around FDD networks it may be challenging to realise this higher utilisation in practice.
- As the actual UK mobile broadband demand varies between our medium and high forecasts the required spectrum can vary by as much as a factor of two.

These results are based on our baseline model settings being realised in practice which include our assumptions on medium Wi-Fi offload and small cell uptake levels.

Finally note on Figure 1 that the green line indicates a view of the amount of spectrum that we estimate was used in practice for mobile broadband services at 2010 and is likely to be used by 2015. This is reduced from the spectrum supplied estimate as it takes account of TDD bands in the UK that have been awarded but currently remain unused. Comparing these 2010 and 2015 spectrum usage estimates with our medium demand spectrum estimates shows a good alignment and generally supports our recommended model settings and medium demand estimate.

Examining the 5 year trends shown in Figure 1 over time we find that:

- **Between 2010 and 2015** demand increases by 9.1[2]x and spectral efficiency improves[3] by 3.8x giving a likely increase in required spectrum of 2.4x. Our result shows spectrum increasing[4] by only 1.5x. The additional improvement in cellular networks leading to these lower than anticipated spectrum estimates is due to changes in the network topology and more specifically the increased roll out of small cells in cellular networks (which will be limited to RATG1 at this point in time due to our baseline model assumption that LTE-A and hence RATG2 will not be deployed in the UK until 2020). Note that the impact on spectrum requirements of small cells is limited to the offload of low mobility traffic though.
- **Between 2015 to 2020** demand increases by 3.8x but spectral efficiency only increases by 1.6x. Therefore a 2.4x spectrum increase is expected compared with the 2.2x spectrum increase estimated by the model. As in the previous 5 year period, this reduction in estimated spectrum requirements from the model compared with anticipated spectrum requirement changes, due to the offset in demand increases by technology improvements, is likely due to network topology changes and the continued deployment of small cells in this time period. However, the impact of small cells is not as great here as it was in the previous 5 year period and actually the most significant increase in spectrum requirements occurs in this 5 year time period. This is largely due to the assumed initial deployment of LTE-A networks in 2020 which can accommodate more demanding services than LTE networks. These more demanding services, however, have higher overheads leading to larger overall spectrum requirements even at low initial demand densities. Note also that there is a significant volume of traffic on both RATG1 and RATG2 networks in parallel in this timeframe and so spectrum requirements include sustaining significant capacity on both of these.
- **Between 2020 to 2025** demand increases by 3.1x but spectral efficiency only increases by 1.7x. Therefore a 1.8x spectrum increase is expected compared with the 0.9x spectrum change (i.e. decrease) estimated by the model. The introduction of LTE-A hotspots from 2020 provides a network layer with a very high spectral efficiency density which explains some of this reduction in spectrum requirements despite the changes in demand levels outstripping improvements in spectrum efficiency on a per cell basis. Also with LTE-A, and with it more demanding services, already having been introduced in 2020 the initial investment in bandwidth to provide coverage for new services via RATG2 networks has already been made at the start of this time period. However, while there is some relief in spectrum requirements between 2020 and 2025 this is not enough to avoid still requiring spectrum releases that go beyond existing plans in time for 2025 and 2030.
- **Between 2025 to 2030** demand increases by 1.8x in suburban areas and spectral efficiency also increases by 1.8x. Therefore spectrum estimates should remain the same compared with the 1.3x change in overall spectrum requirements estimated by the model. However, note that the spectrum bottleneck moves from suburban to rural areas in this timeframe and that there is actually no increase in spectrum requirements in suburban areas in this timeframe which

[2] Increases in demand are based on suburban areas which tend to drive overall spectrum requirements in our results unless otherwise stated.
[3] Increases in spectrum efficiency are based on the average SE improvement across RATGs for the SEs causing the spectrum bottleneck in those years examined.
[4] Increases in spectrum requirements based on the average between the shared and dedicated spectrum requirements results from our baseline medium demand scenario.

aligns with our anticipated change in spectrum requirements. Small cell coverage levels are assumed to increase little in this time period as they have already been deployed to relatively high levels and so the spectrum requirements should remain commensurate with those anticipated by comparing demand increases to spectrum efficiency improvements.

**Our sensitivity analysis indicates that the percentage of high mobility traffic assumed is crucial as this cannot be easily offloaded and drives overall spectrum requirements**

We have performed a sensitivity analysis to determine the impact of changing input assumptions in our baseline model settings on our headline conclusions. This has shown that assumptions on the percentage of high mobility traffic in suburban and rural areas are crucial to overall spectrum requirements. This is because this high mobility traffic must be carried on macrocells due to the limited ability of small cells to support handover for high velocity users. As macrocells have a lower spectral efficiency density than all other network layers the spectrum requirements of these high mobility users become the largest contributor towards overall spectrum requirements across network layers and environments. The assumed percentage of high mobility traffic in suburban and rural areas in the ITU recommended values, which we maintain in our baseline settings, are high compared to current sources on the split between indoor and outdoor traffic levels. Reducing the percentage of high mobility traffic in suburban and rural environments to a maximum of 10% in line with these sources has the impact of reducing spectrum requirements by as much as 28% and potentially delaying the requirement for additional spectrum allocations until 2030 for our medium demand and baseline model settings at least.

Our sensitivity analysis has also examined the impact of assumption on small cell uptake, Wi-Fi offload and the delivery of services via Packet Switched (PS) or Circuit Switched mechanisms with the following findings:

- **The impact of small cell uptake on spectrum requirements is limited to offloading low mobility traffic and hence linked to the availability of other offload techniques such as LTE-A hotspots and Wi-Fi -** Within our spectrum estimates we have followed the ITU's assumption that LTE-A hotspot devices (which we assume to be short range access points operating at high frequencies and wide bandwidths) will be available to provide a very high spectral efficiency density layer to LTE-A networks in capacity constrained areas. In the case where LTE-A hotspots are available in our baseline model settings and for our low, medium and high demand estimates the uptake of other small cell types such as microcells and picocells does not have a large impact on overall spectrum requirements particularly in the later part of our study timescales when existing spectrum allocations become under pressure. This is because all low mobility traffic is easily accommodated across microcells, picocells and hotspots due to the very high spectral efficiency densities of LTE-A hotspots. However, if LTE-A hotspots are not deployed this needs to be compensated for by a higher uptake of other small cell types (microcells and picocells) so that the overall capacity across the small cell layers is still commensurate with our baseline model settings. In practice the balance between the roll out of LTE-A hotspots and the uptake of other small cell types such as picocells and microcells will be an operator decision and overall spectrum requirements remain driven by high mobility user spectrum requirements on macrocells and as such insensitive to small cell uptake provided the small cell layers provide a capacity level commensurate to our baseline model settings. Increasing small cell uptake beyond this point does not decrease overall spectrum requirements.

- **Wi-Fi offload levels, when applied equally across all users types, have a large impact on overall spectrum requirements but arguably will be limited for high mobility users who drive our overall spectrum estimates.** While our sensitivity analysis indicates that Wi-Fi offload has a big impact on spectrum requirements, we note that overall spectrum requirements are largely driven by the requirements of high mobility users who will have a limited opportunity to offload to Wi-Fi in practice and hence should be subject to lower Wi-Fi offload levels. A limitation of the ITU-R M.1768-1 model is that it does not allow Wi-Fi offload levels to vary across different service types and hence the results of our sensitivity analysis around Wi-Fi offload are likely to exaggerate the impact of Wi-Fi offload.
- **Assumptions on whether a service should be delivered via a packet switched (PS) or circuit switched (CS) network can have a significant impact on spectrum estimates and potentially delay additional requirements for spectrum releases until 2030 (under of medium demand case investigated).** In our sensitivity analysis we have examined the impact of modifying the ITU recommended assumption from all streaming and conversational services being delivered via circuit switched mechanisms to only very low rate voice services being delivered over CS networks. This reduces spectrum estimates for our medium demand case by up to approximately 20% and can potentially delay requirements for further spectrum releases until 2030. We therefore recommend that the ITU assumptions in this area are revisited.

Note that to inform our sensitivity analysis in the area of PS and CS assumptions across service types (known as Service Categories (SCs) in the ITU-R M.1768-1 model) we have investigated suitable mean packet sizes, second moment of packet sizes and mean delay levels for SC1-4 and SC 6-10 even though these are not included as packet switched services by the ITU. However, we note that our review of these parameters has been limited in the timescales of this study and that a more detailed review of this area is needed. While the results of our sensitivity analysis give some indication of the size of the potential impact on spectrum requirements that changing assumptions on PS or CS mechanisms for SCs may have we note that it is not clear that the current overheads applied by the queuing theory block of the ITU-R M.1768-1 model are representative of the levels required for delivering guaranteed bit rate services via packet switched mechanisms such as used in Voice over LTE (VoLTE) approaches. Therefore we highlight this as an area for further investigation rather than a firm recommended change to the ITU-R M.1768-1 model baseline settings at this stage.

Our sensitivity analysis indicates that arguably a lower percentage of high mobility traffic and more pessimistic view on LTE-A hotspots should be applied to our baseline model settings. However, exploring the combined effect of these we find that these two changes largely cancel each other in terms of impact on spectrum requirements and lead back to spectrum estimates aligned with our baseline model settings. Our investigation of sensitivity to application rate assumptions also supports the choices made in our baseline model settings.

**Assessment of licensed spectrum requirements against JTG 4-5-6-7 requirements**

JTG 4-5-6-7 is the ITU-R group leading the preparation for agenda item 1.1 at WRC-15 and has requested estimates of the future spectrum demand for terrestrial mobile broadband applications. In its request to ITU-R working parties 5A and 5D to develop spectrum demand estimates, JTG 4-5-6-7 has specifically requested consideration of spectrum requirements for:

- Coverage – which we interpret as spectrum requirements to deliver a minimum cell edge service level to a particular percentage of the population in each Service Environment (SE[5]).
- Capacity – which we interpret as the spectrum requirements to deliver the performance defined for each Service Category[6] (SC) to the "bottleneck" high user demand densities across the SEs within the model which drive overall spectrum requirements.
- Performance – which we interpret as the spectrum requirements to meet the performance defined for each SC by the model inputs to the required user density for each SC and SE combination which is driven by the demand densities.
- High and low market conditions – which we interpret as running the ITU-R M.1768-1 model for more or less aggressive demand forecasts as presented already in Figure 1.
- Asymmetry in demand and potential implications for spectrum requirements – which we interpret as analysing the downlink to uplink demand ratios across SEs within the ITU-R M.1768-1 model and the overhead of assuming FDD as opposed to TDD spectrum allocations based on downlink and uplink spectrum estimates from the model.

We note that the spectrum requirements for coverage, capacity and performance are not independently generated by the ITU-R M.1768-1 model and instead these requirements are intertwined in the overall spectrum estimates generated by the model. For example, although the model generates spectrum estimates based on demand densities, and hence capacity requirements, these are based on initially achieving a baseline coverage level at given performance levels for each service category, determined by the model input settings, and then increasing this spectrum estimate for higher user densities in line with the capacity requirements of each service category.

Given that the ITU-R M.1768-1 model has been developed to target spectrum requirements for capacity our results indicate for this area that:

- The main driver for overall spectrum requirements has moved from intensive dense urban scenarios to suburban environments. Although the dense urban environments have the highest overall demand densities, the suburban capacity requirements are set by high mobility users who must be served on macrocells due to handover limitations on smaller cell types.
- While dense urban areas are traditionally the areas where capacity requirements and hence spectrum requirements are highest this is no longer likely to be the

[5] Service environments are used in the ITU-R M.1768-1 model to define home, office and public area users in dense urban, suburban and rural environments.

[6] Service Categories are used in the ITU-R M.1768-1 model to define different services and their requirements which the demand input to the model represents.

case due to the intensive use of small cells with relatively high spectral efficiency densities alongside existing dense deployments of macrocells in these areas.
- The intensive use of small cells to address traditional capacity bottlenecks in dense urban deployments relies on relatively high coverage levels across macrocells, microcells and picocells in the near future. As small cells increase in density this may lead to an added requirement in these areas for a small cell spectrum layer to meet capacity and performance requirements of networks. Such a layer could drive spectrum requirements more towards our dedicated rather than shared spectrum estimates, depending on the efficacy of interference mitigation techniques for co-channel small cells.

The ITU-R M.1768-1 model takes account of user experience expectations and hence required network performance levels to meet these via the service and market related parameters for each SC and SE combination within the model. Parameters within this such as mean service bit rates and maximum tolerable packet delays can be interpreted as setting a performance benchmark against which spectrum requirements are calculated. Therefore the findings above related to capacity requirements can also be interpreted as the spectrum requirements to meet the performance levels specified by our model inputs for each SC. We have reviewed and selected these model inputs to be representative of applications within these SCs today and out to 2030.

In terms of coverage requirements we note that other contributions to ITU working party 5D have suggested that rural macrocell spectrum requirements estimated by the ITU-R M.1768-1 model may be representative of spectrum for coverage requirements. However, we note that this may not be representative of coverage spectrum requirements in practice due to:

- Spectrum for coverage requirements being driven by local site locations, terrain and carrier frequency limitations whereas the ITU-R M.1768-1 model determines spectrum requirements based on average demand and capacity densities.
- Capturing spectrum requirements for macrocells alone not taking into account the use of small cells such as femtocells to address coverage black spots which may occupy their own dedicated carrier.
- The ITU-R M.1768-1 model giving no indication of spectrum requirements by frequency range whereas for coverage requirements a knowledge of the amount of sub 1GHz spectrum required will be crucial.
- The ITU-R M.1768-1 model generates spectrum estimates per RATG but in practice coverage will need to be provided for multiple air interfaces within each RATG to support legacy terminals.
- The spectrum calculated by the ITU model is driven by average demand levels across SEs. However, in practice in rural areas peak demand levels will likely occur around villages where carriers at higher frequency bands could be used alongside lower frequency carriers to boost capacity in these localised demand peaks.

Overall we conclude that the ITU-R M.1768-1 is not a suitable platform to assess spectrum requirements for coverage and that a more detailed coverage analysis is instead needed.

In terms of asymmetry of uplink and downlink demand our analysis shows that:

- The ratio of downlink to uplink demand varies by SE, due to the selection of services used in each environment, and over time. It can range from 8 to 0.7 when following the ITU recommended distribution of traffic across SCs and SEs and calibrating against our own UK specific uplink and downlink demand estimates.
- Translating uplink and downlink demand in to uplink and downlink spectrum requirements for RATG1 and RATG2 shows that using FDD spectrum assignments instead of more efficient TDD spectrum assignments (without allowances for guard bands) could lead to as much as a 50% overhead in spectrum requirements.
- The environments where downlink traffic is anticipated to be at least double that of uplink traffic out to 2030 were identified as SE2 dense urban office users, SE5 suburban office and public area users and SE6 rural users , within the model structure and baseline input settings. SE6, being a rural environment, is unlikely to drive spectrum requirements on the basis of capacity and so the choice between FDD and TDD spectrum is less critical here. However, significant demand levels could be seen in dense urban and suburban office environments and there may be a case for considering a TDD indoor small cell channel that could potentially be shared across operators to make more efficient usage of spectrum in these environments.
- While we assume different downlink to uplink traffic ratios across device types in our demand analysis and the mixture of device types in the device population varies over time this only appears to generate a slight downward trend in overall downlink to uplink demand ratios, and hence in spectrum requirement ratios, out to 2030 which is not significant.

**Our baseline spectrum estimate for licence-exempt (LE) spectrum indicates that proposed releases at 5GHz could be required by 2020**

We have also examined spectrum requirements for licence-exempt (LE) spectrum which includes demand for:

- Traffic offloaded from cellular networks
- Traffic from a range of devices which only support LE spectrum (e.g. smart TV and home networking devices)

We consider these for both short range LE hotspots similar to today's Wi-Fi access points and longer range LE picocells such as those being proposed to be used in TVWS spectrum. Amongst the home, office and public area environments considered in our study we have found that it is the requirements of the home environment that drive LE hotspot spectrum requirements. This is because high usage of demanding video services such as Smart TV and home multimedia systems occurs in the home and this has a greater impact than the high user densities seen in busy public areas such as transport hubs.

Our analysis of LE spectrum requirements has investigated the impact of the following factors on spectrum estimates:

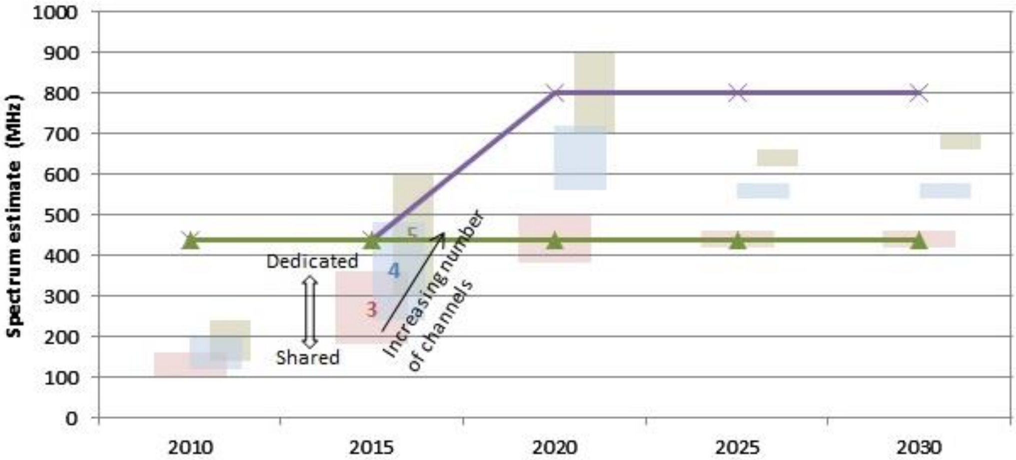
- LE demand levels
- Practical deployment limitations of LE technologies

We have found that LE spectrum requirements are heavily driven by the practicalities of deploying LE systems rather than the demand density directly. These practical limitations of LE systems include:

- Minimum spectrum usage being limited to the discrete bandwidths supported by Wi-Fi technologies
- A requirement for concurrent channels in any location to avoid interference amongst co-sited access points due to the LE nature of deployments

This is illustrated by the lack of difference across the resulting LE hotspot spectrum estimates for our low, medium and very high[7] LE demand scenarios once these practical limitations are applied as shown in Figure 3 to Figure 5. In these figures we examine LE spectrum requirements when between three and six 20MHz channels are required in each area to avoid interference and degraded performance amongst multiple access points deployed in the same area. We also show a best case “shared” spectrum estimate (lower end of bars) and worst case “dedicated” spectrum estimate (upper end of bars) depending on the level of spectrum sharing that can be achieved between LE devices supporting different variants of 802.11 protocols on the same hotspot layer. The spectrum requirement in practice is likely to be between the two of these, but not necessarily the average, and will vary over time as technologies improve. Note that the definitions of dedicated and shared spectrum estimates in this LE case are different to those from our licensed spectrum estimates where these examined sharing amongst network layers rather than protocols using the same network layer.

[7] Note that in the case of LE spectrum estimates we use the term “very high” demand to distinguish from the “high” demand case used in licensed spectrum estimates. This is because our very high LE demand estimates include higher demand levels for devices such as laptops and tablets when they are in areas of a high availability of low cost Wi-Fi data services and demand levels for portable devices with Wi-Fi only capabilities which are not considered in our licensed spectrum estimates.




| Spectrum (MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| 5 channels | Shared | 140 | 300 | 700 | 620 | 660 |
| | Dedicated | 240 | 600 | 900 | 660 | 700 |
| 4 channels | Shared | 120 | 240 | 500 | 500 | 540 |
| | Dedicated | 200 | 480 | 660 | 540 | 580 |
| 3 channels | Shared | 100 | 180 | 380 | 420 | 420 |
| | Dedicated | 160 | 360 | 500 | 460 | 460 |

5 channels

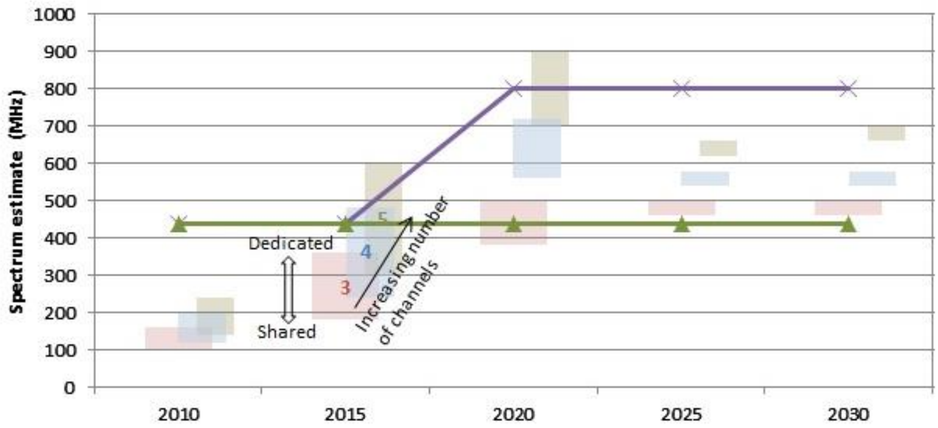
4 channels

3 channels

Potential Wi-Fi spectrum availability with 5GHz extension at 2020

Current Wi-Fi spectrum availability (excludes extension at 5GHz at 2020)

**Figure 3: Licence Exempt hotspot spectrum requirements (MHz) in the low demand scenario with practical limitations of deployments considered for different frequency reuse levels**

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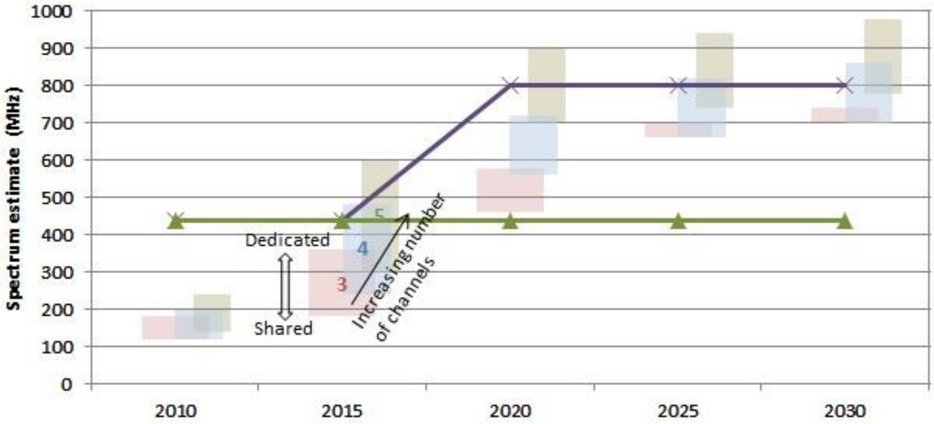
| | Dedicated | 200 | 480 | 720 | 580 | 580 |
| 3 channels | Shared | 100 | 180 | 380 | 460 | 460 |
| | Dedicated | 160 | 360 | 500 | 500 | 500 |

5 channels
4 channels
3 channels
Potential Wi-Fi spectrum availability with 5GHz extension at 2020
Current Wi-Fi spectrum availability (excludes extension at 5GHz at 2020)

**Figure 4: Licence Exempt hotspot spectrum requirements (MHz) in the medium demand scenario with practical limitations of deployments considered for different frequency reuse levels**




| Spectrum (MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| 5 channels | Shared | 140 | 300 | 700 | 740 | 780 |
| | Dedicated | 240 | 600 | 900 | 940 | 980 |
| 4 channels | Shared | 120 | 240 | 560 | 660 | 700 |
| | Dedicated | 200 | 480 | 720 | 820 | 860 |
| 3 channels | Shared | 120 | 180 | 460 | 660 | 700 |
| | Dedicated | 180 | 360 | 580 | 700 | 740 |

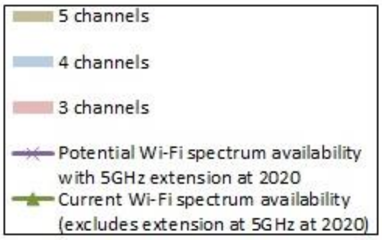
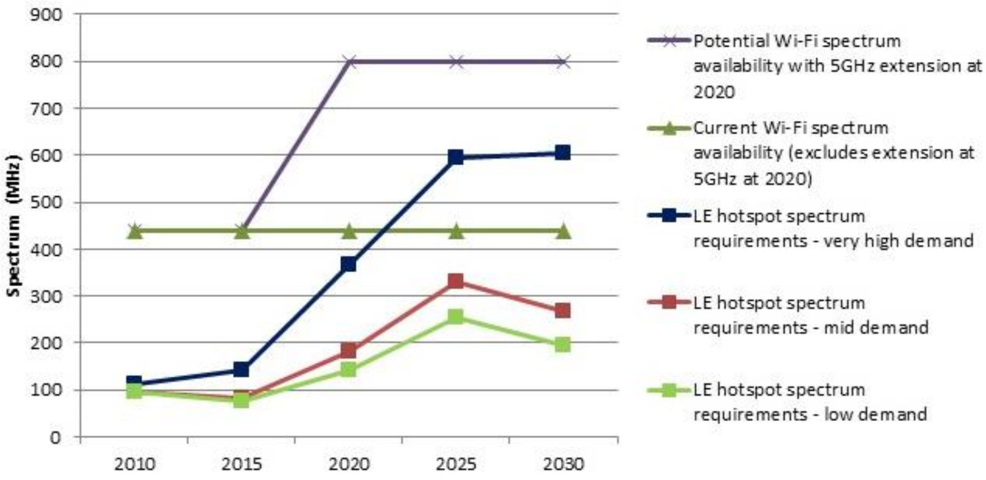



**Figure 5: Licence Exempt hotspot spectrum requirements (MHz) in the very high demand scenario with practical limitations of deployments considered for different frequency reuse levels**

Figure 6 shows our results for LE spectrum estimates prior to practical LE deployment limitations being applied. This shows that based on demand density the LE hotspot spectrum requirements of our very high demand scenario can be as much as twice that of our medium demand case. However, as highlighted already this difference is very much narrowed when practical deployment limitations are taken into account as shown in Figure 3 to Figure 5.




| | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| Potential avail. | 440 | 440 | 800 | 800 | 800 |
| Current avail. | 440 | 440 | 440 | 440 | 440 |
| Very high demand | 112 | 144 | 367 | 594 | 605 |
| Mid demand | 97 | 84 | 183 | 331 | 268 |
| Low demand | 97 | 76 | 141 | 254 | 196 |

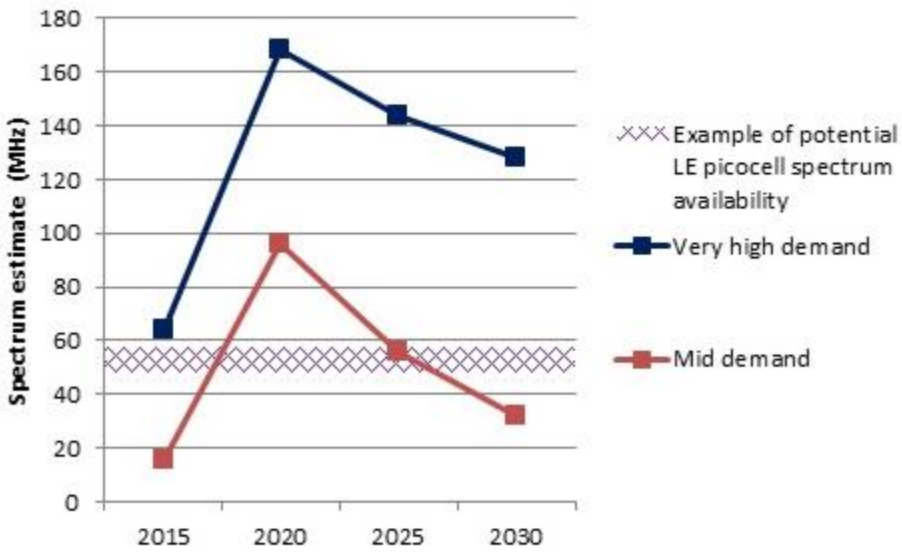
**Figure 6: Licence Exempt hotspot spectrum requirements (MHz) against Wi-Fi spectrum availability at 2.4GHz and 5GHz with and without expanded 5GHz band included after 2020**

In terms of potential extensions to current LE bands we can conclude the following from Figure 3 to Figure 5 for short range hotspots:

- Existing allocations at 5GHz will ease immediate congestion in the 2.4GHz band out to 2020 across all three of our low, medium and very high demand[8] scenarios.
- From 2020 onwards there is a strong case for the extension of the 5GHz band as proposed for WRC-15 across all three of our low, medium and very high demand scenarios.
- In the case of our very high demand scenario it is likely that further LE hotspot spectrum allocations beyond the extension of the 5GHz band as proposed for WRC-15 will be needed by 2030.

In our LE spectrum estimates we also acknowledge an emerging class of wider range LE access points. The longer range is achieved via a higher Effective Isotropic Radiated Power (EIRP) and/ or the use of lower frequency spectrum than traditional LE hotspot access points. We term these longer range access points LE picocells throughout this study and they include products such as the “Super Wi-Fi” devices being proposed to use TV White Space (TVWS) spectrum. These LE picocells will likely require LE bands to be identified with different conditions of use from the LE spectrum already used for LE hotspots. Therefore we develop a separate spectrum estimate for LE picocells. We assume that this will be driven by the requirements of users in outdoor public areas concentrated along streets, roads and railways that would be good targets for longer range LE access points.

[8] For LE hotspots driven by home environments this very high demand case implies concurrent usage of home multimedia networking, Smart TV, laptop/tablet and smartphone devices.




| Spectrum (MHz) | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|
| Very high demand | 64 | 168 | 144 | 128 |
| Mid demand | 16 | 96 | 56 | 32 |

**Figure 7: LE picocell spectrum requirements (MHz) for the medium and very high demand scenarios**

Figure 7 shows our spectrum estimates for LE picocells based on public area traffic levels in our medium and very high uptake scenarios[9] with the very high uptake level representing "shoulder to shoulder" user densities such as in a busy transport hub. This shows that LE picocell spectrum requirements, while much less than those of LE hotspots, could be significant. However, as yet, no spectrum has been identified directly for LE picocells in the UK to date. One candidate for this is TVWS spectrum but this has not yet been quantified for the UK and will be limited particularly in dense urban and suburban areas. Another potential candidate for LE picocell spectrum would be a low power shared access band such as that proposed (but not awarded) at 2.6GHz in the recent auction of 4G spectrum in the UK [12]. In Figure 7 we give an example illustration of LE picocell spectrum that might potentially become available with time based on TVWS availability (which varies by area), based on spectrum databases from the US, and a 2x20MHz low power shared access band becoming available, such as was proposed at 2.6GHz during the auction of 4G spectrum in the UK as already mentioned. These are discussed in more detail in appendix B of our report but in the absence of any LE picocell spectrum being formally identified in the UK aim to give an example of the level that might become available if TVWS were similar to US levels and a 2x20MHz low power shared access channel also became available.

Also it should be noted that the extension of the 5GHz band under current LE conditions will not address requirements for these longer range LE picocells and hence new bands will need to be identified for these that are either at lower frequencies or allow higher transmit power levels to accommodate these longer range access points.

[9] Note that a low demand scenario for LE picocells has not been run as it was the very high demand scenario representing a busy transport hub that was thought to be the most realistic driver for future LE picocell spectrum requirements and hence of most interest.

### Limitations of the ITU-R M.1768-1 model and recommendations for further investigation

This study aims to produce mobile broadband spectrum requirements estimates to support Ofcom's contribution to the ITU working party 5D response to JTG 4-5-6-7 in preparation for agenda item 1.1 at WRC-15. The spectrum estimates produced within this study therefore need to support the ITU process and as such be based around the ITU-R M.1768-1 spectrum requirements model.

During this study we have noted a number of limitations in the ITU-R M.1768-1 model and where possible we have taken mitigating actions in this study to limit the impact of these limitations as summarised on Table 1. However, it has not been possible to address all of these limitations within the timescales of this study or within the framework of ITU-R M.1768-1 and our results should be viewed with this in mind. We have recommended next steps for future studies which would help address these limitations.

| Description of limitation | Mitigating action taken in this study | Recommended next steps |
|---|---|---|
| The modelled sector areas across cell types does not vary with:<br>• Frequency band<br>• Technology or RATG[10] | Included sector sizes based on deployments of UK cellular sites today which will represent the mix of spectrum available in the UK today. While this means that results are more representative of UK networks, this sector size could still vary over time with the introduction of other frequency bands and more sites. Therefore this does not entirely address the model deficiency of sector sizes not varying with frequency band or RATG. | Further expand the ITU model to allow sector sizes to vary over time to represent changing spectrum allocations and site numbers and also to vary by RATG. |
| Spectrum requirements across frequency bands are not reported by the model | None feasible in the study timescales | Reviewing other coverage focused studies such as our 800MHz coverage obligation study for Ofcom [11] against the results of this study to draw conclusions on sub 1GHz spectrum requirements |
| Coverage percentages assumed do not vary with radio access technology group (RATG) | None feasible in the study timescales | Expand model to vary coverage levels by RATG so that lower coverage levels for less mature RATGs can be considered and their introduction more accurately represented over time. |
| Results are limited to spectrum requirements across RATGs as a whole | None feasible in the study timescales | Further develop the ITU-R M.1768-1 model to represent all cellular air interfaces active in the UK i.e. GSM, UMTS, LTE |

[10] Noting that for different RATGs supporting different coding and modulation combinations, levels of MIMO etc. there will be a different signal to noise requirement to meet the same target cell edge performance level and hence cell sizes could be different.

| Description of limitation | Mitigating action taken in this study | Recommended next steps |
| --- | --- | --- |
| rather than specific networks. | | individually rather than collectively under RATG1. |
| Application rates, which describe the supported service levels in particular cell types and RATGs, do not vary with environment. | None feasible in the study timescales | Further develop ITU-R M.1768-1 model to allow application rates to vary by service environment. |
| The relative extent and density of the different layers of the network (macrocells relative to small cells) are inputs to the model rather than an outcome of determining the most efficient network topology. | None feasible in the study timescales | Re-examine spectrum requirements using a model such as the one used in our UHF strategy study for Ofcom [5] which includes deploying cell types in the most efficient manner to meet growing capacity requirements over time. |
| The model does not consider the fine-grained local spatial and temporal structure of the demand, which can significantly impact the required peak network capacity density. | In the case of LE spectrum estimates we calibrate the user densities in each SE in line with our demand density estimates for each SE which represents quite localised demand levels. The queuing theory block in model also allows some overhead for demand peaks. | Update the ITU-R M.1768-1 model to calibrate user densities driving demand densities on a per service and environment basis as used in our LE spectrum analysis rather than on a per teledensity basis as used in our licensed spectrum analysis. Also consider traffic peaks as in our UHF strategy study for Ofcom [5]. |
| The model in its unmodified form does not compute the requirements for licence-exempt spectrum. | We have updated the model to include RATG3 spectrum requirements but note that the ITU model is generally not well suited to the highly localised demand levels of LE hotspots. | Developing a different approach to LE spectrum estimates which examines spectrum requirements and the practical limitations of meeting these in highly localised scenarios such as an apartment block. |
| The model does not facilitate considering different levels of Wi-Fi offload to different user types and SEs | None feasible in the study timescales | Update the ITU-R M.1768-1 model so that the impact of different assumed Wi-Fi offload levels across SEs and user types can be investigated. In particular the impact of a limited offload opportunity for high mobility users on overall spectrum estimates should be investigated. |
| The demand levels input to the model through market settings are not necessarily | We address the deficiency of undistributed traffic in the model by calibrating our UK specific | Further analyse demand inputs and the distribution of traffic in the model and refine |

| Description of limitation | Mitigating action taken in this study | Recommended next steps |
|---|---|---|
| all distributed and contributing to spectrum requirements in the model. | demand densities per teledensity against the demand densities in the model once distributed across RATGs and cell types to ensure that all demand in our forecasts is included in spectrum estimates. | this so that no demand is generated without a cell type and RATG combination being available to serve it. |
| Deployment cost is not considered in the model even though there is a fundamental link between the demand generated in a network and whether it is economical for an operator to provide high end services which drive demand up. | When selecting model input settings we have drawn heavily on our UHF strategy study which examined the most economical capacity enhancements options for operators in given demand and spectrum supply scenarios. | Examin how a more economics based model such as the one used in our UHF strategy study for Ofcom [5] could be used to understand spectrum estimates with network costs kept in mind. |
| The setting for whether a service category is circuit switched or packet switched does not vary with time in the model. This means services cannot migrate to being packet switched rather than circuit switched over time in line with expected cellular network evolutions. We also note that the ITU recommended values assume all conversational and streaming services are delivered via circuit switched networks which may not be a true reflection of today's cellular networks. | We have carried out a sensitivity analysis to determine the importance of assumptions on whether SCs are PS or CS. This has shown that this can have a significant impact on spectrum estimates and potentially delay the date for additional spectrum requirements until 2030 as opposed to 2020 for our medium demand case. | Update ITU-R M.1768-1 model to allow CS and PS assumptions to vary over time and across RATGs, review more fully the appropriateness of assuming PS delivery mechanisms for all SCs and appropriate PS service related parameters for these and whether the overheads for PS mechanisms in the model currently are appropriate for guaranteed bit rate services. |

**Table 1: Summary of model limitations, mitigating actions taken in this study and recommended next steps to address these limitations**

Beyond addressing limitations in the ITU-R M.1768-1 model, there were areas not included in our sensitivity analysis but identified within our study as having a potential impact on results which could be investigated further. These include:

- Investigating the practical performance and impact on spectral efficiencies of small cells in different shared spectrum arrangements.
- The impact on different assumptions on requirements for fixed amounts of bandwidth to be maintained to support legacy networks and devices over time.
- Investigating increasing rather than decreasing mean session duration over time.
- Consider the impact of licencing models which are intermediate between conventional licensed and licence-exempt approaches, such as licensed shared access (LSA).

- Investigating the impact of assuming packet fragmentation for cellular networks and hence assuming minimum rather than medium to maximum packet sizes in service parameters.
- Investigating the packet size distribution for the applications in the ITU SCs further to determine more robust standard error and second moment of packet size values that do not lead to negative packet sizes as is the case with the ITU recommended packet size standard error values.  We also suggest reviewing applying PS settings to more SCs than in the ITU recommended model settings as this could have a significant impact on spectrum estimates and potentially delay additional spectrum requirements until 2030.

## Contents

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# 1. Introduction

## 1.1 Future mobile broadband spectrum requirements are needed as input to agenda item 1.1 at ITU-R WRC-15

The next ITU-R World Radiocommunication Conference is scheduled to take place in November 2015. Agenda item 1.1 scheduled for this meeting will consider additional spectrum allocations for mobile services as follows [1]:

"to consider additional spectrum allocations to the mobile service on a primary basis and identification of additional frequency bands for International Mobile Telecommunications (IMT) and related regulatory provisions, to facilitate the development of terrestrial mobile broadband applications, in accordance with Resolution 233 (WRC-12)"

The rationale for this agenda item is to address demand for additional terrestrial wireless broadband spectrum. The agenda item is forward looking, considering spectrum that could be suitable for a new mobile allocation and/or identification for International Mobile Telecommunications (IMT) networks to meet demand in the next decade and beyond (e.g. 2020 onwards).

It is anticipated that a combination of techniques will need to be used in order to meet the anticipated growth in demand for terrestrial wireless broadband capacity. These are currently envisaged to include additional spectrum allocations, improvements in spectrum efficiency of mobile technologies, increasing the number of mobile base sites and increasing data offloading to Wi-Fi and small cells (including increasing the actual number of small cell sites deployed in UK cellular networks as well as increasing the volume of traffic offloaded to existing small cells).

This agenda item is being led by the ITU-R Joint Task Group 4-5-6-7 (JTG) which has asked for inputs on future spectrum requirements for IMT and other terrestrial mobile broadband applications. Specifically the JTG has asked [2]:

- What amount of the total spectrum requirement is needed for coverage, for capacity and for performance
- How the spectrum requirements might vary between different market settings
- The level of asymmetry between the downlink and uplink for traffic and spectrum requirements.

As part of the preparatory work for this agenda item and in response to this request from JTG 4-5-6-7, ITU-R working parties 5A and 5D are working on estimating spectrum requirements for terrestrial wireless broadband applications.

## 1.2 The existing ITU model for estimating spectrum requirements requires review to reflect UK specific spectrum needs

The process of estimating spectrum demand is a subtle one, depending on the efficient interplay of the three key elements illustrated in Figure 8 in meeting the associated demand:

- The *spectrum* used to deliver the service

- The *technology* which delivers bits over the air
- The *topology* of the cells which comprise the network

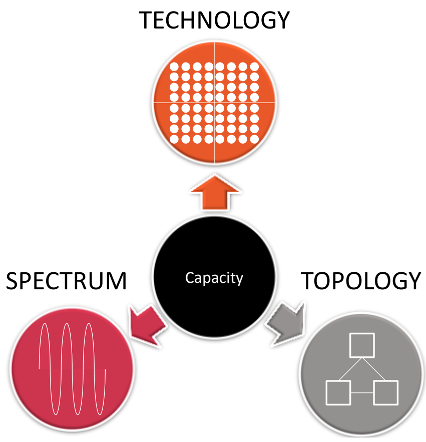



**Figure 8: Capacity appropriate to serve a given demand level depends on a combination of spectrum, technology and topology of the network [3]**

In broad terms, the total network capacity can be expressed as the product of the contributions from these three elements:

| | | | | | | |
|---|---|---|---|---|---|---|
| Capacity [bits per second] | = | *Quantity of spectrum [hertz]* | x | *Cell Spectrum Efficiency [bits per second per hertz per cell]* | x | *Number of cells [no units]* |
| ***Capacity*** | | ***Spectrum*** | | ***Technology*** | | ***Topology*** |

Therefore a gain in any single one of these elements will produce an overall capacity enhancement.

Demand for wireless networks is rarely uniform across the area to be served, and limits in capacity appear in localised areas. As a result, it is often more relevant to examine the density of capacity in a small area:

| | | | | | | |
|---|---|---|---|---|---|---|
| *Capacity density* | = | *Quantity of spectrum* | x | *Cell Spectrum Efficiency* | x | *Cell density* |
| *[bits per second per km$^2$]* | | *[hertz]* | | *[bits per second per hertz per cell]* | | *[cells per km$^2$]* |
| ***Capacity*** | | ***Spectrum*** | | ***Technology*** | | ***Topology*** |

The 'right' balance between capacity-enhancing techniques in these three categories depends on a range of market- and operator-dependent factors, including the relative cost versus benefit of each technique at a given time.  Some examples of these factors are given in Figure 9.

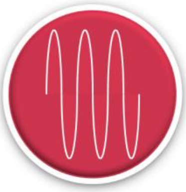
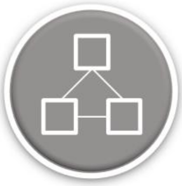
| Spectrum | Topology | Technology |
|---|---|---|
|  |  |  |
| • Existing mobile spectrum bands (900, 1800, 2100, 2600, 3500 MHz)<br>• New mobile spectrum bands (800, 2600 MHz)<br>• Potential public sector spectrum<br>• Potential 700 MHz band | • Macrocells<br>• Outdoor small cells (microcells/metrocells)<br>• Indoor licensed-spectrum small cells for offload (femtocells/picocells)<br>• Indoor licence exempt-spectrum small cells for offload (e.g. Wi-Fi) | • Advanced modulation and coding techniques, including LTE-Advanced and its evolutions<br>• Antenna techniques, including MIMO/space-time coding<br>• Interference management techniques, including CoMP approaches<br>• Additional sectorisation |

**Figure 9: Capacity-enhancing techniques considered in our previous study for Ofcom**

Regulators from across the world regularly produce their own estimates of future spectrum demand.  In Ofcom's case this has included previous work such as:

- The "Predicting areas of spectrum shortage" study by PA Consulting Group [4]
- The "Techniques for increasing the capacity of wireless broadband networks; UK 2012 -2030" study by Real Wireless [5]
- The "Estimating the Utilisation of Key Licence-Exempt Spectrum Bands" study by Mass Consultants [6] and subsequent on-going work to estimate demand for licence exempt spectrum

However, due to the range of factors to consider when estimating spectrum requirements as discussed earlier, the approach to modelling demand for spectrum varies significantly across these making it difficult to make comparisons across them and to form a coherent view of spectrum requirements across all frequency bands.  This problem only gets worse at an ITU level when member states produce spectrum estimates based on their own individual methodologies.

To overcome this issue the ITU-R has specified the methodology to estimate spectrum requirements in its latest revision of document ITU-R M.1768-1 [7]. This recommendation describes a methodology for the calculation of terrestrial spectrum requirement estimation for International Mobile Telecommunications (IMT) systems and is being used as the basis for the spectrum estimates being developed by working party 5D for consideration under agenda item 1.1 in WRC-15.

This model has in the past been used to estimate spectrum requirements for WRC '07 agenda item 1.4 in Report ITU-R M.2078 [8].  However, these spectrum estimates were derived from the following:

- Mobile broadband traffic forecasts and demand density estimates based on market studies from various ITU-R members from 2006.

- An assessment of technology parameters from the EU WINNER study [9] and subsequent discussions around the production of M.2078 which date from 2006.
- Generic network settings that are thought to be representative of the majority of ITU-R regions but which may not reflect the UK mobile broadband market accurately in terms of site number, roll out of small cells, uptake of Wi-Fi, roll out of LTE and LTE-A etc.

## 1.3 Making use of the ITU-R spectrum requirements methodology Ofcom would like to understand both licensed and licence exempt (LE) spectrum requirements to 2030

Ofcom commissioned this study to help inform UK's input on the spectrum estimate work being carried out in ITU-R WP5D as part of the preparatory work for WRC-15 Agenda Item 1.1.

The purpose of this study is to obtain an accurate and robust estimate of the demand for spectrum for terrestrial mobile broadband applications in the UK for the period from 2015 to 2030 based on evidence from market trend data. This includes the following steps:

1. Producing an estimate of UK mobile data traffic demand for the period from 2015 to 2030 based on evidence from market trend data.
2. Using this traffic demand and other relevant information, identifying and justifying appropriate input parameters to be used in the spectrum estimation methodology developed by the ITU-R as defined in the latest version of Recommendation ITU-R M.1768-1 [7].
3. Producing an estimate of the UK spectrum requirement for IMT networks based on the ITU-R methodology, including:
    - The total spectrum needed for coverage, for capacity and for performance (including the corresponding frequency ranges);
    - How the spectrum requirement varies for the cases of low and high demand (e.g. different market settings as was done in Report ITU-R M.2078);
    - The level of asymmetry between downlink and uplink for traffic and the impact on spectrum requirements.
4. Adapting as necessary the ITU-R methodology to also estimate the spectrum requirement for traffic to be carried over Wi-Fi networks and produce a corresponding spectrum estimate.
5. Identifying the key sensitivities that will affect the spectrum estimation and producing a matrix of results that takes account of such sensitivity analyses.
6. Identifying any deficiencies in the methodology that might affect the spectrum estimation and proposing how these could be addressed and quantified.

Alongside this study Ofcom has issued a Call for Input to allow stakeholders an opportunity to express their views on issues related to the future spectrum demand for terrestrial mobile broadband applications and the pros and cons of specific frequency bands as potential candidates to help fulfil that demand. We have also taken into consideration the responses from this Call for Input process when determining suitable input parameters for the ITU-R spectrum estimation model used in this study.

## 1.4 Our approach and structure of this report

This study has been split into two parallel work streams that examine:

- UK specific demand forecasts for mobile broadband traffic levels as input to the ITU-R M.1768 model
- Development of the ITU-R M.1768-1 model to produce spectrum estimates out to 2030 and include LE spectrum requirements. This has included the critical review of default ITU-R input parameter settings for the ITU-R M.1768-1 model which include, for example, spectrum efficiency and the distribution of traffic across different radio access technologies.

This study has followed the stages suggested by Ofcom in section 1.3 with the results of these captured in this final report as follows:

- Chapter 1 describes the study background and aims.
- Chapter 2 reports our spectrum requirements results against the UK landscape for spectrum availability and discusses spectrum requirements against the categories requested by JTG 4-5-6-7.
- Chapter 3 summarises the basis for our spectrum estimates including our analysis of mobile broadband demand in the UK and updates to model inputs against the ITU-R default settings.
- Chapter 4 includes our analysis of the sensitivity of our spectrum estimates to variations in input assumptions such as the rate of deployment of small cells and the amount of offload of cellular traffic to Wi-Fi networks.
- Chapter 5 summarises the key findings from this study and discusses recommendations for further investigation to overcome deficiencies in the ITU-R M.1768-1 model.

We have also produced a series of appendices to support this main body report as follows:

- Appendix A – details of our simulation and modelling methodology for spectrum estimates in this study and updates made to the ITU-R M.1768-1 model obtained from ITU working party 5D.
- Appendix B – details our assumptions on spectrum availability in the UK over time
- Appendix C – details our analysis of UK specific mobile broadband demand
- Appendix D – details our critique of ITU recommended values for service and market related parameters for the ITU-R M.1768-1 model
- Appendix E – details our critique of ITU recommended values for network and technology related parameters for the ITU-R M.1768-1 model
- Appendix F – details our assumed traffic distribution across intermediary devices in our demand analysis
- Appendix G – summarises CFI responses from stakeholders and our actions against these

## 1.5 Overview of ITU-R M.1768-1 model and terminology

This section provides a brief introduction to the ITU-R M.1768-1 spectrum requirements model by way of background and to introduce terminology used throughout this report.

Figure 10 gives an overview of the ITU method for spectrum estimation as captured in ITU-R recommendation M.1768-1.

This broadly entails estimating a traffic demand density across a range of services in different environments and then comparing this with the spectral efficiency density that would be achieved across the range of wireless networks using a mix of topology types in that environment. This includes:

- Defining user density and traffic demand across a range of services (known as Service Categories (SCs)) in each of the environments considered by the model (known as Service Environments (SEs)).
- Taking account of the specification of the SCs, the traffic in each SE from these service categories is then distributed across the available air interfaces (Radio Access Technology Groups (RATGs)) based on:
  - The distribution of traffic across RATGs setting at the model input
  - Whether the RATG is able to support a given SC (by providing data rates at or above the mean service rate required for a given SC)
- Examining the network layers and topology of the various wireless networks available in each of the SEs to determine how the traffic, now distributed by combinations of SE and RATG, should be distributed between macrocells, microcells, picocells and hotspots in each SE and RATG combination.
- The spectrum efficiency density within each cell type for a given RATG then being assessed against the demand per cell type within a given environment and RATG to assess the spectrum requirement for this combination. This is repeated across each combination of cell type, RATG and SE so that the resulting spectrum requirements of macrocells, microcells, picocells and hotspots across the teledensities of dense urban, suburban and rural environments are reported from the model for each RATG considered.

Figure 11 to Figure 13 provides a reminder from the ITU-R M.1768-1 documentation of the SEs considered in the model, user groups within these SEs and the SCs considered in the model. These SEs and SCs are referred to extensively throughout this report and so these tables are included for reference.

Note also that the term RATG is extensively used throughout this report also which is the term used by ITU to group different classes of wireless air interfaces together as follows:

- RATG1 includes GSM, UMTS and LTE
- RATG2 includes LTE-A onwards
- RATG3 covers short range wireless technologies such as Wi-Fi

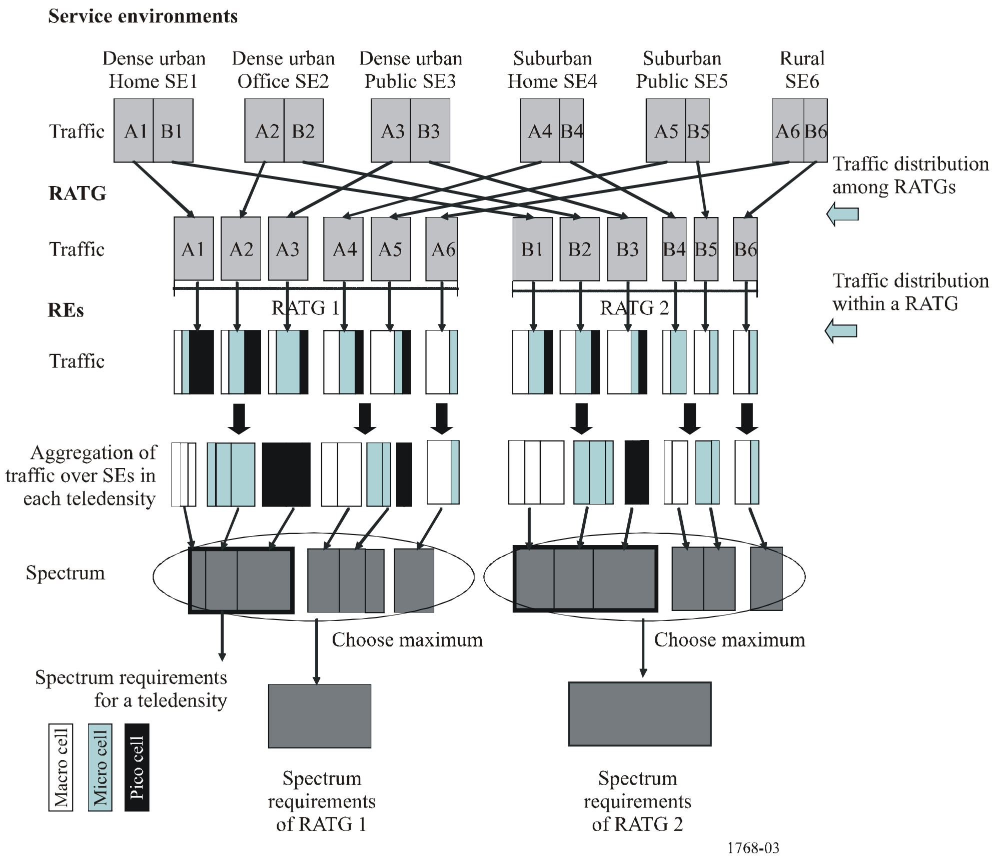
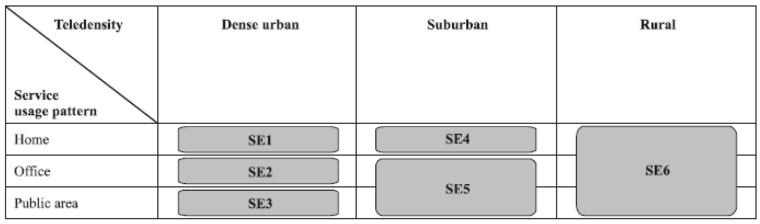



**Figure 10: Overview of ITU spectrum estimation methodology [7]**



**The identification of Service Environments**

| Teledensity / Service usage pattern | Dense urban | Suburban | Rural |
|---|---|---|---|
| Home | SE1 | SE4 | SE6 |
| Office | SE2 | SE5 | |
| Public area | SE3 | | |

**Figure 11: Service environments within the ITU-R M.1768-1 model [7]**

TABLE 7

**Examples of user groups and applications of service environments**

| | User groups | Applications |
|---|---|---|
| SE1 | Private user, business user | Voice, Internet access, games, e-commerce, remote education, multimedia applications |
| SE2 | Business user, small and medium size enterprise | Voice, Internet access, video conferencing, e-commerce, mobile business applications |
| SE3 | Private user, business user, public service user (e.g. bus driver, emergency service), tourist, sales people | Voice, Internet access, video conferencing, mobile business applications, tourist information, e-commerce |
| SE4 | Private user, business user | Voice, Internet access, games, e-commerce, multimedia applications, remote education |
| SE5 | Business user, enterprise | Voice, Internet access, e-commerce, video conferencing, mobile business applications |
| SE6 | Private user, farm, public service user | Voice, information application |

**Figure 12: User groups within the SEs in the ITU-R M.1768-1 model [7]**

**Service category number**

| | Traffic class / Service type | Conversational | Streaming | Interactive | Background |
|---|---|---|---|---|---|
| >30Mbps | Super high multimedia | SC 1 | SC 6 | SC 11 | SC 16 |
| >2Mbps | High multimedia | SC 2 | SC 7 | SC 12 | SC 17 |
| >144kbps | Medium multimedia | SC 3 | SC 8 | SC 13 | SC 18 |
| >16kbps | Low rate data and low multimedia | SC 4 | SC 9 | SC 14 | SC 19 |
| <16kbps | Very low rate data(1) | SC 5 | SC 10 | SC 15 | SC 20 |

(1) This includes speech and SMS.

**Figure 13: Service categories within the ITU-R M.1768-1 model [7]**

In addition the ITU model considers four different cell types to be potentially available to cellular networks which for the purpose of this study we interpret as follows:

- Macrocells which are wide area cellular sites as traditionally deployed by operators for coverage.
- Microcells are medium range outdoor celluar sites to add capacity to a network in high demand areas or to provide coverage in a localised not-spot area. These include outdoor small cells or metrocells.
- Picocells are small cells with ranges similar to today's enterprise and residential femtocells in cellular networks. Note these are not restricted to indoor usage and in the case of Wi-Fi may well be used more extensively outdoors. These can be used to add both capacity in busy localised areas or coverage in localised not-spot situations such as might occur in buildings.
- Hotspots are very small cells similar to today's Wi-Fi access points. As with picocells these can be used to add both capacity in busy localised areas or coverage in localised not-spot situations such as might occur in buildings.

The ITU working party 5D has provided an Excel spread sheet implementation of the M.1768-1 model which we have used as the basis of our analysis in this study. An overview of the processes and inputs within this spread sheet are given in Figure 14. This also highlights areas where we have modified the model which includes:

- Extending model timescales out to 2030
- Adding spectrum estimates for licence exempt (LE) spectrum i.e. RATG3
- Adding a calibration process so that the distributed demand across teledensities in the model can be matched to our own UK forecasts of demand in these environments.

Further details of our modelling methodology and updates to the ITU-R M.1768-1 Excel model are provided in Appendix A.

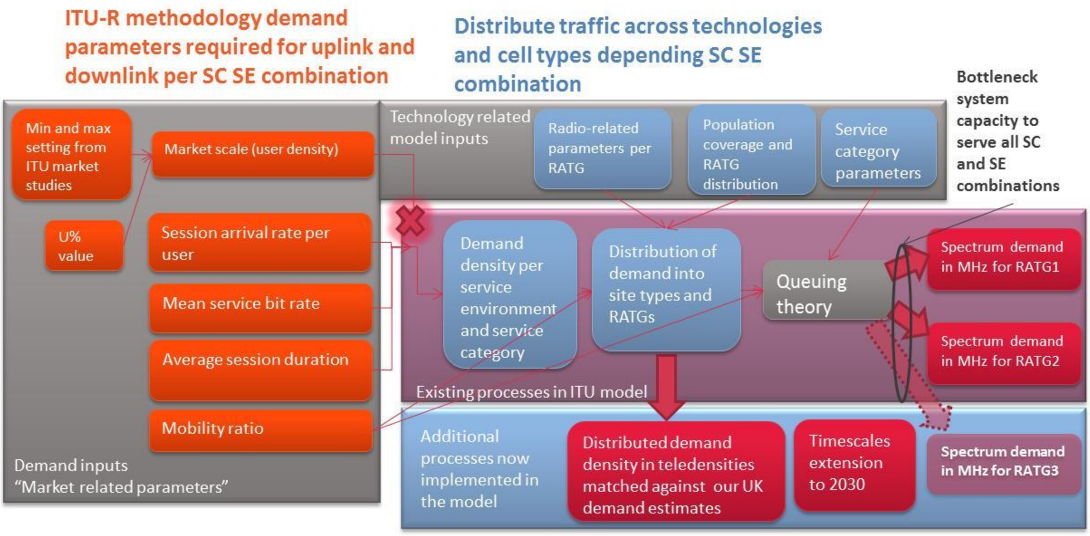



**Figure 14: Overview of processes which Real Wireless have added to the ITU-R M.1768-1 model**

# 2. Our baseline spectrum estimates show pressure on existing licensed and LE spectrum by as early as 2020

This chapter presents our spectrum requirements forecasts for wireless broadband services in both licensed and licence exempt services out to 2030 based on using the ITU-R M.1768-1 spectrum requirements model. These results are then interpreted against the requirements for responding to WRC-15 agenda item 1.1 as set out by the ITU-R JTG 4-5-6-7 which largely request [2]:

- Spectrum requirements for coverage
- Spectrum requirements for capacity
- Spectrum requirements for performance
- Spectrum requirements for high and low market conditions
- Discussion of asymmetry in demand and potential implications for spectrum requirements

## 2.1 Our spectrum requirements estimates are based on using the ITU-R M.1768-1 model which has some limitations

This study aims to produce mobile broadband spectrum requirements estimates to support Ofcom's contribution to the ITU working party 5D response to JTG 4-5-6-7 in preparation for agenda item 1.1 at WRC-15. The spectrum estimates produced within this study therefore need to support the ITU process and as such be based around the ITU-R M.1768-1 spectrum requirements model. However, due to the complexities of estimating spectrum requirements and the various drivers for spectrum requirements which are difficult to capture in a single model, we have noted some deficiencies that should be taken into consideration when interpreting the results presented by this study.

Where possible we have taken mitigating actions in this study to limit the impact of these limitations as summarised on Table 2. However, it has not been possible to address all of these limitations within the timescales of this study or within the framework of ITU-R M.1768-1 and our results should be viewed with this in mind. We have also recommended next steps for future studies which would help address these limitations.

| Description of limitation | Mitigating action taken in this study | Recommended next steps |
|---|---|---|
| The modelled sector areas across cell types does not vary with:<br>• Frequency band<br>• Technology or RATG[11] | Included sector sizes based on deployments of UK cellular sites today which will represent the mix of spectrum available in the UK today. While this means that results are more representative of UK networks, this sector size could still vary over time with the introduction of other frequency bands and more sites. Therefore this does not entirely address the model deficiency of sector sizes not varying with frequency band or RATG. | Further expand the ITU-R M.1768-1 model to allow sector sizes to vary over time to represent changing spectrum allocations and site numbers and also to vary by RATG. |
| Spectrum requirements across frequency bands are not reported by the model | None feasible in the study timescales | Review other coverage focused studies such as our 800MHz coverage obligation study for Ofcom [11] against the results of this study to draw conclusions on sub 1GHz spectrum requirements |
| Coverage percentages assumed do not vary with radio access technology group (RATG). Therefore situations arise where the coverage of LTE-A at initial roll out has to be modelled at the same coverage level as more established LTE networks as the coverage levels cannot be varied between RATG1 and RATG2 in the model. | None feasible in the study timescales | Expand the ITU-R M.1768-1 model to vary coverage levels by RATG so that lower coverage levels for less mature RATGs can be considered and their introduction more accurately represented over time. |
| Results are limited to spectrum requirements across RATGs as a whole rather than specific networks. For example, RATG1 will cover GSM, UMTS and LTE networks which each will require their own discrete amounts of spectrum to be maintained over time to ensure backwards compatibility in the network. | None feasible in the study timescales | Further develop the ITU-R M.1768-1 model to represent all cellular air interfaces active in the UK i.e. GSM, UMTS, LTE individually rather than collectively under RATG1. |
| Application rates, which describe the supported service levels in particular cell types and RATGs, do not vary with environment. | None feasible in the study timescales | Further develop the ITU-R M.1768-1 model to allow application rates to |

[11] Noting that for different RATGs supporting different coding and modulation combinations, levels of MIMO etc. there will be a different signal to noise requirement to meet the same target cell edge performance level and hence cell sizes could be different.

| Description of limitation | Mitigating action taken in this study | Recommended next steps |
|---|---|---|
| However, the target cell edge data rates and average data rates of a cell will vary between teledensities. For example a macrocell in a dense urban environment will have a much smaller sector area and hence cell edge performance level than macrocells in rural areas. | | vary by service environment. |
| The relative extent and density of the different layers of the network (macrocells relative to small cells) are inputs to the model, rather than an outcome of determining the most efficient network topology. | None feasible in the study timescales | Re-examine spectrum requirements using a model such as the one used in our UHF strategy study for Ofcom [5] which includes deploying cell types in the most efficient manner to meet growing capacity requirements over time. |
| The model does not consider the fine-grained local spatial and temporal structure of the demand, which can significantly impact the required peak network capacity density. | In the case of LE spectrum estimates we calibrate the user densities in each SE in line with our demand density estimates for each SE which represents quite localised demand levels. The queuing theory block in model also allows some overhead for demand peaks. | Update the ITU-R M.1768-1 to calibrate user densities driving demand densities on a per SE basis as used in our LE spectrum analysis rather than on a per teledensity basis as used in our licensed spectrum analysis. Also consider traffic peaks as in our UHF strategy study for Ofcom [5]. |
| The model in its unmodified form does not compute the requirements for licence-exempt spectrum. | We have updated the model to include RATG3 spectrum requirements but note that the ITU model is generally not well suited to the highly localised demand levels of LE hotspots. | Develop a different approach to LE spectrum estimates which examines spectrum requirements and the practical limitations of meeting these in highly localised scenarios such as an apartment block. |
| The model does not facilitate considering different levels of Wi-Fi offload in different SEs and across different user types. The model distributes traffic across RATGs based on the "Traffic distribution ratio among available RATGs" input settings which can vary by year but not by SE. When examining demand that could have potentially been | None feasible in the study timescales | Update the ITU-R M.1768-1 model so that the impact of different assumed Wi-Fi offload levels across SEs and user types can be investigated. In particular the impact of a limited offload opportunity for high mobility users on overall |

| Description of limitation | Mitigating action taken in this study | Recommended next steps |
|---|---|---|
| delivered via licensed spectrum, we interpret the ratio of traffic in RATG3 compared to RATG1 and RATG2 as the Wi-Fi offload level but this RATG3 ratio is applied equally across SEs and so the higher Wi-Fi offload levels of indoors users compared to high speed outdoor users cannot be directly investigated. | | spectrum estimates should be investigated |
| The demand levels input to the model through market settings are not necessarily all distributed and contributing to spectrum requirements in the model. The model distributes traffic from each SE to RATGs in line with the "Traffic distribution ratio among available RATGs" input settings. It then examines the cell types available within each RATG to distribute the traffic per RATG across cell types within that RATG. However, it is only at this stage that the model checks if the available cell types within a RATG can support the type of traffic distributed to that RATG. This means that some high mobility traffic may be distributed to a RATG such as RATG3, representing in early years Wi-Fi, which can only support stationary users. This traffic is reported as undistributed in the model and does not contribute to the overall spectrum requirements. To partially overcome this we calibrate the traffic once distributed amongst RATGs and cell types within the ITU model against our UK specific demand estimates (see appendix A) rather than the total demand density at the model inputs prior to this distribution. | We address the deficiency of undistributed traffic in the model by calibrating our UK specific demand densities per teledensity against the demand densities in the model once distributed across RATGs and cell types to ensure that all demand in our forecasts is included in spectrum estimates. | Further analyse demand inputs and the distribution of traffic in the model and refine so that no demand is generated without a cell type and RATG combination being available to serve it. |
| Deployment cost is not considered in the model even though there is a fundamental link between the demand generated in a network and whether it is economical for an | When selecting model input settings we have drawn heavily on our UHF strategy study which examined the most economical capacity enhancements options | Examine how a more economics based model such as the one used in our UHF strategy study for Ofcom [5] could be used to understand |

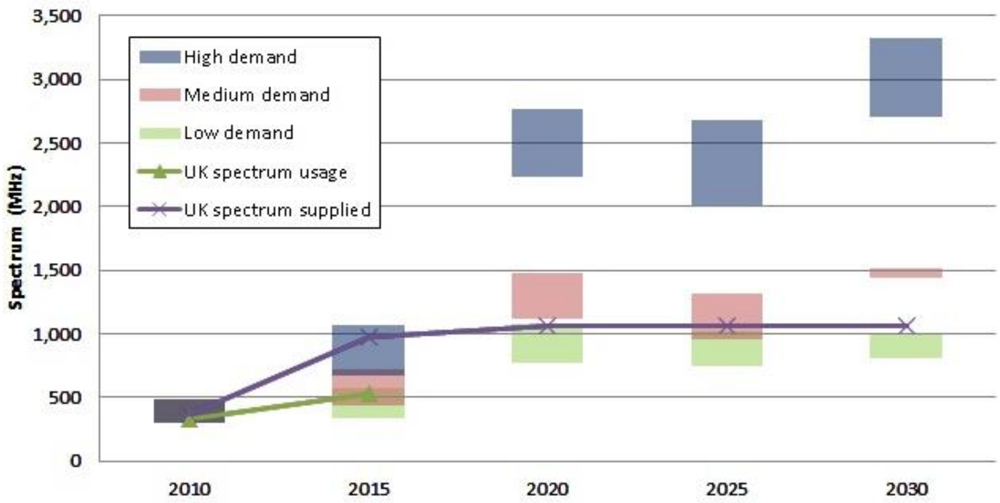
| Description of limitation | Mitigating action taken in this study | Recommended next steps |
|---|---|---|
| operator to provide high end services which drive demand up. | for operators in given demand and spectrum supply scenarios. | spectrum estimates with network costs kept in mind. |
| The setting for whether a service category is circuit switched or packet switched does not vary with time in the model. This means services cannot migrate to being packet switched rather than circuit switched over time in line with expected cellular network evolutions. We also note that the ITU recommended values assume all conversational and streaming services are delivered via circuit switched networks which may not be a true reflection of today's cellular networks. | We have carried out a sensitivity analysis to determine the importance of assumptions on whether SCs are PS or CS. This has shown that this can have a significant impact on spectrum estimates and potentially delay the date for additional spectrum requirements until 2030 as opposed to 2020 for our medium demand case. | Update the ITU-R M.1768-1 model to allow CS and PS assumptions to vary over time and across RATGs, review more fully the appropriateness of assuming PS delivery mechanisms for all SCs and appropriate PS service related parameters for these and whether the overheads for PS mechanisms in the model currently are appropriate for guaranteed bit rate services. |

**Table 2: Summary of model limitations, mitigating actions taken in this study and recommended next steps to address these limitations**

We consider the most significant of these limitations to be the lack of consideration of costs within the model. This is because there is a link between demand for cellular services and investment in network improvements i.e. users will not have access to high speed services on a network if it is uneconomical for an operator to deploy these out at the time. Our model for simulating techniques for enhancing capacity in cellular networks as used in our previous UHF strategy study for Ofcom [5] went some way towards addressing this and many of the other deficiencies listed above and could potentially be used in further work to examine the economic viability and efficiency of spectrum estimates produced by the ITU-R M.1768-1 model.

## 2.2 Our baseline spectrum estimate for licensed spectrum shows the existing UK plan of spectrum releases could become insufficient from 2020 onwards

Within this study we have considered demand for licensed spectrum at a low, medium and high market setting as detailed in Appendix C and summarised in section 3.1.1. Figure 15 shows our results for licensed spectrum requirements across these three demand scenarios using our recommended baseline settings for the ITU-R M.1768-1 model (summarised in section 3). These results are based on demand for licensed spectrum after some offload of traffic to Wi-Fi (in line with our medium Wi-Fi offload levels as shown in section 4.2.1) has been removed from the total potential demand for licensed spectrum.




| Spectrum(MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| High demand | Shared | 295 | 665 | 2,230 | 2,010 | 2,710 |
| | Dedicated | 490 | 1,070 | 2,770 | 2,675 | 3,325 |
| Mid demand | Shared | 295 | 440 | 1,120 | 950 | 1,445 |
| | Dedicated | 490 | 720 | 1,475 | 1,315 | 1,515 |
| Low demand | Shared | 295 | 340 | 775 | 740 | 805 |
| | Dedicated | 490 | 575 | 1,080 | 1,015 | 995 |

**Figure 15: Our low, medium and high demand baseline licensed spectrum estimate results (MHz) against UK spectrum usage in 2010 and 2015 and anticipated UK spectrum supply over time without future allocations of mobile broadband spectrum at WRC-15**

The blue, pink and green blocks in this figure give a range for our spectrum requirements estimates for each of our high, medium and low demand scenarios respectively. For each of these cases we provide:

- A dedicated spectrum result (upper end of the coloured blocks) where macrocells, microcells, picocells and hotspots for each RATG all require a dedicated spectrum layer. Note that this is slightly different to the ITU definition of dedicated spectrum which allows for some sharing between layers. However, our revised definition of dedicated spectrum estimates presents an upper bound on spectrum requirements for the scenario being considered.
- A shared spectrum result (lower end of the coloured blocks) where all cell types for a given RATG share spectrum. This aligns with the ITU's definition of shared spectrum estimates and gives a lower bound on spectrum requirements for the scenario being considered.

In practice some sharing of spectrum across cell types is achieved in cellular networks and therefore a spectrum requirement between the dedicated and shared result is likely to be the most realistic. The position of the most realistic spectrum requirement value between this shared and dedicated spectrum estimate will vary over time depending on operator approaches to frequency reuse in their networks, enhancements in technologies to reduce interference between network layers sharing spectrum, the location of deployments of small cells and whether they are isolated from wider area cells in indoor environments etc.

In Figure 15 we compare these spectrum estimates for different market settings against our estimate of the volume of mobile broadband spectrum either already awarded or likely to be awarded over our timeline to 2030. This is shown by the purple line in Figure 15. The frequency bands that we consider and their availability over time in the estimate of spectrum availability is summarised in Figure 16. Note that all frequency bands considered here already have a mobile service allocation in the ITU-R Table of Allocations.

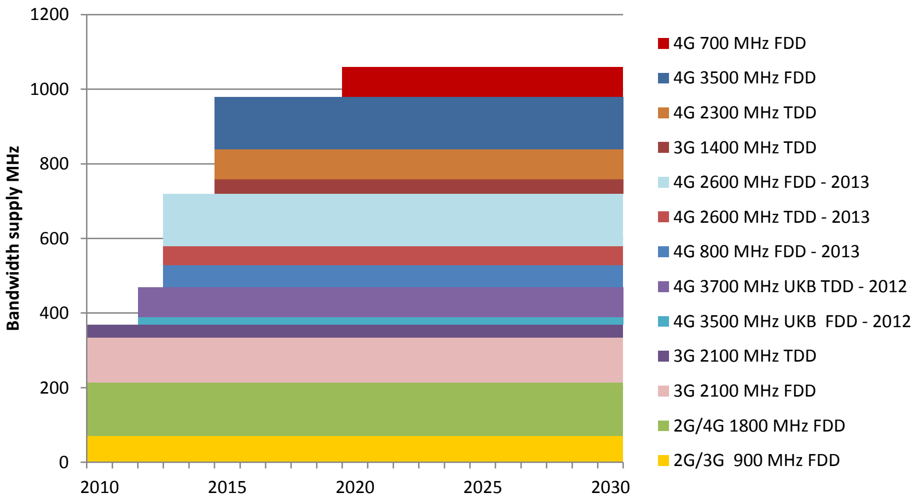



**Figure 16: Our assumed availability of UK mobile broadband spectrum out to 2030, in the absence of new allocations at WRC-15**

Figure 15 shows that in the low demand case current UK plans for mobile broadband spectrum release are potentially enough to keep pace with spectrum requirements out to 2030. This is largely because the improvements in network capacity due to increased spectral efficiencies and increased small cell deployments are largely enough to keep pace with demand increases from 2020 onwards in this scenario.

In our medium demand case we see that planned awards of spectrum in the UK are likely to be enough to keep pace with demand up to 2015. However, by 2020 spectrum is likely to come under pressure with our optimistic shared spectrum estimates for this scenario just exceeding spectrum supply at this time.

In the high demand case mobile broadband spectrum requirements up to 2015 are commensurate with the levels of spectrum planned to be available if current UK spectrum release plans are followed and all spectrum awarded by 2015 is fully utilised. However, as in the baseline medium demand case, additional spectrum beyond existing plans needs to be identified by 2020 to keep pace with demand and spectrum requirements for the high demand case.

Therefore across all three scenarios we conclude that by 2020 currently awarded and planned awards of mobile broadband spectrum in the UK will not be sufficient to keep pace with demand if our medium and high estimates of UK mobile broadband demand and baseline model settings are realised in practice. We also note that the difference between our medium and high forecasts for UK mobile broadband demand being realised in practice could cause as much as a doubling in spectrum requirements.

Note that while the model results show some reduction in spectrum requirements between 2020 and 2025 in practice it is likely that any additional spectrum allocations to meet demand in 2020 would, rather than lying unused in 2025 due to network improvements, facilitate increased performance levels and services by 2025 that would drive up demand to keep this spectrum utilised in practice.

As a check on how realistic and representative of UK networks our spectrum estimates are the green line in Figure 15 indicates a view of the amount of spectrum that we estimate was used in practice for mobile broadband services at 2010 and is likely to be used by 2015. This is reduced from the spectrum supplied estimate as it takes account of TDD bands in the UK that have been awarded but currently remain unused as discussed further in appendix B. Comparing these 2010 and 2015 spectrum usage estimates with our medium demand spectrum estimates shows a good alignment and generally supports our recommended model settings and medium demand estimate which are revisions to the ITU recommended values in these areas (as described further in section 3).

### 2.2.1 5 yearly trends in our licensed spectrum estimates

Generally across our low, medium and high demand spectrum estimates presented in Figure 15 increases in demand between consecutive time periods outstrips spectral efficiency improvements in the available air interfaces. However, spectrum requirements do not grow by as much as the increase in demand relative to spectrum efficiency improvements in any given time period would suggest as highlighted by the following discussion per consecutive time period shown. Increases in demand, spectral efficiency and spectrum requirements given here are based on our medium demand estimates but similar trends are followed in our high and low demand cases also.

**Spectrum estimates for 2010 to 2015**
Between 2010 and 2015 demand increases by 9.1[12]x and spectral efficiency improves[13] by 3.8x giving a likely increase in required spectrum of 2.4x. Our result shows spectrum increasing[14] by only 1.5x. The additional improvement in cellular networks leading to these lower than anticipated spectrum estimates is due to changes in the network topology and more specifically the increased deployment of small cells in cellular networks (which will be limited to RATG1 at this point in time due to our baseline model assumption that LTE-A and hence RATG2 will not be deployed in the UK until 2020). Note that the impact on spectrum requirements of small cells is limited to the offload of low mobility traffic though (as discussed further later).

**Spectrum estimates for 2015 to 2020**
Between 2015 to 2020 demand increases by 3.8x but spectral efficiency only increases by 1.6x. Therefore a 2.4x spectrum increase is expected compared with the 2.2x spectrum increase estimated by the model. As in the previous 5 year period, this is reduction in estimated spectrum requirements compared with the anticipated change, due to the offset in demand increases by technology improvements, is likely due to network topology changes and the further deployment of small cells in this time period. However, the impact of small cells is not as great here as it was in the previous 5 year period and actually the most significant increase in spectrum requirements occurs in this 5 year time period. This is

[12] Increases in demand are based on suburban areas which tend to drive overall spectrum requirements in our results unless otherwise stated.
[13] Increases in spectrum efficiency are based on the average SE improvement across RATGs for the SEs causing the spectrum bottleneck in those years examined.
[14] Increases in spectrum requirements based on the average between the shared and dedicated spectrum requirements results from our baseline medium demand scenario.

largely due to the assumed roll out of LTE-A networks in 2020 which can accommodate more demanding services. These newly introduced services have high overheads leading to increases in overall spectrum requirements even at low initial demand densities. Note also that there is a significant volume of traffic on both RATG1 and RATG2 networks in parallel in this timeframe and so spectrum requirements include sustaining significant capacity on both of these.

**Spectrum estimates for 2020 to 2025**
Between 2020 to 2025 demand increases by 3.1x but spectral efficiency only increases by 1.7x. Therefore a 1.8x spectrum increase is expected compared with the 0.9x spectrum change (i.e. decrease) estimated by the model. The introduction of LTE-A hotspots from 2020 provides a network layer with a very high spectral efficiency density which explains some of this reduction in spectrum requirements despite the changes in demand levels outstripping improvements in spectrum efficiency on a per cell basis. Also with LTE-A, and with it more demanding services, already having been introduced in 2020 the initial investment in bandwidth to provide coverage for these newly introduced networks and services has already been made at the start of this time period. However, while there is some relief in spectrum requirements between 2020 and 2025 this is not enough to avoid still requiring spectrum releases that go beyond existing plans in time for 2025 and 2030.

**Spectrum estimates for 2025 to 2030**
Between 2025 to 2030 demand increases by 1.8x in suburban areas and spectral efficiency also increases by 1.8x. Therefore spectrum estimates should remain the same compared with the 1.3x change in overall spectrum requirements estimated by the model. However, note that the spectrum bottleneck moves from suburban to rural areas in this timeframe and that there is actually no increase in spectrum requirements in suburban areas in this timeframe which aligns with our anticipated change in spectrum requirements. Small cell coverage levels are assumed to increase little in this time period as they have already been deployed to relatively high levels and so the spectrum requirements should remain commensurate with those anticipated by comparing demand increases to spectrum efficiency improvements.

### 2.2.1 Our licensed spectrum estimates indicate that suburban environments will remain the spectrum bottleneck scenario out to 2025

Figure 17 shows the detailed breakdown of spectrum requirements for our medium demand scenario over time across:

- Teledensities
- Cell types
- RATGs

Examining results across the three teledensities shows that the spectrum requirements are largely driven by suburban areas (see in Figure 17). This is because while the demand density in suburban areas in our medium demand forecast is roughly only half that of dense urban areas:

- Microcell coverage levels are lower in suburban areas than in dense urban areas (see appendix E) and so more traffic needs to be carried on the less dense and spectrally efficient macrocell layer in suburban areas.

- Macrocell and microcells are also rolled out more densely in dense urban areas, as reflected by smaller sector areas (see section appendix E) in the model compared with suburban areas, giving better spectral efficiency density in these dense urban areas.

***Spectrum requirement in 2010 in MHz***

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 45 | 150 | 20 | 0 | 0 | 0 | 0 | 0 | 45 | 150 | 20 | 0 | | | | 215 | 0 | |
| Sub Urban | 295 | 190 | 5 | 0 | 0 | 0 | 0 | 0 | 295 | 190 | 5 | 0 | | | | 490 | 0 | |
| Rural | 160 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 160 | 0 | 5 | 0 | | | | 165 | 0 | |
| Overall | | | | | | | | | | | | | 295 | | 295 | 490 | 0 | 490 |

***Spectrum requirement in 2015 in MHz***

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 40 | 440 | 110 | 0 | 0 | 0 | 0 | 0 | 40 | 440 | 110 | 0 | | | | 590 | 0 | |
| Sub Urban | 360 | 270 | 90 | 0 | 0 | 0 | 0 | 0 | 360 | 270 | 90 | 0 | | | | 720 | 0 | |
| Rural | 100 | 5 | 55 | 0 | 0 | 0 | 0 | 0 | 100 | 5 | 55 | 0 | | | | 160 | 0 | |
| Overall | | | | | | | | | | | | | 440 | | 440 | 720 | 0 | 720 |

***Spectrum requirement in 2020 in MHz***

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 40 | 240 | 190 | 0 | 160 | 110 | 25 | 10 | 200 | 350 | 215 | 10 | | | | 470 | 305 | |
| Sub Urban | 30 | 315 | 155 | 0 | 805 | 140 | 20 | 10 | 835 | 455 | 175 | 10 | | | | 500 | 975 | |
| Rural | 30 | 5 | 105 | 0 | 315 | 10 | 10 | 5 | 345 | 15 | 115 | 5 | | | | 140 | 340 | |
| Overall | | | | | | | | | | | | | 315 | 805 | 1120 | 500 | 975 | 1475 |

***Spectrum requirement in 2025 in MHz***

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 30 | 120 | 180 | 0 | 130 | 175 | 105 | 55 | 160 | 295 | 285 | 55 | | | | 330 | 465 | |
| Sub Urban | 20 | 140 | 145 | 0 | 770 | 190 | 20 | 5 | 790 | 330 | 165 | 5 | | | | 305 | 985 | |
| Rural | 25 | 0 | 105 | 0 | 645 | 0 | 5 | 5 | 670 | 0 | 110 | 5 | | | | 130 | 655 | |
| Overall | | | | | | | | | | | | | 180 | 770 | 950 | 330 | 985 | 1315 |

***Spectrum requirement in 2030 in MHz***

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 15 | 45 | 175 | 0 | 110 | 160 | 65 | 30 | 125 | 205 | 240 | 30 | | | | 235 | 365 | |
| Sub Urban | 15 | 55 | 140 | 0 | 905 | 175 | 15 | 5 | 920 | 230 | 155 | 5 | | | | 210 | 1100 | |
| Rural | 15 | 0 | 105 | 0 | 1270 | 0 | 5 | 5 | 1285 | 0 | 110 | 5 | | | | 120 | 1280 | |
| Overall | | | | | | | | | | | | | 175 | 1270 | 1445 | 235 | 1280 | 1515 |

**Figure 17: Detailed results from our medium demand baseline licensed spectrum requirements scenario**

Note that by 2030 in rural areas the lack of small cells and reliance on a coverage based macrocell layer with large sector areas and low spectral efficiency densities means that rural macrocell requirements overtake those of suburban macrocells. This is discussed further in section 2.2.4.

Figure 18 and Figure 19 show a similar detailed breakdown of spectrum requirements results for our high and low demand scenarios. Across all three market settings we find that suburban macrocell spectrum requirements largely drive overall spectrum requirements due to the high reliance on macrocells to accommodate mobile users in mobile environments in all three cases. The exception to this is in 2015 where dense urban microcells in both the low and high demand scenarios briefly require the most spectrum as in the baseline medium demand case. Also in the baseline medium demand case rural macrocell requirements just exceed suburban macrocell requirements by 2030 but this does not occur in the low and high demand cases.

*Spectrum requirement in 2010 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 45 | 150 | 20 | 0 | 0 | 0 | 0 | 0 | 45 | 150 | 20 | 0 | | | | 215 | 0 | |
| Sub Urban | 295 | 190 | 5 | 0 | 0 | 0 | 0 | 0 | 295 | 190 | 5 | 0 | | | | 490 | 0 | |
| Rural | 160 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 160 | 0 | 5 | 0 | | | | 165 | 0 | |
| Overall | | | | | | | | | | | | | 295 | 0 | 295 | 490 | 0 | 490 |

*Spectrum requirement in 2015 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 60 | 665 | 115 | 0 | 0 | 0 | 0 | 0 | 60 | 665 | 115 | 0 | | | | 840 | 0 | |
| Sub Urban | 565 | 410 | 95 | 0 | 0 | 0 | 0 | 0 | 565 | 410 | 95 | 0 | | | | 1070 | 0 | |
| Rural | 100 | 5 | 55 | 0 | 0 | 0 | 0 | 0 | 100 | 5 | 55 | 0 | | | | 160 | 0 | |
| Overall | | | | | | | | | | | | | 665 | 0 | 665 | 1070 | 0 | 1070 |

*Spectrum requirement in 2020 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 65 | 470 | 210 | 0 | 180 | 210 | 35 | 10 | 245 | 680 | 245 | 10 | | | | 745 | 435 | |
| Sub Urban | 50 | 620 | 170 | 0 | 1610 | 280 | 30 | 10 | 1660 | 900 | 200 | 10 | | | | 840 | 1930 | |
| Rural | 30 | 5 | 105 | 0 | 335 | 10 | 10 | 5 | 365 | 15 | 115 | 5 | | | | 140 | 360 | |
| Overall | | | | | | | | | | | | | 620 | 1610 | 2230 | 840 | 1930 | 2770 |

*Spectrum requirement in 2025 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 45 | 225 | 195 | 0 | 175 | 385 | 190 | 55 | 220 | 610 | 385 | 55 | | | | 465 | 805 | |
| Sub Urban | 30 | 270 | 155 | 0 | 1740 | 430 | 30 | 10 | 1770 | 700 | 185 | 10 | | | | 455 | 2210 | |
| Rural | 25 | 0 | 105 | 0 | 605 | 0 | 5 | 5 | 630 | 0 | 110 | 5 | | | | 130 | 615 | |
| Overall | | | | | | | | | | | | | 270 | 1740 | 2010 | 465 | 2210 | 2675 |

*Spectrum requirement in 2030 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 25 | 75 | 175 | 0 | 200 | 435 | 125 | 30 | 225 | 510 | 300 | 30 | | | | 275 | 790 | |
| Sub Urban | 20 | 100 | 145 | 0 | 2535 | 480 | 30 | 5 | 2555 | 580 | 175 | 5 | | | | 265 | 3050 | |
| Rural | 15 | 0 | 105 | 0 | 1400 | 0 | 5 | 5 | 1415 | 0 | 110 | 5 | | | | 120 | 1410 | |
| Overall | | | | | | | | | | | | | 175 | 2535 | 2710 | 275 | 3050 | 3325 |

**Figure 18: Detailed results from our high demand baseline licensed spectrum requirements scenario**

*Spectrum requirement in 2010 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 45 | 180 | 20 | 0 | 0 | 0 | 0 | 0 | 45 | 180 | 20 | 0 | | | | 245 | 0 | |
| Sub Urban | 295 | 190 | 5 | 0 | 0 | 0 | 0 | 0 | 295 | 190 | 5 | 0 | | | | 490 | 0 | |
| Rural | 160 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 160 | 0 | 5 | 0 | | | | 165 | 0 | |
| Overall | | | | | | | | | | | | | 295 | 0 | 295 | 490 | 0 | 490 |

*Spectrum requirement in 2015 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 35 | 340 | 105 | 0 | 0 | 0 | 0 | 0 | 35 | 340 | 105 | 0 | | | | 480 | 0 | |
| Sub Urban | 280 | 210 | 85 | 0 | 0 | 0 | 0 | 0 | 280 | 210 | 85 | 0 | | | | 575 | 0 | |
| Rural | 80 | 5 | 55 | 0 | 0 | 0 | 0 | 0 | 80 | 5 | 55 | 0 | | | | 140 | 0 | |
| Overall | | | | | | | | | | | | | 340 | 0 | 340 | 575 | 0 | 575 |

*Spectrum requirement in 2020 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 30 | 170 | 185 | 0 | 155 | 75 | 20 | 10 | 185 | 245 | 205 | 10 | | | | 385 | 260 | |
| Sub Urban | 25 | 215 | 150 | 0 | 560 | 100 | 20 | 10 | 585 | 315 | 170 | 10 | | | | 390 | 690 | |
| Rural | 30 | 5 | 105 | 0 | 315 | 10 | 10 | 5 | 345 | 15 | 115 | 5 | | | | 140 | 340 | |
| Overall | | | | | | | | | | | | | 215 | 560 | 775 | 390 | 690 | 1080 |

*Spectrum requirement in 2025 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 25 | 90 | 180 | 0 | 115 | 120 | 95 | 55 | 140 | 210 | 275 | 55 | | | | 295 | 385 | |
| Sub Urban | 20 | 110 | 145 | 0 | 560 | 140 | 15 | 5 | 580 | 250 | 160 | 5 | | | | 275 | 720 | |
| Rural | 20 | 0 | 105 | 0 | 385 | 0 | 5 | 5 | 405 | 0 | 110 | 5 | | | | 125 | 395 | |
| Overall | | | | | | | | | | | | | 180 | 560 | 740 | 295 | 720 | 1015 |

*Spectrum requirement in 2030 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lice |
| Dense Urban | 15 | 40 | 170 | 0 | 95 | 105 | 55 | 30 | 110 | 145 | 225 | 30 | | | | 225 | 285 | |
| Sub Urban | 15 | 50 | 140 | 0 | 635 | 120 | 10 | 5 | 650 | 170 | 150 | 5 | | | | 205 | 770 | |
| Rural | 10 | 0 | 105 | 0 | 585 | 0 | 5 | 5 | 595 | 0 | 110 | 5 | | | | 115 | 595 | |
| Overall | | | | | | | | | | | | | 170 | 635 | 805 | 225 | 770 | 995 |

**Figure 19: Detailed results from our low demand baseline licensed spectrum requirements scenario**

### 2.2.2 Macrocell traffic generated by high mobility users drives the spectrum requirements in "bottleneck" suburban areas

Figure 20 shows licensed spectrum requirements for suburban areas over time detailed by network layer based on using our recommended baseline settings for the ITU-R M.1768-1 model and our UK specific medium demand forecast. Unlike dense urban environments, discussed in the next section, this shows a heavy reliance on macrocells as microcell coverage levels are assumed in the model inputs to be lower in suburban areas than in dense urban areas. Note that the traffic distribution across the network layers of different cell types in the suburban areas remains roughly the same across all three of our demand scenarios.

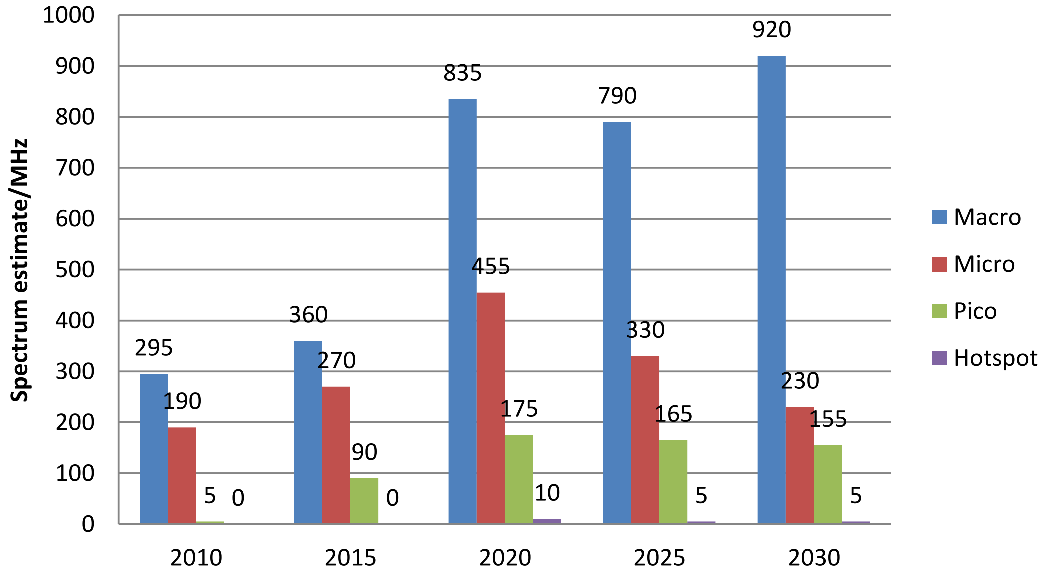



**Figure 20: Licensed spectrum estimates by network layer in suburban areas**

We note that the heavy reliance on macrocells in suburban environments is partially due to high mobility ratios being assumed for some demanding SCs in this environment. Unlike the dense urban environment, there is a higher probability that users will be in vehicles or on trains and travelling at high velocities (>50km/hr) in suburban areas than in dense urban areas where most users will be stationary or pedestrians. Supported mobility class assumptions in our baseline settings which follow the ITU recommended values mean that these high velocity users can only be accommodated on the macrocell layer. We investigate further the impact of changing mobility assumptions in suburban environments on spectrum estimates in our sensitivity analysis.

There is a large increase in macrocell traffic between 2015 and 2020 as prior to this the macrocell network layer in our baseline settings is limited to carrying services below 2Mbps which is the likely LTE cell edge throughput in coverage limited scenarios used for the RATG1 application rate from 2015 onwards. However, with the introduction of LTE-A in 2020 the supported application rate that we assume for RATG2 macrocells increases and the macrocell layer becomes capable of carrying more demanding services (see appendix E). While our RATG1 application rate settings are representative of a coverage limited rural environment they may not be appropriate for a suburban environment where cell sizes are smaller and cell edge throughputs are likely to be much higher. This is a limitation of the current ITU-R M.1768-1 model where application rates cannot be varied by teledensity or service environment but only by cell type. This is investigated further in our sensitivity analysis.

### 2.2.3 Use of small cells in dense urban areas will relieve pressure on spectrum there but not necessarily on overall spectrum requirements

Figure 21 shows licensed spectrum requirements for dense urban areas over time detailed by network layer based on using our recommended baseline settings for the ITU-R M.1768-1 model and our UK specific medium demand forecast. This shows a heavy reliance in dense urban environments, where demand densities will be at the highest levels, on microcells today and increasingly on smaller cells over time. This increased usage of smaller cell types with higher spectrum efficiency densities over macrocells in dense urban environments compared with suburban areas, which were driven by macrocell requirements as discussed in the previous section, shows why, despite having higher demand densities than suburban environments, the spectrum requirements for dense urban areas do not produce the overall spectrum bottleneck in our baseline spectrum estimates. Note also that there is a higher opportunity to offload traffic to smaller cells in dense urban areas than suburban areas also due to the proportion of high mobility traffic in dense urban areas tending to be lower than in suburban areas due to user velocities being more restricted in built up urban areas.

As was the case in the suburban environment there is a large increase in macrocell traffic between 2015 and 2020 due to the macrocell layer being limited to carrying services below 2Mbps by LTE cell edge rates until the introduction of LTE-A in 2020 in our model baseline settings for application rate (see appendix E).

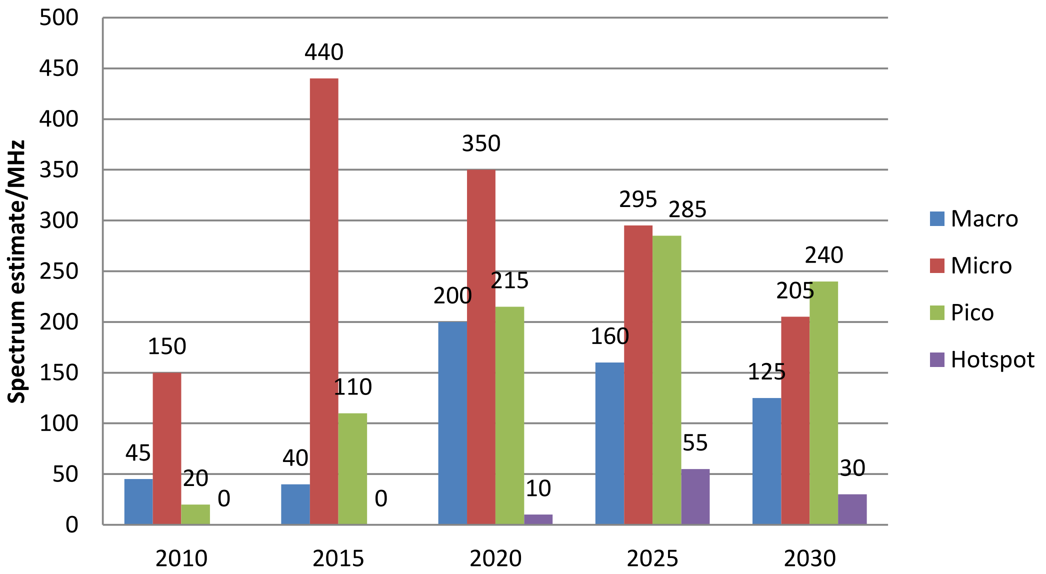



**Figure 21: Licensed spectrum estimates by network layer in dense urban areas**

Note that overall spectrum requirements remain driven by suburban macrocell requirements over any of the spectrum requirement levels estimated for the dense urban environment in our medium demand baseline case.

In the case of our high demand spectrum estimates, microcells dominate the spectrum requirement in dense urban areas as was the case in the medium demand case. However, in the low demand case microcell spectrum requirements are reduced to the extent that they come into the same region as picocell spectrum requirements from 2020 onwards (see Figure 22 and Figure 23). This may have some implications for the sharing of carriers between the wider area and small cell layers of the network.

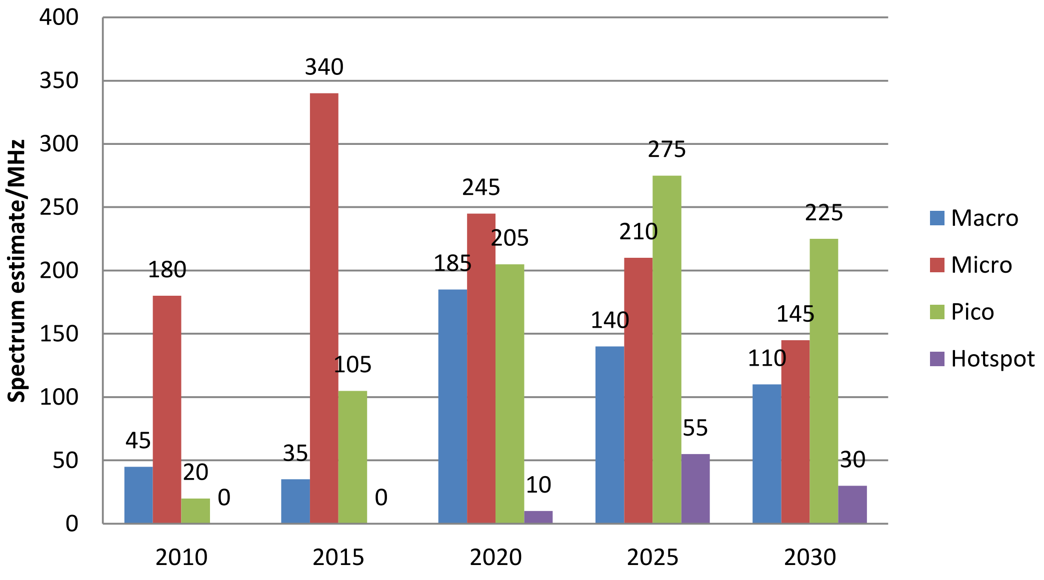



**Figure 22: Licensed spectrum estimates in the dense urban environment for the low market setting**

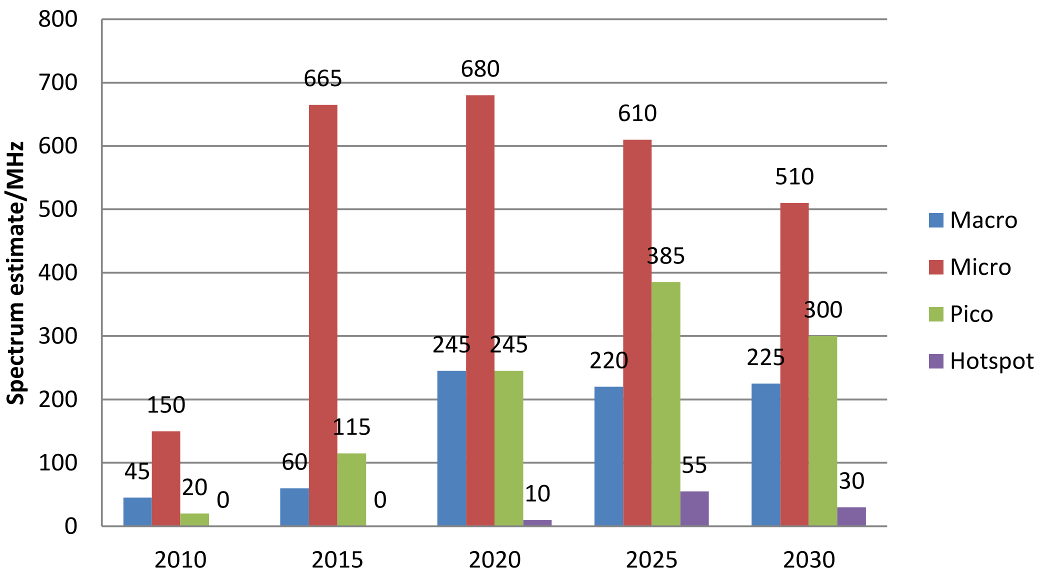



**Figure 23: Licensed spectrum estimates in the dense urban environment for the high market setting**

### 2.2.4 Our licensed spectrum estimates indicate that in rural areas network densification is required to prevent this environment becoming a driver for overall spectrum requirements in later years

Figure 24 shows licensed spectrum requirements for rural areas over time detailed by network layer based on using our recommended baseline settings for the ITU-R M.1768-1 model and our UK specific medium demand forecast. Unlike the suburban and dense urban cases earlier microcell and picocell coverage levels are assumed to be very low in rural areas and so there is a heavy reliance on the macrocell layer.

The macrocell sector area in rural areas is much larger than in dense urban and suburban areas and so the overall spectral efficiency density in rural areas is much lower than in dense urban and suburban areas (see appendix E). Due to the low density of users in rural areas this is not usually an issue and coverage rather than capacity drives site numbers in rural areas. However, by 2030 macrocell spectrum requirements in rural areas start to approach those of suburban macrocells indicating that some densification of the network (via the roll out for more macrocells to reduce sector size and hence enhance spectral efficiency densities) in rural areas will be needed. This densification of the network in rural areas in later years was also observed in the results of our previous UHF strategy study for Ofcom [5].

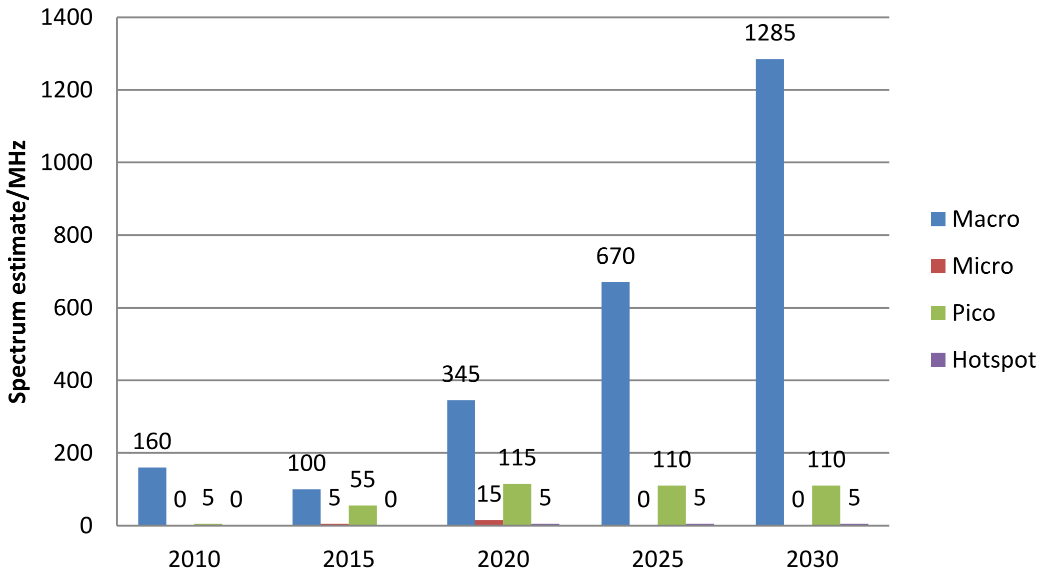



**Figure 24: Licensed spectrum estimates by network layer in rural areas**

These growing spectrum requirements for rural areas assume that the performance expectations of rural users keep pace with the SCs considered in the ITU-R M.1768-1 model. The alternative to network densification in rural areas to avoid rural areas becoming the driver for overall spectrum requirements would be for rural users to accept lower network performance above the increased tariffs that might result from costly network densification. Another alternative would be to deploy low cost small cells more aggressively in rural areas so that rural users could at least avail of higher rate services when in mostly indoor environments and accept lower outdoor performance from the macrocell network. This does of course assume that the fixed line broadband services to rural areas can support small cell deployments inside or around buildings. However, we note from the results of our sensitivity analysis that the volume of high mobility traffic compared to other SEs in rural areas is quite high and limits the extent to which offload to small cells can be used.

Note also from Figure 24 that the model results suggest that in 2015 and 2020 there will be some use of microcells but by 2025 this will have migrated onto more spectrally efficient picocells and hotspots. However, in practice it is unlikely that an operator would deploy microcells and then shortly afterwards remove them. It is much more likely that the microcells either would never be deployed, and more small cells of other types would be deployed earlier instead, or else the microcells would be deployed and continue to be used out to 2030, with picocells perhaps being deployed at a lower level than assumed in our baseline model settings.

### 2.2.5 Potential variations in spectrum estimates around our baseline case based on our sensitivity analysis

As described in detail in chapter 4, we have performed a sensitivity analysis to determine the range of spectrum estimates for plausible variations in our input assumptions around the baseline results reported here. This has found that:

- Assumptions on the percentage of high mobility traffic in suburban and rural areas are crucial to overall spectrum requirements. Reducing the percentage of high mobility traffic in suburban and rural environments to a maximum of 10% (as opposed to 20% in the ITU recommended model setting and our baseline model settings), in line with sources on the ratio of outdoor to indoor traffic, can have the impact of reducing spectrum requirements by as much as 28% and potentially postponing requirements for additional spectrum allocations from 2020 until 2030 in our medium demand case at least.
- The impact of small cell uptake on spectrum requirements is limited to offloading low mobility traffic and hence linked to the availability of other efficient offload routes including LTE-A hotspots and Wi-Fi access points. In practice the balance between the roll out of LTE-A hotspots and the uptake of other small cell types such as picocells and microcells will be an operator decision and overall spectrum requirements will likely remain driven by high mobility user spectrum requirements on macrocells. As such overall spectrum requirements become relatively insensitive to small cell uptake in the later parts of the timescales of this study (where existing and planned spectrum supply becomes under pressure) provided all small cell layers, including LTE-A hotpots and Wi-Fi, provide a capacity level commensurate to our baseline model settings i.e. sufficient to carry all low mobility traffic. Increasing small cell uptake further beyond this point does not decrease overall spectrum requirements as the demand levels of high mobility users start to drive overall spectrum requirements beyond this point.
- Wi-Fi offload levels, when applied equally across all users types as in our sensitivity analysis, have a large impact on overall spectrum requirements. However, arguably, similar to the case of licensed small cells, the potential impact of Wi-Fi offload levels will be very limited for high mobility mobile users who drive our overall spectrum estimates. Therefore our sensitivity analysis is likely to exaggerate the impact of Wi-Fi offload on spectrum estimates provided that the offload combination of licensed small cells and Wi-Fi is already at a sufficient level to accommodate all low mobility traffic and hence traffic from high mobility users drives the overall spectrum requirements as in the later part of our timeline for our baseline model settings and medium demand levels.
- Assumptions on whether a SC should be delivered via a packet switched (PS) or circuit switched (CS) network can have a significant (up to 20%) impact on spectrum estimates and potentially delay additional requirements for spectrum releases until 2030 (under of medium demand case investigated). Note that to inform our sensitivity analysis in this area we have investigated suitable mean

packet sizes, second moment of packet sizes and mean delay levels for SC1-4 and SC 6-10 even though these are not included as packet switched services by the ITU. However, we note that our review of these parameters has been limited in the timescales of this study and that a more detailed review of this area is needed. While the results of our sensitivity analysis give some indication of the size of the potential impact on spectrum requirements that changing assumptions on PS or CS mechanisms for SCs may have we note that it is not clear that the current overheads applied by the queuing theory block of the model are representative of the levels required for delivering guaranteed bit rate services via packet switched mechanisms such as used in Voice over LTE (VoLTE) approaches. Therefore we highlight this as an area for further investigation rather than a firm recommended change to the ITU-R M.1768-1 model baseline settings at this stage.

## 2.3 Comparison of our licensed spectrum estimates with ITU working party 5D spectrum estimates

In this section we briefly compare the spectrum estimates generated via our recommended model settings and demand forecasts against those produced to date by ITU Working Party 5D to:

- Highlight where spectrum estimates may be quite different for the UK compared to other ITU regions
- Justify our changes to ITU recommended settings for model parameters

Comparing first our demand estimate assumptions against those from the ITU, Figure 25 shows the assumed growth over the initial 2010 starting demand level assumed in the various market settings considered by ITU and our current study. From this we can see that the growth rates assumed in our low demand case largely align with those from the ITU for their low market setting. The same is true for the high demand setting. Note however, that while growth rates align here the absolute 2010 starting demand levels that these are calculated relative to are different (see Figure 44 in section 3.2 for further details on comparing absolute demand densities).

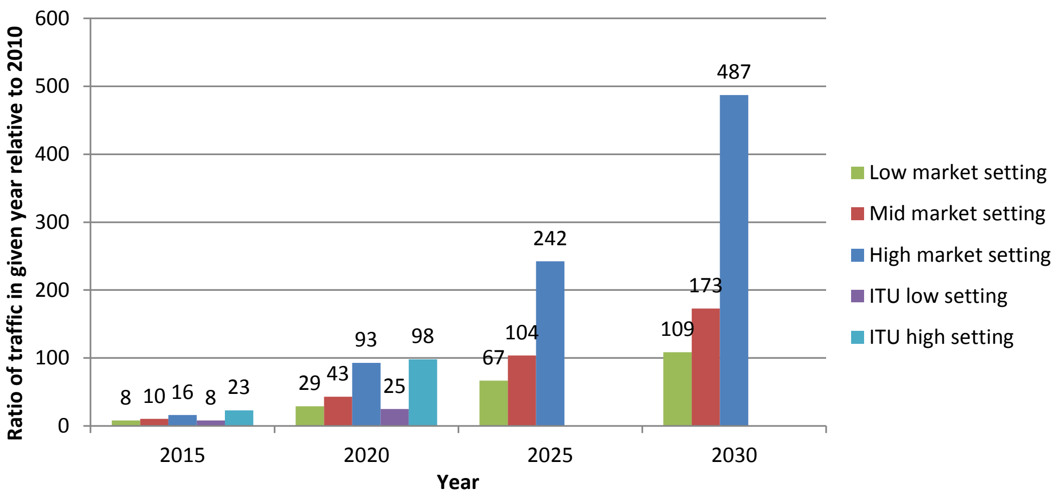
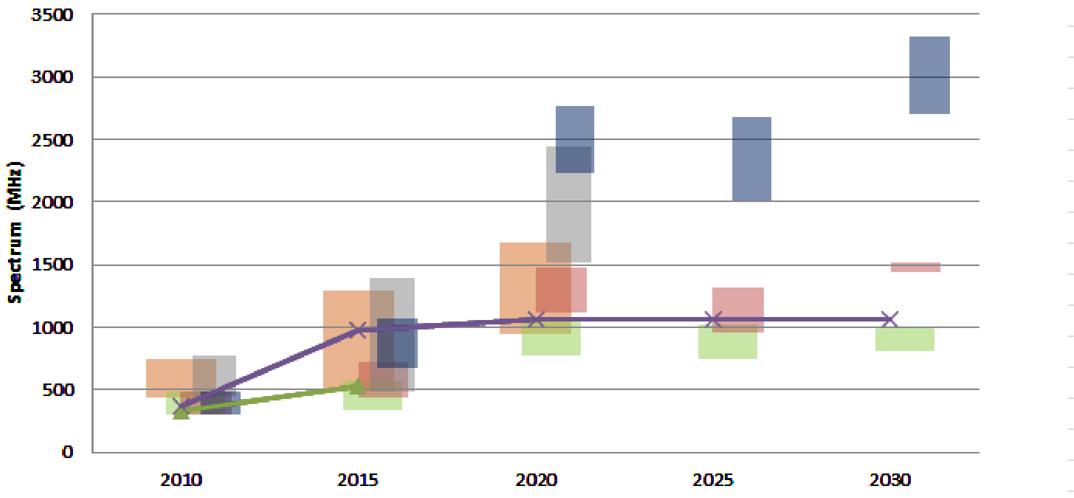



**Figure 25: Comparison of the assumed growth compared with initial 2010 demand levels assumed within the Real Wireless and ITU low, medium and high market settings**

Figure 26 compares spectrum estimates across our low, medium and high demand scenarios using our recommended model settings with those produced by ITU working party 5D for their low and high market settings and recommended model settings. This shows that:

- In 2010 and 2015 there is little difference between the spectrum estimates for the ITU's low and high demand cases whereas in the Real Wireless case this difference is more distinct.
- The Real Wireless high spectrum estimates overlap to a certain extent with those for the ITU high market setting but by 2020 are very much at the top end of the ITU estimates.
- The Real Wireless medium spectrum estimates seem to align better with the ITU low market setting than the Real Wireless low demand spectrum estimates.




| Spectrum (MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| ITU low | Shared | 435 | 480 | 945 | | |
| | Dedicated | 740 | 1290 | 1670 | | |
| RW low | Shared | 295 | 340 | 775 | 740 | 805 |
| | Dedicated | 490 | 575 | 1080 | 1015 | 995 |
| RW medium | Shared | 295 | 440 | 1120 | 950 | 1445 |
| | Dedicated | 490 | 720 | 1475 | 1315 | 1515 |
| ITU high | Shared | 450 | 490 | 1510 | | |
| | Dedicated | 765 | 1390 | 2440 | | |
| RW high | Shared | 295 | 665 | 2230 | 2010 | 2710 |
| | Dedicated | 490 | 1070 | 2770 | 2675 | 3325 |

**Figure 26: Comparison of Real Wireless licensed spectrum estimates (MHz) with those produced by ITU working party 5D**

Note that, while results presented above are on a like for like comparison using our modified version of the ITU-R M.1768-1 model, we have adopted a different approach to dedicated spectrum estimation compared to ITU so that our spectrum estimates between the shared spectrum result and dedicated spectrum result represent a truly best case and worst case estimate of spectrum requirements for the scenario investigated. In the ITU definition of dedicated spectrum estimates some degree of sharing amongst networks layers is assumed depending on whether RATG1 or RATG2 is being considered. For example, if a RATG1 spectrum estimate was obtained in the bottleneck service environment of 100MHz for macrocells, 50MHz for microcells, 30MHz for picocells and 20MHz for hotspots our dedicated result would be 200MHz whereas the ITU reported value would be 180MHz as it is assumed for RATG1 by the ITU that hotspots and picocells share a spectrum layer in the dedicated case.

In practice the degree of sharing amongst layers will change over time depending on operator strategies to small cells, the number of carriers that an operator has available, developments in technology to minimise interference in shared spectrum scenarios, the deployment levels that various cell types reach and the types of environments and levels of isolation between these environments that particular cell types are deployed in. We also note that spectrum efficiency estimates tend to be based on the assumption of a dedicated carrier being available for the cell type being evaluated.

*Spectrum requirement in 2010 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lic |
| Dense Urban | 290 | 170 | 145 | 0 | 0 | 0 | 0 | 0 | 290 | 170 | 145 | 0 | | | | 605 | 0 | |
| Sub Urban | 435 | 160 | 145 | 0 | 0 | 0 | 0 | 0 | 435 | 160 | 145 | 0 | | | | 740 | 0 | |
| Rural | 385 | 0 | 140 | 0 | 0 | 0 | 0 | 0 | 385 | 0 | 140 | 0 | | | | 525 | 0 | |
| Overall | | | | | | | | | | | | | 435 | 0 | 435 | 740 | 0 | 740 |

*Spectrum requirement in 2015 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lic |
| Dense Urban | 205 | 120 | 270 | 0 | 75 | 65 | 200 | 170 | 280 | 185 | 470 | 170 | | | | 595 | 510 | |
| Sub Urban | 235 | 280 | 265 | 0 | 85 | 155 | 115 | 100 | 320 | 435 | 380 | 100 | | | | 780 | 455 | |
| Rural | 210 | 0 | 90 | 0 | 100 | 0 | 40 | 35 | 310 | 0 | 130 | 35 | | | | 300 | 175 | |
| Overall | | | | | | | | | | | | | 280 | 200 | 480 | 780 | 510 | 1290 |

*Spectrum requirement in 2020 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | Macr | Micro | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lic |
| Dense Urban | 265 | 120 | 25 | 20 | 250 | 665 | 205 | 120 | 515 | 785 | 230 | 140 | | | | 430 | 1240 | |
| Sub Urban | 280 | 60 | 20 | 10 | 360 | 220 | 25 | 10 | 640 | 280 | 45 | 20 | | | | 370 | 615 | |
| Rural | 195 | 0 | 10 | 10 | 210 | 0 | 10 | 10 | 405 | 0 | 20 | 20 | | | | 215 | 230 | |
| Overall | | | | | | | | | | | | | 280 | 665 | 945 | 430 | 1240 | 1670 |

**Figure 27: Detailed spectrum estimates (from our updated model) for ITU low market setting and ITU default model settings**

*Spectrum requirement in 2010 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micr | Pico | Hotsp | Macr | Micr | Pico | Hotsp | Macr | Micr | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lic |
| Dense Urban | 295 | 220 | 150 | 0 | 0 | 0 | 0 | 0 | 295 | 220 | 150 | 0 | | | | 665 | 0 | |
| Sub Urban | 450 | 170 | 145 | 0 | 0 | 0 | 0 | 0 | 450 | 170 | 145 | 0 | | | | 765 | 0 | |
| Rural | 400 | 0 | 140 | 0 | 0 | 0 | 0 | 0 | 400 | 0 | 140 | 0 | | | | 540 | 0 | |
| Overall | | | | | | | | | | | | | 450 | 0 | 450 | 765 | 0 | 765 |

*Spectrum requirement in 2015 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micr | Pico | Hotsp | Macr | Micr | Pico | Hotsp | Macr | Micr | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lic |
| Dense Urban | 220 | 185 | 270 | 0 | 80 | 100 | 200 | 170 | 300 | 285 | 470 | 170 | | | | 675 | 550 | |
| Sub Urban | 280 | 290 | 270 | 0 | 100 | 160 | 115 | 100 | 380 | 450 | 385 | 100 | | | | 840 | 475 | |
| Rural | 250 | 0 | 90 | 0 | 110 | 0 | 40 | 35 | 360 | 0 | 130 | 35 | | | | 340 | 185 | |
| Overall | | | | | | | | | | | | | 290 | 200 | 490 | 840 | 550 | 1390 |

*Spectrum requirement in 2020 in MHz*

| Teledensity | RATG1 | | | | RATG2 | | | | Total licenced | | | | Shared | | | Dedicated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Macr | Micr | Pico | Hotsp | Macr | Micr | Pico | Hotsp | Macr | Micr | Pico | Hotsp | RATG1 | RATG2 | Total lic | RATG1 | RATG2 | Total lic |
| Dense Urban | 295 | 195 | 35 | 20 | 365 | 1180 | 225 | 125 | 660 | 1375 | 260 | 145 | | | | 545 | 1895 | |
| Sub Urban | 330 | 85 | 20 | 10 | 550 | 365 | 35 | 10 | 880 | 450 | 55 | 20 | | | | 445 | 960 | |
| Rural | 220 | 0 | 10 | 10 | 310 | 0 | 10 | 10 | 530 | 0 | 20 | 20 | | | | 240 | 330 | |
| Overall | | | | | | | | | | | | | 330 | 1180 | 1510 | 545 | 1895 | 2440 |

**Figure 28: Detailed spectrum estimates (from our updated model) for ITU high market setting and ITU default model settings**

Comparing the capacity bottlenecks found in our results at 2020 with those from ITU working party 5D for low and high market settings we find that in the ITU results the spectrum bottleneck occurs in suburban macrocells for RATG1 and dense urban microcells for RATG2. This is in contrast to our medium demand results where suburban microcells are the bottleneck for RATG1 and suburban macrocells are the spectrum bottleneck for RATG2. This is likely due to differences in assumed application rates between our recommended baseline model settings and those used by the ITU (see appendix E). We assume RATG1 macrocells are used for coverage and assume cell edge application rates for these. The ITU results in contrast assume high end application rates for RATG1 which would allow more demanding SCs to be carried onto RATG1 macrocells and making them the spectrum bottleneck as opposed to microcells in our case.

The RATG2 bottleneck on macrocells in our results are likely due to mobile users with high SCs having to use RATG2 macrocells rather than RATG1 macrocells and so the bottleneck that the ITU had for RATG1 macrocells is shifted to the RATG2 macrocells in our case.

The largest total dedicated spectrum requirement for 2020 occurs in dense urban environments in the ITU working party 5D results but this occurs in suburban environments in our medium demand results. This is likely due to our recommended baseline coverage levels for cellular small cells particularly in dense urban areas being at higher coverage levels than recommended by the ITU. This is to reflect the relatively high uptake of small cells by UK operators as seen by the UK being one of only two countries to date where all cellular operators have femtocell offerings. This higher small cell deployment level in dense urban areas means that in our results, despite having the highest traffic density, the demand of dense urban areas is offloaded to more efficient small cells to such an extent that the driver for overall spectrum requirements shifts to high mobility user in suburban areas who cannot be easily offloaded to either small cells or Wi-Fi.

## 2.4 Spectrum estimates interpreted against JTG 4-5-6-7 requirements

As discussed in section 1.1, ITU JTG 4-5-6-7 are co-ordinating inputs for the discussion of agenda item 1.1 at WRC-15 and as part of this have requested estimates of the future spectrum demand for terrestrial mobile broadband applications. In their request for ITU working parties 5A and 5D to develop spectrum demand estimates they have specifically requested consideration of [2]:

- Coverage – which we interpret as spectrum requirements to deliver a minimum cell edge service level to a particular percentage of the population in each SE.
- Capacity – which we interpret as the spectrum requirements to deliver the performance defined for each SC to the "bottleneck" high user demand densities across the SEs within the model which drive overall spectrum requirements.
- Performance – which we interpret as the spectrum requirements to meet the performance defined for each SC by the model inputs to the required user density for each SC and SE combination which is driven by the demand densities.
- High and low market conditions – which, as already discussed in section 2.2, we interpret as running the ITU-R M.1768-1 for more or less aggressive demand forecasts.
- Asymmetry in demand and potential implications for spectrum requirements – which we interpret as analysing the downlink to uplink demand ratios across SEs within the ITU-R M.1768-1 model and the overhead of assuming FDD as opposed to TDD spectrum allocations based on downlink and uplink spectrum estimates from the model.

We note that the spectrum requirements for coverage, capacity and performance are not independently generated by the ITU-R M.1768-1 model and instead these requirements are intertwined in the overall spectrum estimates generated by the model. For example, although the model generates spectrum estimates based on demand densities, and hence capacity requirements, these are based on initially achieving a baseline coverage level at given performance levels for each service category, as determined by the model input settings, and then increasing this spectrum estimate for higher user densities in line with the capacity requirements of each service category.

Within this section we consider our baseline medium demand spectrum estimate results against each of these JTG requirements.

### 2.4.1 Spectrum requirements for coverage

In environments where user density and hence traffic density is reasonably low operators can deploy macrocell sites at the maximum spacing that propagation losses at the available carrier frequency will allow whilst still maintaining a cell edge signal to noise ratio that supports targeted minimum user throughputs. In these low population density areas it is usually the case that all traffic within the cell area can be accommodated in the amount of spectrum licensed to the operator. Therefore in these coverage limited scenarios it is not the volume of spectrum that is the main concern but instead acquiring access to spectrum at sub 1GHz levels with favourable propagation characteristics which will minimise site build costs. These coverage limited scenarios tend to occur in rural areas where population densities are low.

In contrast to these coverage limited scenarios, in dense urban and potentially suburban areas population densities and hence traffic densities can be very high. In such cases if a network was deployed at the maximum cell site spacing as in the coverage limited case large volumes of spectrum would be required to provide sufficient capacity to the users within the coverage area of the cell site. To address this cell sites are deployed in these capacity limited areas with some overlap between the coverage areas of each site to reuse available carriers on a more frequent basis than in the coverage limited scenarios. This will help improve the spectrum efficiency density of the network and reduce spectrum requirements.

The ITU-R M.1768-1 model has mainly focused on the second of these two cases. It broadly examines the traffic density for the different SEs and SCs, translates this into a demand density within these SEs based on the requirements of the SCs generating the traffic and then compares this with the spectrum efficiency density of the network for the available RATG and cell type combinations in that SE to calculate the level of spectrum required for each cell type within each RATG to meet the traffic requirements of the user density in that SE.

As proposed by other contributions to ITU working party 5D [10], spectrum requirements for coverage can arguably be interpreted from the ITU-R M.1768-1 model results for rural macrocells as the deployment of macrocells in rural areas will largely be driven by coverage rather than capacity requirements in these low traffic density areas. However, this approach of using rural macrocell spectrum estimates as the basis for spectrum requirements for coverage has some limitations including:

- The model provides a spectrum estimate per cell type and RATG combination based on meeting traffic levels at a given user density. However, within RATG1 there are multiple cellular air interfaces that would need spectrum to be available for each active operator to ensure coverage and backwards compatibility for legacy handsets in the device population. For example, UK cellular networks still maintain GSM carriers alongside their UMTS networks but these are considered jointly under RATG1 in the ITU-R M.1768-1 model. With the deployment of LTE this will mean that consideration will need to be given to spectrum requirements to maintain coverage potentially for three cellular air interfaces in parallel.
- The spectrum calculated by the ITU model is driven by average demand levels across SEs. However, in practice in rural areas peak demand levels will likely occur around villages where carriers at higher frequency bands could be used alongside lower frequency carriers to boost capacity in these localised demand peaks.
- Spectrum for coverage requirements will be driven by local site locations, terrain and carrier frequency limitations whereas the ITU-R M.1768-1 model determines spectrum requirements based on average demand and capacity densities.
- Capturing spectrum requirements for macrocells alone does not take into account the use of small cells such as femtocells to address coverage black spots which may occupy their own dedicated carrier.
- The ITU-R M.1768-1 model gives no indication of spectrum requirements by frequency range whereas for coverage requirements knowledge of the amount of sub 1GHz spectrum required will be crucial.

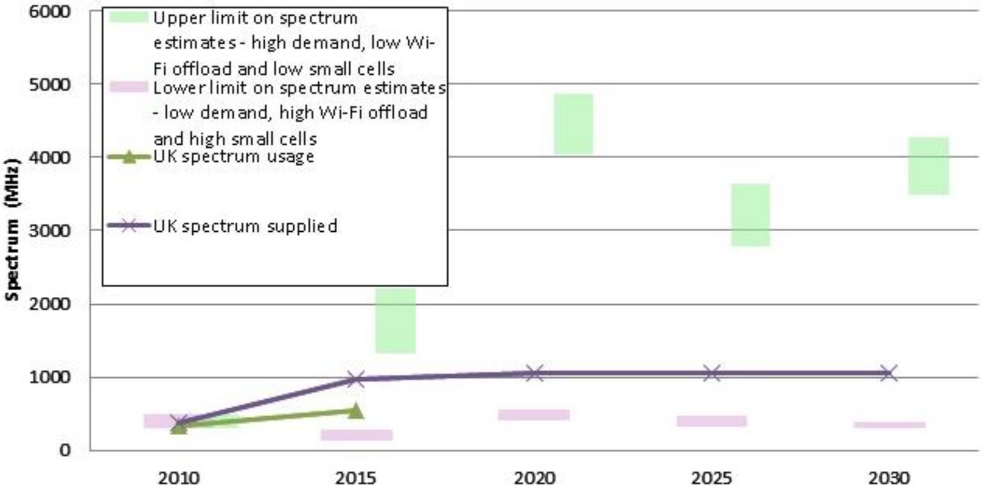
In summary the ITU-R M.1768-1 model has not been developed with coverage in mind and instead a separate coverage modelling exercise similar to that undertaken for Ofcom to understand the implications of placing a coverage obligation on spectrum at 800MHz [11] is required if an accurate estimate of spectrum requirements for coverage is needed.

### 2.4.2 Spectrum requirements for capacity

As discussed in the previous section the ITU-R M.1768-1 model has been designed with generating spectrum requirements in capacity limited scenarios in mind. Therefore the results already presented for our baseline model settings as discussed in section 2.2 can be interpreted as spectrum requirements for capacity. From across these results in terms of spectrum requirements for capacity we note that:

- The main driver for overall spectrum requirements has moved from intensive dense urban scenarios to suburban environments. This is because although the dense urban environments have the highest overall demand densities, the suburban capacity requirements are set by high mobility users, who must be served on macrocells due to handover limitations on smaller cell types.
- While dense urban areas are traditionally the areas where capacity requirements and hence spectrum requirements are highest this is no longer likely to be the case due to the intensive use of small cells with relatively high spectral efficiencies alongside existing dense deployments of macrocells in these areas.
- The intensive use of small cells in dense urban deployments relies on relatively high coverage levels across macrocells, microcells and picocells in the near future in these areas. As small cells increase in density this may lead to an added requirement in these areas for a small cell spectrum layer to meet capacity and performance requirements of networks. Such a layer could drive spectrum requirements more towards our dedicated rather than shared spectrum estimates, depending on the efficacy of interference mitigation techniques for co-channel small cells.

Figure 29 presents a worst case and best case view on the levels that spectrum requirements for capacity might reach based on various offload settings around our low and high market setting for demand.




| Spectrum (MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| Upper limit | Shared | 295 | 1330 | 4045 | 2790 | 3485 |
| | Dedicated | 490 | 2210 | 4880 | 3630 | 4270 |
| Lower limit | Shared | 295 | 140 | 415 | 330 | 305 |
| | Dedicated | 490 | 285 | 545 | 480 | 380 |

**Figure 29: Licensed spectrum estimates (MHz) for our high forecast of UK demand for broadband services assuming a low offload to Wi-Fi and low uptake of small cells**

The worst case view corresponds to (see our sensitivity analysis in section 4 for input settings these correspond to):

- Demand levels in line with our high market setting forecast
- Offload to Wi-Fi at low levels and so maximising the demand on licensed spectrum
- The uptake of small cells at a low level and so minimising the spectral efficiency densities of cellular networks and maximising spectrum requirements

The best case view corresponds to (see our sensitivity analysis in section 4 for input settings these correspond to):

- Demand levels in line with our low market setting forecast
- Offload to Wi-Fi at high levels and so minimising the demand on licensed spectrum
- The uptake of small cells at a high level and so maximising the spectral efficiency densities of cellular networks and minimising spectrum requirements

Note that while the model results show some reduction in spectrum requirements between 2020 and 2025 in practice it is likely that any additional spectrum allocations to meet demand in 2020 would, rather than lying unused in 2025 due to network improvements, facilitate increased performance levels and services by 2025 that would drive up demand to keep this spectrum utilised in practice.

As highlighted earlier the spectrum requirements for capacity discussed here intrinsically also contain spectrum requirements for given performance levels set by the model inputs and to a certain extent coverage requirements. Although the model generates spectrum estimates based on demand densities and hence capacity requirements in cases where users densities are very low these spectrum estimates effectively represent a simplistic spectrum estimate for providing a baseline coverage level. As user densities for various services increase in line with service requirements this baseline coverage estimate will remain as an intrinsic part of the overall spectrum estimate and be added to but not replaced by capacity considerations.

### 2.4.3 Spectrum requirements for performance

The ITU M.1768-1 model takes account of user experience expectations and hence required network performance levels to meet these via the service and market related parameters for each SC and SE combination within the model. Parameters within this such as mean service bit rates and maximum tolerable packet delays can be interpreted as setting a performance benchmark against which spectrum requirements are calculated. Therefore the findings of the previous section related to capacity requirements can also be interpreted as the spectrum requirements to meet the performance levels specified by our model inputs for each SC. We have reviewed and selected these model inputs to be representative of applications within these SCs today and out to 2030.

An alternative interpretation of spectrum requirements for performance as proposed within ITU working party 5D [10] is to assume that small cells are deployed in areas where high network performance and enhanced user experience is needed and hence can be interpreted from the spectrum requirements for small cells. The dense urban spectrum requirements from our baseline spectrum estimate as shown in Figure 21 show a heavy reliance on smaller cells as opposed to macrocells with the spectrum requirements of these smaller cell layers giving an indication of spectrum needed for performance in dense urban environments at least.

Figure 30 shows a potential worst case spectrum estimate for spectrum requirements for performance requirements in dense urban environments for comparison which is based on (see our sensitivity analysis in section 4 for input settings these correspond to):

- Demand levels in line with our high market setting demand forecast
- Offload to Wi-Fi at low levels and hence demand levels on licensed spectrum are at their highest
- The uptake of small cells at a high level indicating a focus by operators on enhancing performance levels in networks. Note this will improve the spectral efficiency density of cellular networks and reduce spectrum requirements.

Note that while this is the potential worst case spectrum estimate for spectrum requirements for dense urban areas where capacity is traditionally at its highest, the overall spectrum requirements in this high demand case are still largely driven by the requirements of high mobility suburban users as discussed in our sensitivity analysis in section 4.2.

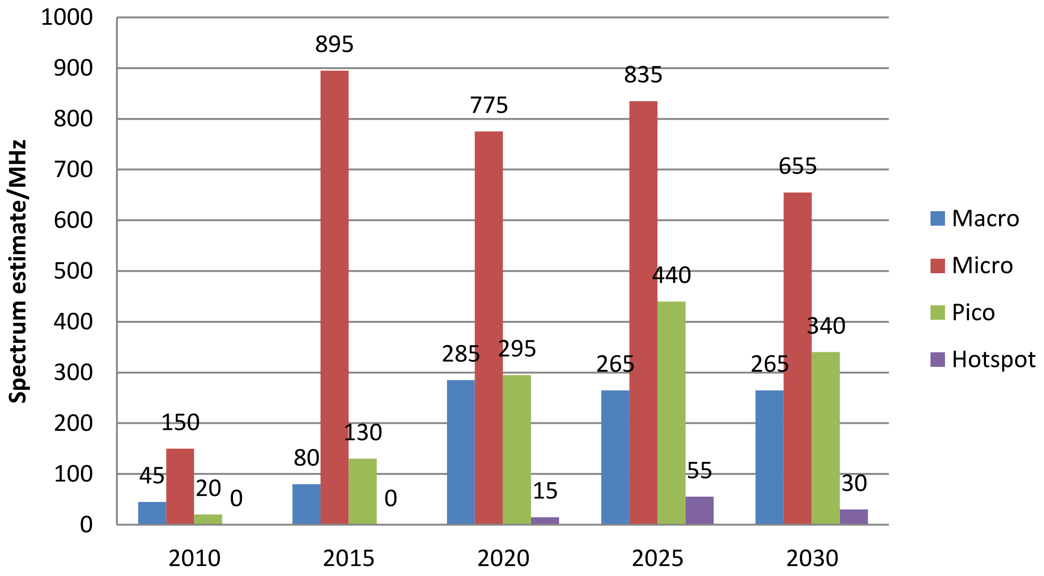



**Figure 30: Licensed spectrum estimates (MHz) for dense urban areas for our high forecast of UK demand for broadband services assuming a low offload to Wi-Fi and high uptake of small cells**

### 2.4.4 Asymmetry between uplink and downlink demand

Asymmetry between uplink and downlink demand levels can in some cases give an indication of the potential for making use of TDD vs. FDD spectrum to meet growing spectrum requirements. Figure 31 presents the downlink to uplink ratio across the various SEs considered in the ITU model for our medium demand forecast for the UK. Note that while we calibrate user density in the model to ensure that the distributed uplink and downlink demand densities in each teledensity match those of our UK specific demand forecasts we have not altered how the ITU model distributes this demand amongst SCs and SEs as we have no basis to assume that this distribution would be any different in the UK compared to other ITU regions.

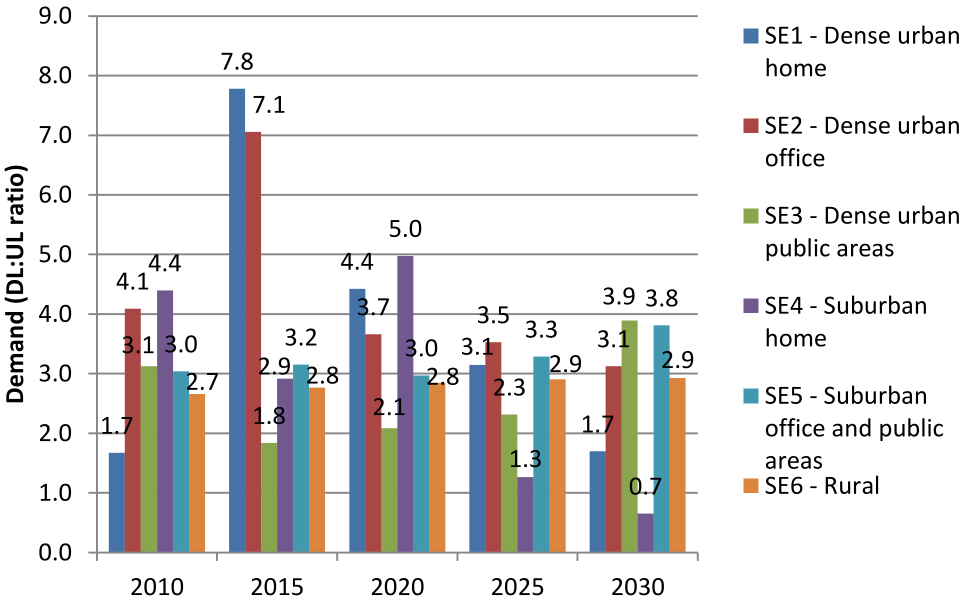



**Figure 31: Asymmetry in demand across SEs for our medium forecast of UK demand for mobile broadband services**

From Figure 31 it can be seen that SEs with high downlink to uplink ratios are not necessarily maintained over time and so while there may be a case for considering TDD spectrum for SE 1 dense urban home users in 2015 we see that the case is less strong in 2020 and by 2030 the downlink to uplink traffic in this environment is much more balanced. We assume different uplink to downlink ratios across different device types over time as detailed in appendix E and this is, to a certain extent, reflected by a trend of reducing downlink to uplink ratios over time in Figure 31 although this is not significant.

From Figure 31 SE2 dense urban office users, SE5 suburban office and public area users and SE6 rural users are the environments where downlink traffic is anticipated to be at least double that of uplink traffic. SE6 being a rural environment is unlikely to drive spectrum requirements on the basis of capacity and so the choice between FDD and TDD spectrum is less critical here. However, significant demand levels could be seen in dense urban and suburban office environments and there may be a case for considering a TDD indoor small cell channel that could potentially be shared across operators to make more efficient usage of spectrum in these environments.

The spectrum estimates generated by the ITU-R M.1768-1 model include an uplink and downlink spectrum estimates which are simply summed to gain the overall spectrum requirement estimate. This assumes the optimal arrangement of TDD vs. FDD spectrum to carry demand in the model but in practice this is likely to be a best case estimate as the UK spectrum market in particular is heavily dominated by FDD spectrum and a cellular ecosystem focused on FDD devices and equipment. With this in mind Figure 32 and Figure 33 show the potential implications on our baseline spectrum estimates for the medium demand scenario if FDD spectrum is assumed. This shows that the overhead in spectrum estimates for using a FDD type spectrum allocation over TDD (ignoring the impact of guard bands) could be as much as 50%.

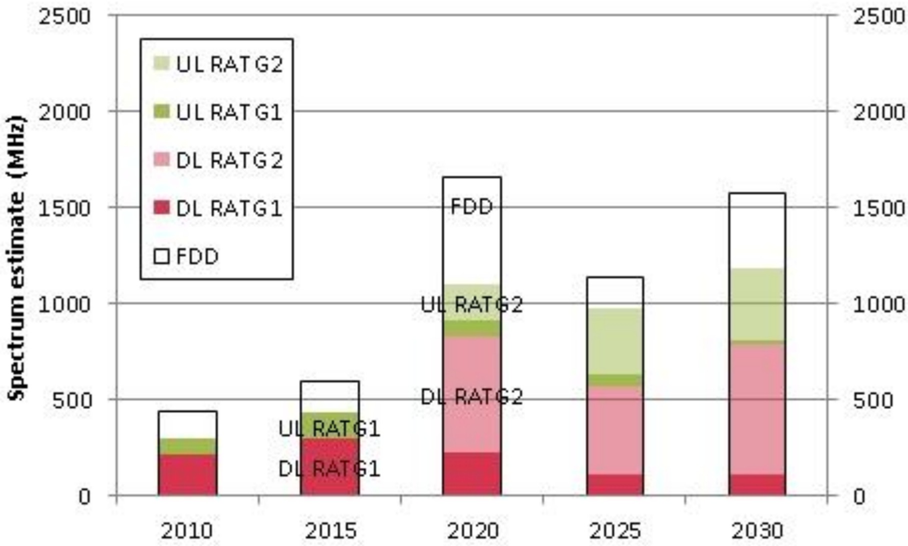



**Figure 32: Shared licensed spectrum estimates for our baseline medium demand scenario interpreted for FDD spectrum**

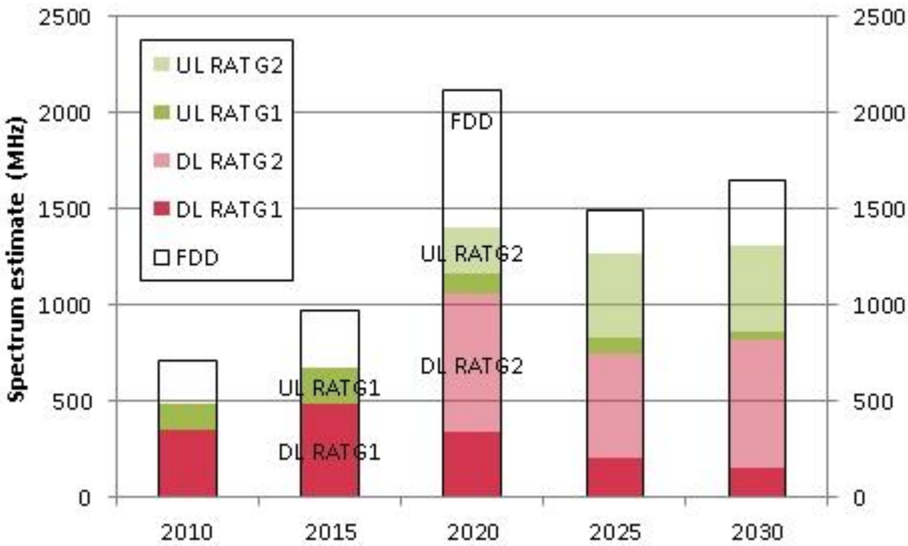



**Figure 33: Dedicated licensed spectrum estimates for our baseline medium demand scenario interpreted for FDD spectrum**

## 2.5 Our spectrum estimates for LE spectrum indicates that proposed releases at 5GHz could be required by 2020

As well as our spectrum estimates for licensed spectrum discussed so far we have also examined spectrum requirements for licence-exempt (LE) spectrum. These consider serving demand in LE spectrum made up of:

- Traffic offloaded from cellular networks
- Traffic from a wide range of devices which only support LE spectrum (e.g. smart TV and home networking devices)

To serve this demand we consider spectrum requirements for two types of LE cell types which are:

- Hotspots as per traditional Wi-Fi access points which can be either indoor or outdoor access points with their EIRP limited in line with today's LE spectrum EIRP levels
- Picocells which are higher powered and hence higher range LE access points which have higher EIRP levels than the limits applied to today's LE spectrum. This could potentially include "Super Wi-Fi" devices in TVWS and are likely to be used outdoors or in large public areas

LE high power access points that use TVWS are currently in trials and we assume will start to be available from 2015. Beyond this other forms of LE picocells may be available such as a shared access channel dedicated to higher powered LE devices.

As discussed later in section 3.1.2, we have considered low, medium and very high[15] demand scenarios in our LE spectrum estimates. Figure 34 shows that in all three demand scenarios the home environment is the driver for LE hotspot spectrum requirements over the office environment. We assume that public areas would be served by longer range picocells and the spectrum estimates shown are based on this. In this case spectrum requirements for public areas are still less than for the home and office environments which is an effect that would only be amplified by more efficient hotspots in public areas.

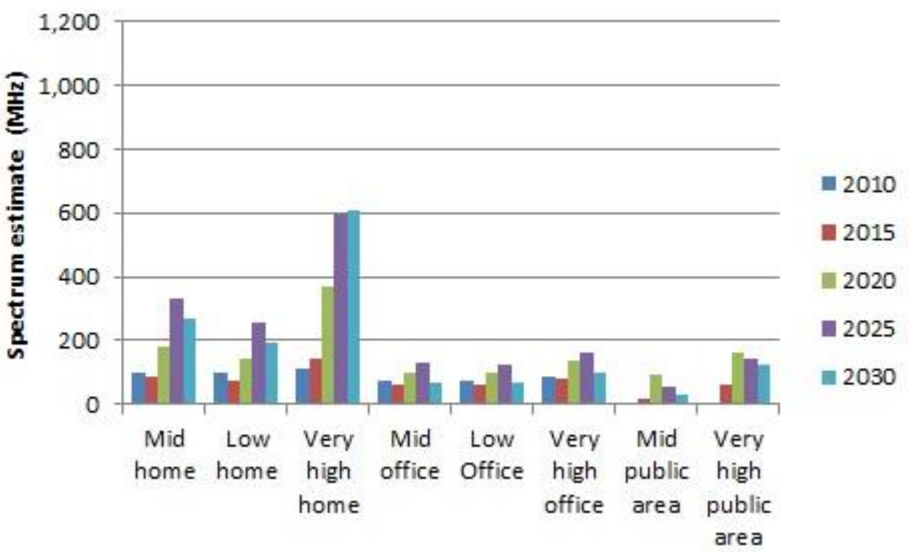



**Figure 34: LE spectrum requirements (MHz) in different environments for low, medium and high LE demand levels**

Overall the spectrum requirements for Wi-Fi hotspots are higher than for picocells despite having a better spectral efficiency per sector compared to picocells and an overall better spectral efficiency density due to hotspots having a smaller sector area. This is because the

[15] Note the "very high" term is used to distinguish from our high demand licensed case as additional LE only variants of laptops and tablets are considered in this scenario beyond those of cellular enabled only devices in our licensed estimates. Also higher traffic per device estimates are used based on increased usage when users have low cost access to broadband via Wi-Fi. This is discussed further in appendix C and section 3.1.2.

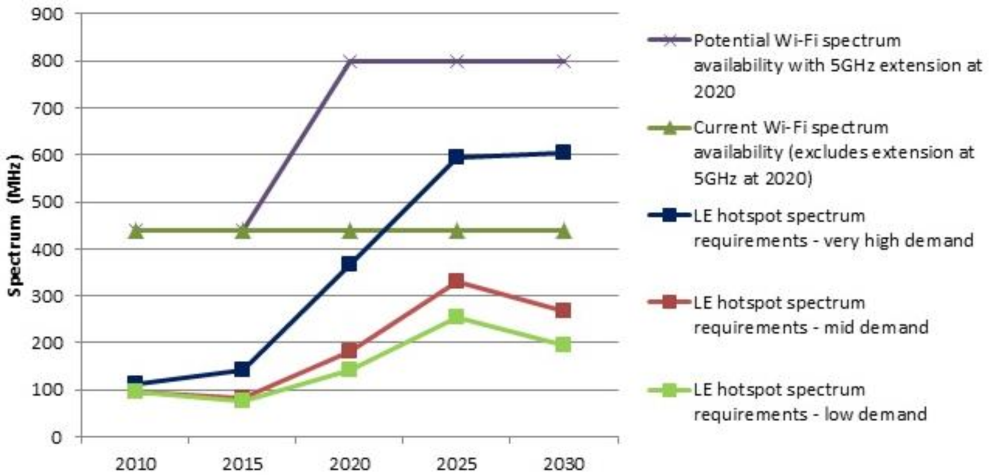
traffic levels in public areas even at very high user densities will be relatively small compared with those in home environments due to:

- Public area users being limited to using small screen portable devices and being in transit and so likely to have short session durations.
- Home users making intensive use of demanding video streaming application such as Smart TV and home multimedia network systems alongside the portable devices that would be found in public areas.

A comparison of demand between LE scenarios is discussed further in our demand analysis in appendix C.

### 2.5.1 LE hotspot spectrum requirements

Figure 35 presents our spectrum estimates for LE hotspot requirements in our low, medium and very high demand scenarios. Note that as we are only considering LE hotspot spectrum that a shared and dedicated view of spectrum requirements is not relevant here as was presented in the licensed spectrum estimates.




| | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| Potential avail. | 440 | 440 | 800 | 800 | 800 |
| Current avail. | 440 | 440 | 440 | 440 | 440 |
| Very high demand | 112 | 144 | 367 | 594 | 605 |
| Mid demand | 97 | 84 | 183 | 331 | 268 |
| Low demand | 97 | 76 | 141 | 254 | 196 |

**Figure 35: LE hotspot spectrum requirements (MHz) against Wi-Fi spectrum availability at 2.4GHz and 5GHz with and without expanded 5GHz band included after 2020**

For comparison we also show the current volume of Wi-Fi spectrum available at 2.4GHz and 5GHz and the potential amount of spectrum that could be available if the extension of the 5GHz LE band as proposed at WRC-15 is approved (see appendix B for details of LE spectrum availability). Note in 2010 that although LE spectrum at 5GHz was available to Wi-Fi devices only a small subset of devices were able to use this higher band and most were restricted in practice to the 3 x20MHz channels or 60MHz available at 2.4GHz. Comparing 60MHz against our LE spectrum estimates for 2010 shows that the 2.4GHz would have been becoming increasingly congested at this time which indeed it was. This has been relieved in the short term by the use of part of the 5GHz band for LE devices although there are plans to expand LE support in this band further as already mentioned.

Examining the trends for every 5 years in this result (with values given for our medium demand case) we see:

- Between 2010 and 2015 a low growth in spectrum requirements is seen even though licence exempt demand density grows by 5.5x in this period. There is a 2.3x increase in the spectral efficiency of hotspots to offset some of this increase in demand. However, it is likely that this lack of increase in LE spectrum requirements in the model is an artefact of some demanding service categories being included for LE hotspots in 2010 at low user densities. These demanding SCs will have high baseline spectrum requirements to initially provide coverage for these demanding services which do not increase greatly for increased demand by 2015 as the initial investment of a large bandwidth to serve these SCs in 2010 has already been made.
- Between 2015 and 2020 there is a 3.2x increase in demand density but only a 1.1x increase in the spectrum efficiency of hotspots so spectrum estimates show a relatively sharp increase reflecting the increase in demand density in this time.
- Between 2020 and 2025 there is a 2.5 x increase in demand density but this is largely offset by an approximate doubling in spectral efficiency values due to higher orders of MIMO becoming available in LE devices. However, a steep increase in spectrum requirements is still seen as the improvement in device capability also increases supported service rates and allows more demanding SCs to be carried on LE networks which have high baseline spectrum requirements.
- Between 2025 and 2030 there is a 2.5x increase in demand density but again spectrum efficiency values approximately double in this time period due to improved device capabilities (through even higher orders of MIMO or next generations of 802.11 standards becoming available). This increase in device capabilities also increases supported application rates but as these were already relatively high in 2025 there is not the same large increase in spectrum requirements due to new services as was observed between 2020 and 2025.

However, the spectrum estimates given in Figure 35 are optimistic as they do not allow for practical limitations of LE deployments including:

- Discrete bandwidths supported by Wi-Fi technologies
- A requirement for concurrent channels in any location to avoid interference amongst co-sited access points due to the LE nature of deployments

Figure 36 to Figure 38 examine LE spectrum requirements with these practical limitations allowed for. Here we examine spectrum estimates when between three and six 20MHz channels are required in each area to avoid interference and degraded performance amongst multiple access points deployed in the same area.

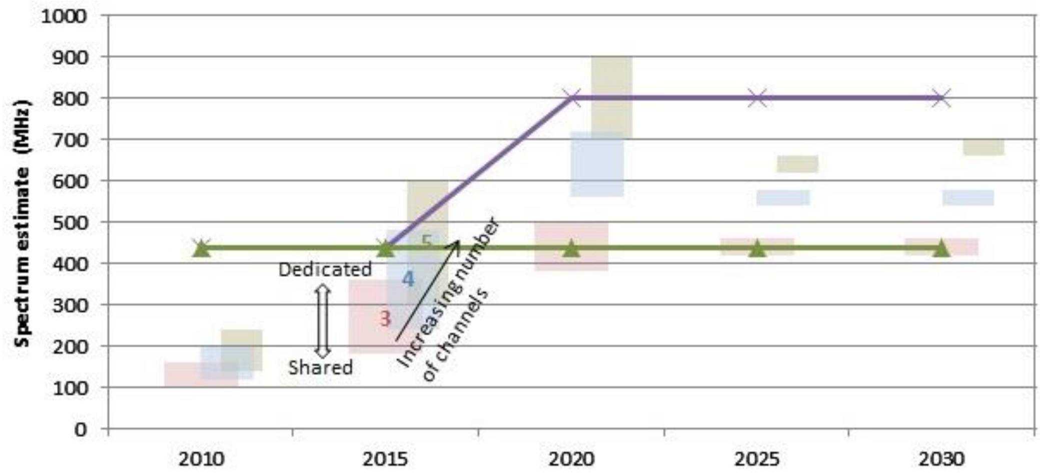
We also show a best case “shared” spectrum estimate (lower end of bars) and worst case “dedicated” spectrum estimate (upper end of bars) depending on the level of spectrum sharing that can be achieved between LE devices supporting different variants of 802.11 protocols on the same hotspot layer. In the best case shared view (lower end of the bars) we assume that channels are shared across multiple Wi-Fi air interfaces. For example in the best case shared view (lower end of the bars) the spectrum requirements of 802.11g and

802.11n devices at 2.4GHz are assumed to be time interleaved on the same channel rather than separate channels being required for each of these. In the worst case dedicated view (upper end of the bars) we calculate the number of channels required per Wi-Fi air interface separately and then sum across these on the assumption that devices running different Wi-Fi air interfaces require different channels. In addition in the dedicated case if multiple air interfaces are being widely used in the same band we assume that a minimum of 3 channels per air interface are needed to minimise interference between access points as discussed earlier.

The spectrum requirement in practice is likely to be between the two of these, but not necessarily the average, and will vary over time as technologies improve. Note that the definition of dedicated and shared spectrum estimates in this LE case are different to those from our licensed spectrum estimates where these examined sharing amongst network layers rather than protocols using the same network layer.

Comparing the spectrum requirements across our three demand levels in Figure 36 to Figure 38 shows that LE hotspot spectrum requirements are driven more by the practical deployment limitations on spectrum requirements than by demand density. For example from Figure 35 we would expect spectrum requirements for our medium demand scenario to be as much as half that of our very high demand scenario based on demand alone. However, Figure 37 and Figure 38 indicate that with practical deployment limitations allowed for spectrum requirements become much more commensurate between these two cases.

Given these additional constraints, our LE hotspot spectrum estimates suggest the existing 2.4GHz and 5GHz LE spectrum allocations could come under pressure by as early at 2020 with the further extension of the 5GHz band for LE usage likely to relieve this until around 2030. However, under the very high demand case further LE bands may need to be identified by 2030.




| Spectrum (MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| 5 channels | Shared | 140 | 300 | 700 | 620 | 660 |
| | Dedicated | 240 | 600 | 900 | 660 | 700 |
| 4 channels | Shared | 120 | 240 | 500 | 500 | 540 |
| | Dedicated | 200 | 480 | 660 | 540 | 580 |
| 3 channels | Shared | 100 | 180 | 380 | 420 | 420 |
| | Dedicated | 160 | 360 | 500 | 460 | 460 |

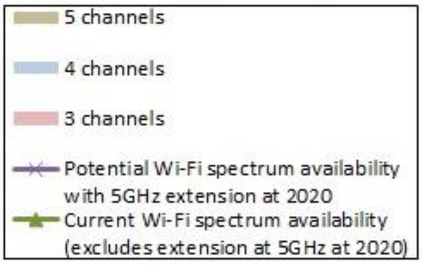
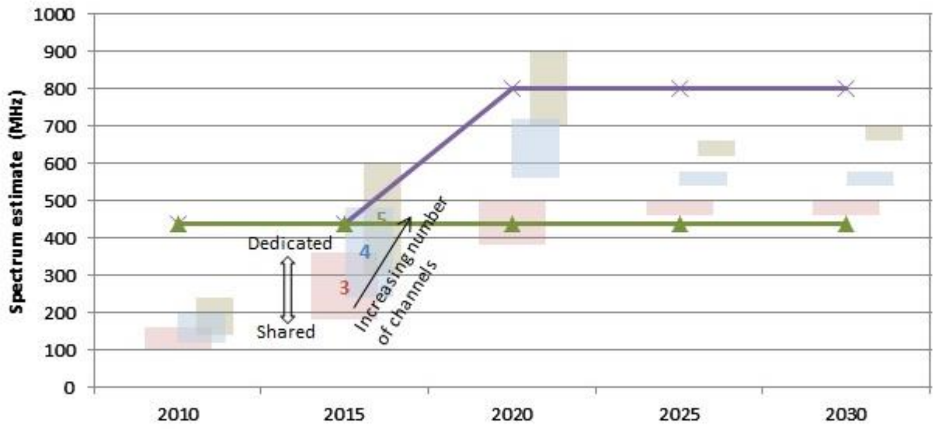



**Figure 36: LE hotspot spectrum requirements (MHz) in the low demand scenario with practical limitations of deployments considered for different frequency reuse levels**




| Spectrum(MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| 5 channels | Shared | 140 | 300 | 700 | 620 | 660 |
| | Dedicated | 240 | 600 | 900 | 660 | 700 |
| 4 channels | Shared | 120 | 240 | 560 | 540 | 540 |
| | Dedicated | 200 | 480 | 720 | 580 | 580 |
| 3 channels | Shared | 100 | 180 | 380 | 460 | 460 |
| | Dedicated | 160 | 360 | 500 | 500 | 500 |

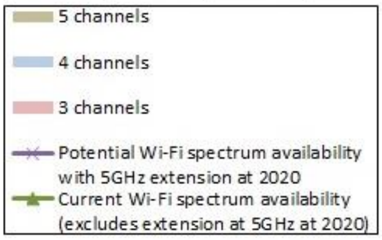
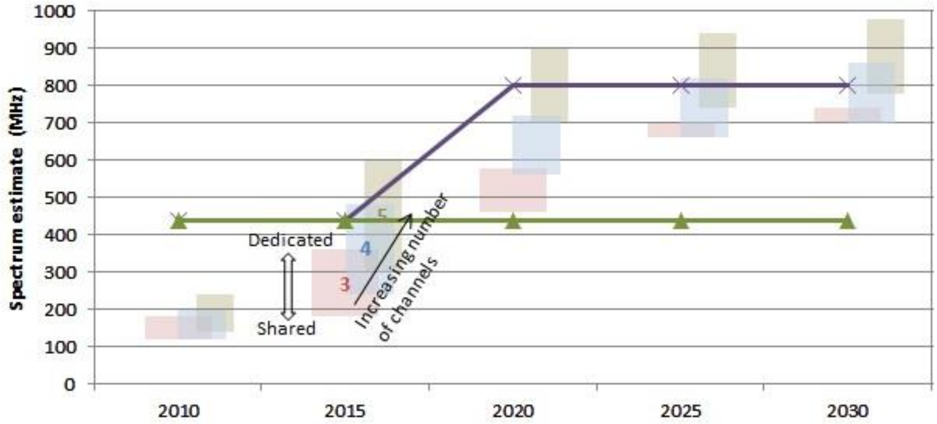



**Figure 37: LE hotspot spectrum requirements (MHz) in the medium demand scenario with practical limitations of deployments considered for different frequency reuse levels**




| Spectrum (MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| 5 channels | Shared | 140 | 300 | 700 | 740 | 780 |
| | Dedicated | 240 | 600 | 900 | 940 | 980 |
| 4 channels | Shared | 120 | 240 | 560 | 660 | 700 |
| | Dedicated | 200 | 480 | 720 | 820 | 860 |
| 3 channels | Shared | 120 | 180 | 460 | 660 | 700 |
| | Dedicated | 180 | 360 | 580 | 700 | 740 |

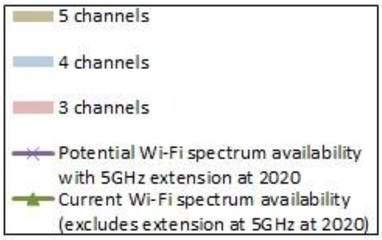



**Figure 38: LE hotspot spectrum requirements (MHz) in the very high demand scenario with practical limitations of deployments considered for different frequency reuse levels**

### 2.5.2 LE picocell spectrum requirements

Figure 39 shows our spectrum estimates for LE picocells based on public area traffic levels in our medium and very high uptake scenarios[16] with the very high uptake level representing "shoulder to shoulder" user densities such as in a busy transport hub. This shows that LE picocell spectrum requirements, while much less than those of LE hotspots, could be significant. However, as yet no spectrum has directly been identified for LE picocells in the UK to date. One candidate for this is TVWS spectrum but this has not been quantified for the UK yet and will be limited particularly in dense urban and suburban areas. Another potential candidate for LE picocell spectrum would be a low power shared access band such as that proposed (but not awarded) at 2.6GHz in the recent auction of 4G spectrum in the UK [12].

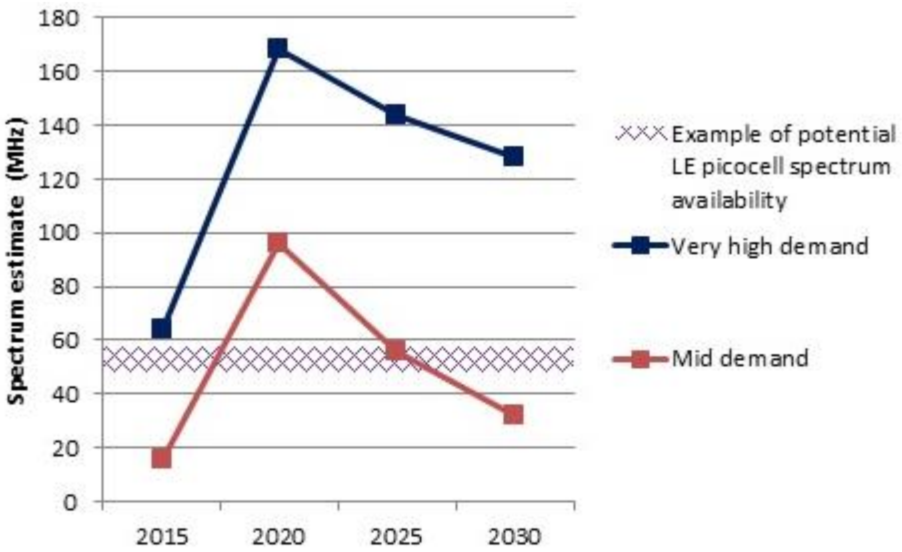
In Figure 39 we give an example illustration of LE picocell spectrum that might potentially become available with time based on TVWS availability (which varies by area), based on spectrum databases from the US, and a 2x20MHz low power shared access band becoming available, such as was proposed at 2.6GHz as mentioned. Our assumptions on LE

[16] Note that a low demand scenario for LE picocells has not been run as it was the very high demand scenario representing a busy transport hub that was thought to be the most realistic driver for future LE picocell spectrum requirements and hence of most interest.

spectrum availability are discussed in more detail in appendix B but in the absence of any LE picocell spectrum being formally identified in the UK aim to give an example of the level that might become available if TVWS were similar to US levels and a 2x20MHz low power shared access channel also became available.

Also it should be noted that the extension of the 5GHz band under current LE conditions will not address requirements for these longer range LE picocells and hence new bands will need to be identified for these that are either at lower frequencies or allow higher transmit power levels to accommodate these longer range access points.

The results in Figure 39 follow the same 5 yearly trends as seen for hotspots earlier but with the exception of the time period from 2020 to 2025 when picocell spectrum requirements decrease whereas hotspot spectrum requirements increased. In the picocell case there is also an approximate doubling in spectral efficiency between 2020 and 2025 due to higher orders of MIMO becoming available in LE devices. However, we assume that the supported application rates of LE picocells will be capped at 50Mbps in line with ITU recommended values and the use of picocells for high volumes of users rather than high data rates to a few users as is the case for hotspot environments. This capping of the supported application rate for picocells means that more demanding SCs with large bandwidth requirements are not seen on LE picocells in this time period in contrast to LE hotspots.




| Spectrum (MHz) | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|
| Very high demand | 64 | 168 | 144 | 128 |
| Mid demand | 16 | 96 | 56 | 32 |

**Figure 39: LE picocell spectrum requirements (MHz) for the medium and very high demand scenarios**

# 3. Our analysis is based on updated input assumptions against ITU recommended settings for the ITU-R M.1768-1 model

We present a high level summary in this chapter of our input assumptions to the ITU-R M.1768-1 model and in particular highlight model settings that we have altered from the ITU-R working party 5D default model settings and our justification for these.

This includes:

- Our development of UK specific demand estimates for wireless broadband services.
- Revisions of the service and market related parameters, which describe the characteristics such as the mean bit rate and maximum tolerable delay of various wireless services that are used at any point in time, in the ITU-R M.1768-1 model following our critique of the ITU-R default settings for these.
- Revisions of network and technology related parameters in the ITU-R M.1768-1 model to make these more UK specific and up to date following our review of the ITU default settings for these.

## 3.1 Our spectrum estimate is based upon UK specific demand levels

As part of this study we have developed UK specific estimates of forecast demand levels for mobile broadband services in the UK. This is made up of:

- Demand for licensed spectrum which is the demand generated by mobile or portable devices (such as laptops and smartphones) that have a cellular capability and are availing of a service that could have been carried over licensed spectrum. This has been reduced by an offload percentage representing the amount of the total demand for licensed spectrum which is carried on or “offloaded” to Wi-Fi networks.
- Demand for LE spectrum which is made up of:
    - Traffic offloaded from licensed spectrum
    - Traffic from devices with Wi-Fi only capability and applications which are unlikely to ever make use of cellular spectrum, such as Smart TV. We class this as LE specific traffic rather than offloaded traffic.

Our approach to estimating demand levels in the UK is detailed in appendix C and is based around a “bottom up” approach which:

- Assesses demand per device type.
- Assesses device penetration levels.
- Combines the above two points with population levels to estimate demand densities in different environments.
- Combines demand across these different environments to achieve UK forecasts which can be verified against other UK demand forecasts from other sources to ensure that our bottom up demand estimates are credible.

### 3.1.1 Low, medium and high demand forecasts for licensed spectrum

We have reviewed our "bottom up" demand forecasts for licensed spectrum against UK wide demand forecasts from other sources. This comparison has shown that our "bottom-up" demand estimates represent a relatively high and aggressive uptake of mobile broadband services relative to other forecasts. We have therefore chosen to use our "bottom-up" demand forecast to represent a high market setting in this study (in line with JTG 4-5-6-7 requirements requesting spectrum estimates for both low and high market settings).

For our baseline medium UK demand scenario we have reverted to the mid forecast from our previous UHF strategy study which was also based on a "bottom up" analysis at the time but aligns better with more recent forecasts of demand at a UK level than the revised "bottom up" demand estimate from the current study.

Our proposed low market setting is based on an increased version of the low market setting from our UHF strategy study for Ofcom. This increase has been applied as the original low scenario did not require any new site builds of any type (but required some antenna upgrades to existing sites) which was not thought to be a realistic representation of how cellular networks are likely to evolve out to 2030.

These low, medium and high demand forecasts are shown in Figure 40 and largely represent:

- A low demand growth scenario with minimal expansion to existing networks needed to keep pace with demand via increasing sector numbers or adding small cells.
- A medium demand scenario representing realistic demand growth levels on mobile networks which require some network upgrade and expansion and use of small cells to keep pace with demand within current spectrum availability limitations (but found to be still economic for operators).
- A high scenario (as per the "bottom up" demand forecasts in this study based on Cisco's latest demand per device forecasts) which is an aggressive demand growth scenario where, without the introduction of additional spectrum, network expansion costs could start to become uneconomical. Comparing our high demand scenario from this current study against the high demand case from our UHF strategy study shows that our latest high demand case is in a similar region but a slight reduction on this previous study.

The demand levels shown in Figure 40 are prior to any offload to Wi-Fi. Once a Wi-Fi offload percentage has been applied (depending on the Wi-Fi offload scenario being investigated as discussed in section 4.2.1) these licensed spectrum demand estimates are used to calibrate the distributed RATG1 and RATG2 demand against in our run of the ITU-R M.1768-1 model focused on licensed spectrum estimates.

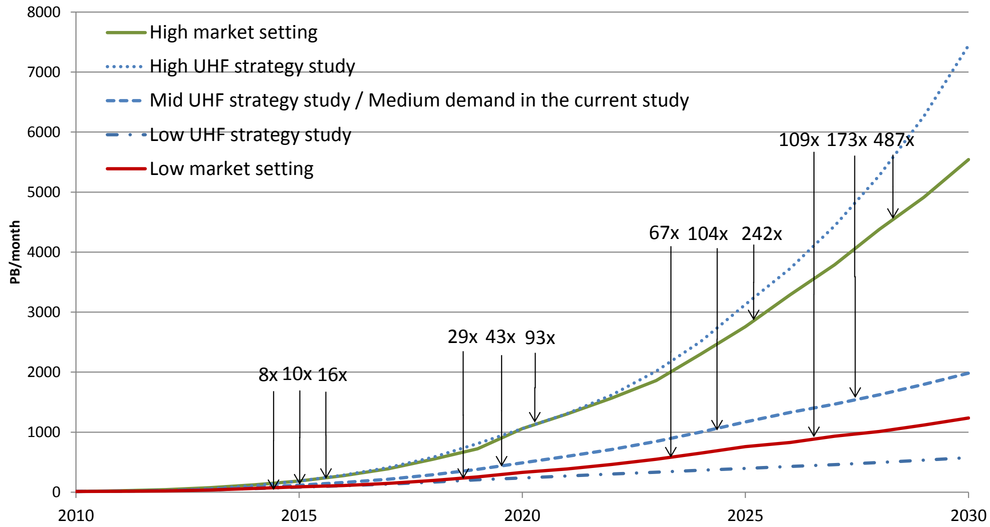



**Figure 40: Total potential demand for licensed mobile spectrum (before offload to Wi-Fi) for the low, medium and high market settings used in this study compared against forecasts from our UHF strategy study for Ofcom [5]**

### 3.1.2 Low, medium and high demand forecasts for LE spectrum

In the case of LE spectrum requirements we have modelled the following three scenarios for demand levels:

1. **Very high-** An intensive home networking scenario with a family of users on different devices at once. This would include the smart TV and M2M home networking[17] traffic per device estimates plus a laptop/tablet and smartphone all using the home access point concurrently.
2. **Mid** - A challenging but realistic peak demand on home Wi-Fi access points made up of smart TV and M2M home networking wireless device usage as per our current baseline LE estimates.
3. **Low** - A scenario where smart TV is not used in the average household but home networking M2M devices are still used along with a laptop/tablet i.e. Wi-Fi is used more for home IT than for home entertainment

These LE demand scenarios are specific to the home environment which drives overall spectrum requirements for LE hotspots. However, note that in each of these three scenarios we also consider the traffic levels that would be generated in office and public areas by a subset of the home environment devices more appropriate to these areas. For example we assume that Smart TV traffic should not contribute to traffic in public areas but that traffic here will be made up of a proportion of the overall traffic from devices such as tablets, laptops and smartphones that users are more likely to use on the move.

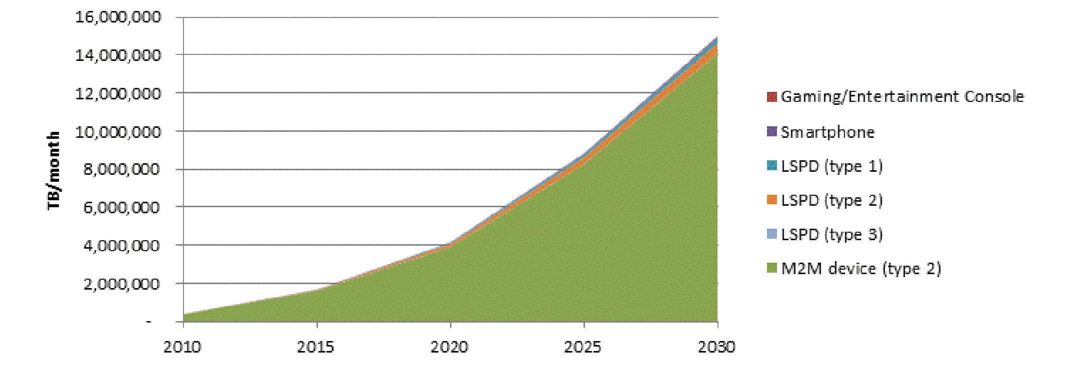
Note also that to distinguish from the high demand case developed for the demand for licensed spectrum, we class our LE higher demand scenario as a "very high" demand scenario. This very high LE demand scenario considers estimates of traffic per mobile device, such as laptops, which are far greater than those considered under our demand for

[17] Note M2M in this context refers to home networking devices such as wireless printers or wireless multimedia systems with high traffic requirements as opposed to smart metering M2M devices.

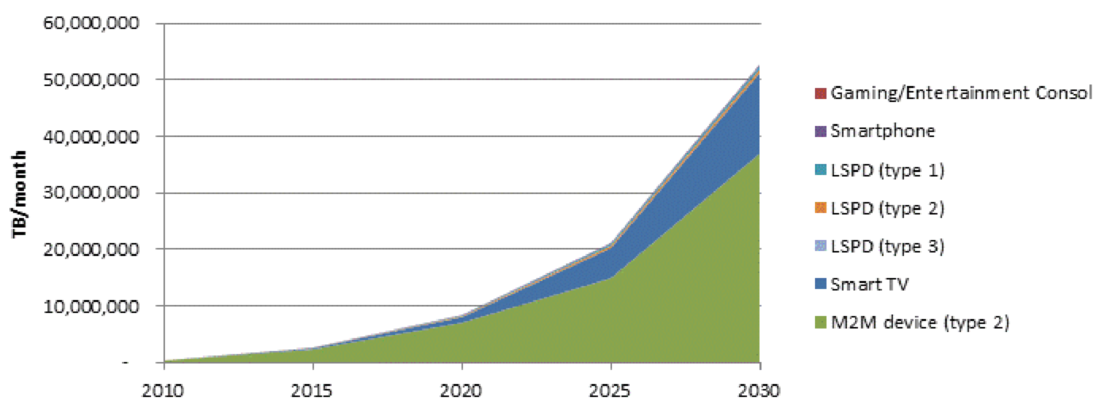
licensed spectrum. These higher traffic estimates per device represent traffic from Wi-Fi only portable devices as well as those with cellular support and are representative of users with a frequent, free connection to Wi-Fi who are not limited in their data consumption. Therefore, the size of the demand is very high and predominantly driven by video streaming services which can consume tens of GB per day across multiple devices.

The overall LE demand levels assumed in our very high, medium and low LE scenarios are shown in Figure 41 with the assumptions behind these given in our demand analysis in appendix C. Note that within these we consider:

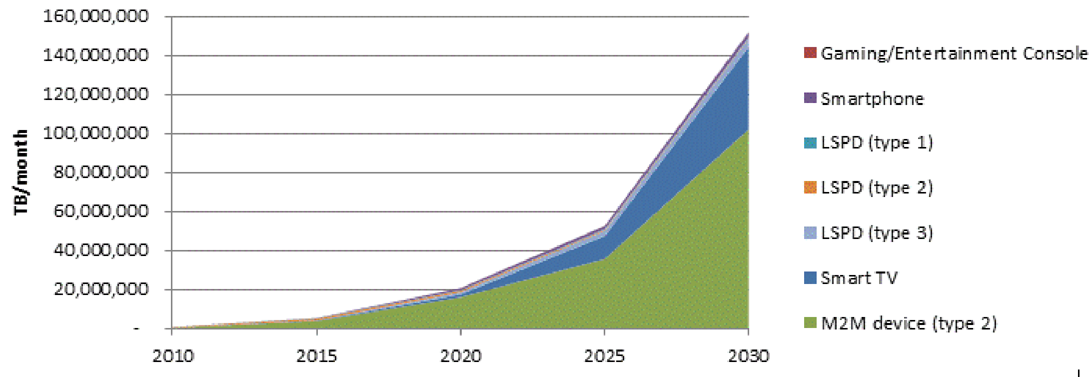
- Gaming consoles
- Smartphones
- Large Screen portable devices (LSPD) type 1, 2 and 3 made up of laptops, tablets and hybrids of these respectively.
- M2M type 2 devices which refer to home networking devices such as wireless printers or wireless multimedia systems with high traffic requirements as opposed to smart metering M2M devices.




**Low traffic growth**




**Mid traffic growth**




**High traffic growth**

**Figure 41: Total Low/Mid/High LE traffic across devices**

To show how our LE demand forecasts translate to scenarios for public areas, which we assume will drive LE picocells spectrum requirements, Figure 42 illustrates the user densities for high end service categories in dense urban public areas implied by our very high and medium demand forecasts for LE services. This shows that the medium demand case represents a busy transport hub such as an airport with many users in close proximity to each other but still with some personal space. The very high demand scenario shows user densities in the personal space category implying users who are shoulder to shoulder such as in a busy train station during peak travel periods in areas of London's King's Cross station.

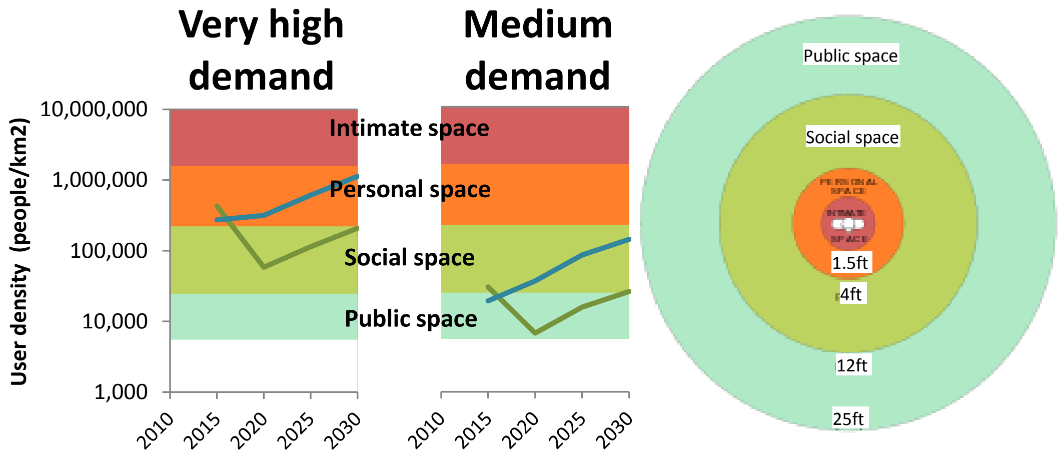
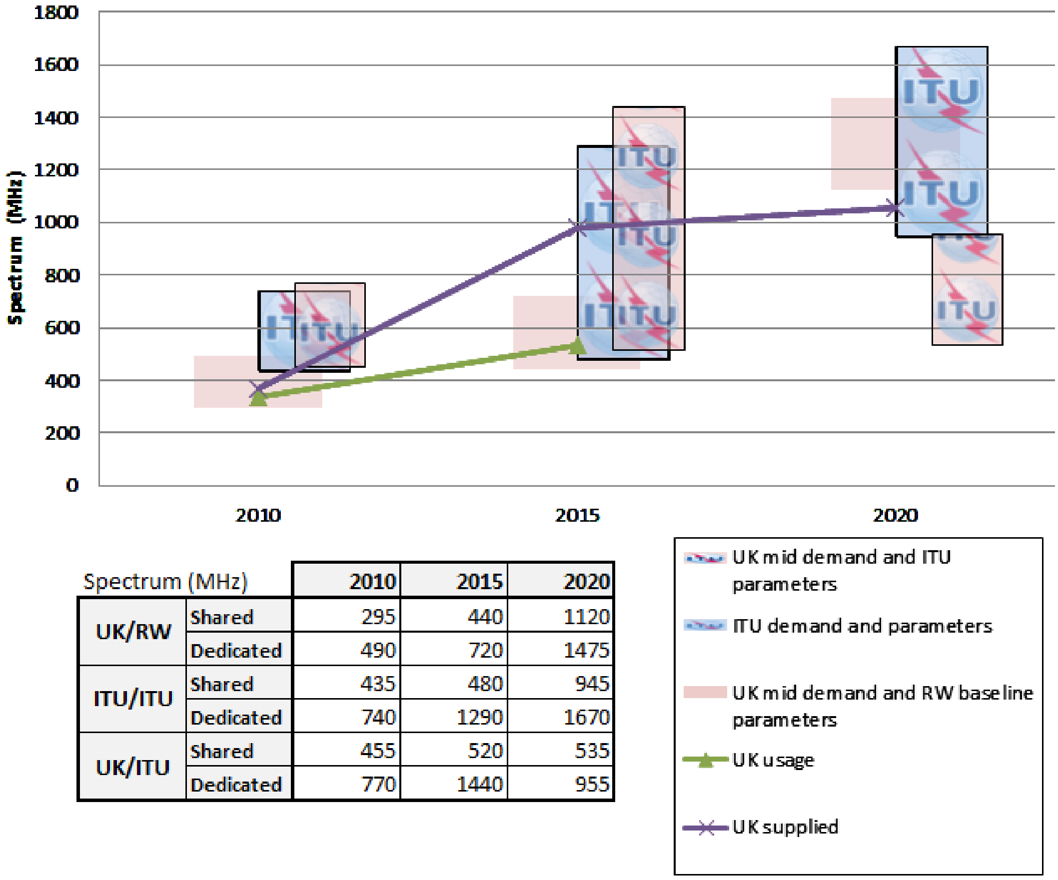



**Figure 42: User densities assumed for high end services in dense urban public areas by our medium and very high LE demand levels**

## 3.2 Rationale for revising ITU-R working party 5D recommended M.1768-1 model settings for the UK situation

Within this study we initially produced spectrum estimates using the ITU-R M.1768-1 model with the ITU recommended settings and low demand scenario as outlined in working party 5D's work in progress response to JTG 4-5-6-7 regarding spectrum requirements for wireless broadband services in preparation for agenda item 1.1 at WRC-15. The spectrum estimates from this are shown by the blue ITU logo bars on Figure 43.




| Spectrum (MHz) | | 2010 | 2015 | 2020 |
|---|---|---|---|---|
| UK/RW | Shared | 295 | 440 | 1120 |
| | Dedicated | 490 | 720 | 1475 |
| ITU/ITU | Shared | 435 | 480 | 945 |
| | Dedicated | 740 | 1290 | 1670 |
| UK/ITU | Shared | 455 | 520 | 535 |
| | Dedicated | 770 | 1440 | 955 |

**Figure 43: Comparison of spectrum estimates between ITU default case, ITU default case with UK specific mid demand and Real Wireless recommended baseline settings with UK specific mid demand (dedicated spectrum estimate at upper end of bars and shared spectrum estimate at lower end of the bars given in MHz).**

The spectrum estimates obtained in Figure 43 with the ITU recommended model settings and low demand scenario align with those given by working party 5D in [13] noting the following differences in reported spectrum estimate results between our updated version of the ITU-R M.1768-1 model and the original model provided by working party 5D:

- A minimum spectrum deployment of 5MHz as in our recommended baseline model settings rather than 20MHz as used by working party 5D.
- Dedicated spectrum estimates that require a separate frequency layer each for macrocell, microcells, picocells and hotspots rather than the assumption in working party 5D's analysis that for RATG1 macrocells, microcells and small cells (including both picocells and hotspots) require separate spectrum layers and that for RATG2 macrocells and microcells share a spectrum layer and with picocells and hotspots sharing a small cell spectrum layer.

To verify that the results from our updated implementation of the ITU-R M.1768-1 model matches those given by ITU working party 5D, the conversion of the results from Figure 43 to be compared on a like for like basis with the 2020 spectrum estimate provided by working party 5D is given in Table 3. Our 2020 spectrum estimates after this conversion for RATG1 of 440MHz and for RATG2 of 900MHz tally with working party 5D's result in [13].

| | Macrocells | Microcells | Picocells | Hotpots | Total |
|---|---|---|---|---|---|
| Dense urban RATG1 result from our version of model with ITU default settings and ITU low demand setting but 5MHz resolution (as per Figure 43) | 265 MHz | 120 MHz | 25 MHz | 20 MHz | |
| Dense urban RATG1 result from our version of model with ITU default settings and ITU low demand setting but 20MHz resolution as per ITU result | 280 MHz | 120 MHz | 40 MHz | 20 MHz | |
| ITU dedicated spectrum estimate for RATG1 based on a macrocell, microcell and small cell layer (maximum across hotspots and picocells) | | | | | **440MHz** |
| | | | | | |
| Dense urban RATG2 result from our version of model with ITU default settings and ITU low demand setting but 5MHz resolution (as per Figure 43) | 250 MHz | 665 MHz | 205 MHz | 120 MHz | |
| Dense urban RATG2 result from our version of model with ITU default settings and ITU low demand setting but 20MHz resolution as per ITU result | 260 MHz | 680 MHz | 220 MHz | 120 MHz | |
| ITU dedicated spectrum estimate for RATG2 based on a macrocell and microcell shared layer and small cell layer (maximum across hotspots and picocells) | | | | | **900MHz** |

**Table 3: Conversion of 2020 spectrum estimates from Figure 43 for a like for like comparison against ITU working party 5D spectrum estimates**

This shows that the same spectrum requirements as found by working party 5D are still obtained when our updated model is used with the ITU recommended model settings and market settings showing that our updates have not changed the model's original computations but have only added functionality.

We next updated the demand that is distributed by the model so that it represented our UK specific medium demand scenario rather than the ITU's own low demand estimate. However, we maintained all other model input parameters as per the ITU's recommended settings in [10]. The red ITU logo bars on Figure 43 show the spectrum requirements results for this scenario.

To understand the expected change in spectrum requirements between these two scenarios we examined differences in the demand density between the ITU low demand forecast used in the first scenario and our own UK specific medium demand case used in the second. These are shown in Figure 44.

Examining the detailed breakdown of the spectrum requirements results for these two scenarios showed that the maximum total spectrum required across all cell types occurred in the following environments in these two scenarios:

- ITU low demand and ITU model settings - Suburban for 2010 and 2015 dense urban for 2020
- Our UK medium demand forecast and ITU model settings – Suburban for 2010, 2015 and 2020

The changes in demand densities between the ITU low demand forecast and our UK specific medium demand forecast in suburban environments for 2010 and 2015 which corresponded to the spectrum bottleneck scenario in both cases are highlighted in Figure 44.

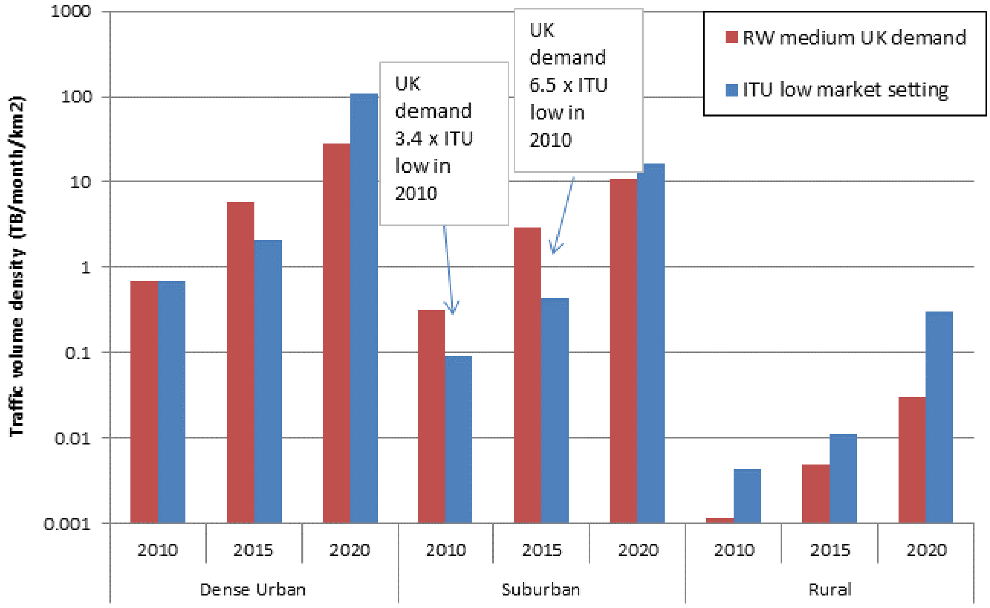



**Figure 44: Comparison of demand densities in different teledensities for ITU demand from working party 5D against our UK specific medium demand estimates**

Comparing the difference in estimated spectrum requirements between these two scenarios from Figure 43 with these changes in demand level between these two scenarios in Figure 44 shows that the spectrum estimate does not change to the extent expected. In 2010 and 2015 despite the demand input to the model changing by a factor of 3.4 and 6.5 times respectively we see that the spectrum requirements for these two years changes relatively little between the blue ITU logo bars, showing the ITU estimate of spectrum requirements in a low demand scenario, and the red ITU logo bars, showing the case when ITU recommended model settings are used but with our UK specific medium demand case. This implies that when the ITU-R M.1768-1 model is configured with the recommended ITU settings for 2010 and 2015 at least that the spectrum estimate becomes relatively insensitive to demand.

To understand this apparent insensitivity of the model to demand we reviewed spectrum requirements across the various service categories (SCs) considered in the model and identified that a number of these which had particularly high spectrum requirements even when user densities were set to very low levels (see appendix D). Upon reviewing the service and market related parameters recommended by the ITU for these SCs we found that, in particular, challenging mean packet sizes and maximum tolerable delay settings for some SCs seemed to be the source of these high spectrum requirements. We therefore developed our own revised recommendations for baseline settings for these service and market related model parameters as summarised in section 3.3.

In addition to this we have also reviewed technology and network related parameters within the model, which include settings such as cell area and spectrum efficiency, and developed our own revised recommendations on these to bring them in line with current and expected capabilities of UK networks. These recommended changes are summarised in section 3.4.

Finally, the red bars in Figure 43 show the spectrum requirement results for a third scenario where we ran the model with our revised recommended baseline model input settings and UK specific medium demand scenario which included:

- Modifying service and market related parameters as summarised in section 3.3.
- Modifying technology and network related parameters as summarised in section 3.4.
- Updating the demand being distributed by the model so that it represented our UK specific medium demand scenario rather than the ITU's own low demand estimates once the updates to the other input parameters on the two above points were implemented.

For comparison Figure 43 also shows anticipated UK broadband spectrum usage and supply (see appendix B for details) where:

- Spectrum used (green line) indicates the volume of awarded licensed spectrum that we anticipate was likely to be heavily used in practice by the UK cellular market in 2010 and 2015. As discussed in appendix B this allows for some awarded bands not being heavily used in practice such as TDD spectrum bands due to the FDD centric nature of the UK cellular industry.
- Spectrum supply (purple line) indicates the total amount of licensed spectrum that has been made available to the UK market for wireless broadband services through spectrum awards since 2010 and includes bands in 2010 and 2015 that may be licensed but not widely used in practice throughout the UK.

In the pessimistic case of the dedicated spectrum requirement results (upper end of the bars) the amount of broadband spectrum that was in use at 2010 or is anticipated to be in use by 2015 aligns best with the spectrum estimate when the ITU-R M.1768-1 model is updated to use our recommended baseline setting and UK specific medium demand levels.

In the optimistic case of the shared spectrum estimates (lower end of the bars) all three estimates of spectrum requirements align reasonably well with actual and anticipated UK spectrum availability in 2010 and 2015. However, we have based our analysis in this study on our recommended baseline settings and UK specific demand estimates given the better match of the dedicated spectrum estimates for this case.

## 3.3 We have revised ITU default service parameter settings against services available today

As already discussed in the previous section, we found that, for 2010 and 2015 at least, the ITU-R M.1768-1 model is relatively insensitive to demand when configured with input parameters as recommended by the ITU (in working party 5D's work in progress response to JTG 4-5-6-7 in response to agenda item 1.1 for WRC-15 [10]). Upon further investigation we found that this was due to a number of SCs within the model generating high spectrum requirements even for low user densities of these SCs.

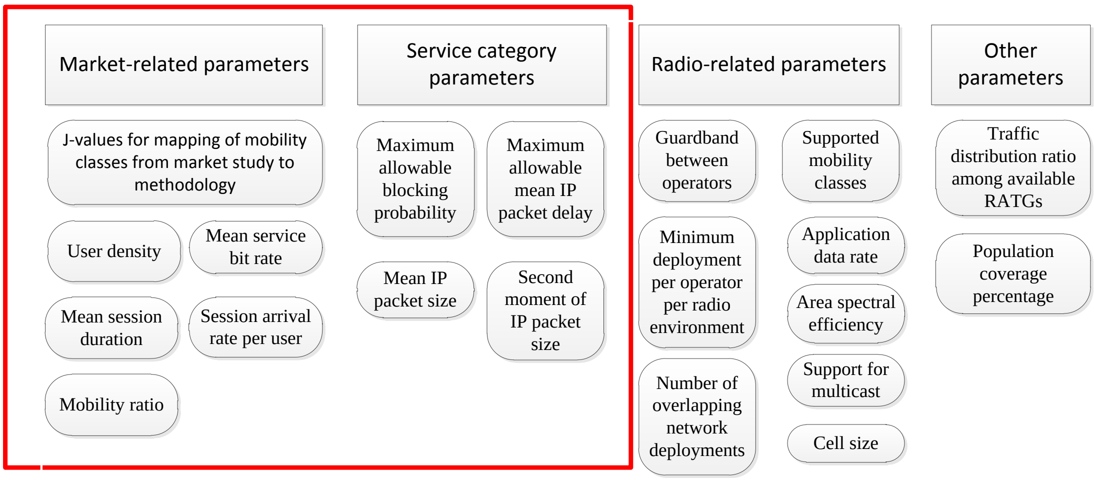



**Figure 45: Input parameters required by the ITU M.1758 model with service and market related parameters as reviewed in this chapter highlighted (based on [13])**

This prompted our review of market and service related parameters within the ITU-R M.1768-1 model as highlighted in Figure 45. The outcome of this review and our recommended baseline settings for these parameters are summarised on Table 4 and detailed in appendix D.

This table also highlights the level of changes suggested relative to ITU recommended values. The most major changes that we have suggested are to:

- Mean packet delay
- Mean packet size (and hence second moment of packet size)

These two parameters have a particularly strong impact on the spectrum requirements generated for various SCs due to the queuing theory block implemented in the ITU-R M.1768-1 model. We found that the ITU recommended setting for mean packet delay was very short compared against maximum tolerable delay times for services suggested by NGNM and 3GPP. We also found that mean packet sizes in the ITU recommended settings appeared high and did not allow for fragmentation of packets to make them more appropriate for transmission over cellular networks. These two parameters in particular placed difficult constraints to meet within the queuing theory block of the model and resulted in high spectrum requirements for certain SCs when the model was configured with the ITU recommended model settings.

| Parameter | Recommended updates | Comments | Impact on spectrum requirements of input revision |
|---|---|---|---|
| User density | Calibrate to match UK specific demand | The user density for each service category and service environment is calibrated so that the distributed demand per teledensity matches Real Wireless UK specific demand forecasts for each teledensity. | Generally our baseline UK user densities are slightly higher than the ITU low market setting which would drive spectrum requirements up. Note that the impact is mixed across SEs and demand scenarios though. |
| Mean service bit rate | ITU default values | We maintain mean service bit rates as per ITU default settings but note that in combination with our application rate settings that this means little or no traffic in SC 11 and SC 16 representing services above 30Mbps (which are unlikely to target wireless networks in the near term at least). | No impact. |
| Mean session duration | Use WINNER values | WINNER values are close to ITU default mean session duration settings but have a consistent 10% reduction per year whereas ITU default settings fluctuate over time. | Minor as very close to ITU default setting. |
| Session arrival rate | ITU default setting | We have not reviewed session arrival rates in detail and have used the ITU default settings for this in our analysis. | No impact |
| Mobility ratio | ITU default settings | Our baseline follows the ITU default settings on the basis that suggested updates were relatively minor. We also investigate changes in mobility ratio further in our sensitivity analysis. | No impact |
| Maximum allowable blocking probability | ITU default setting | We have not reviewed the maximum allowable blocking probability in detail and have used the ITU default settings for this in our analysis. | No impact |
| Maximum allowable mean IP packet delay | Update to use NGMN and 3GPP values | The tolerable packet delays in the ITU default settings are much lower than those recommended by 3GPP and NGMN. This has a big impact on spectrum requirements in the queuing theory element of the model and | Increasing the tolerable packet delays in our baseline compared with ITU settings will decrease overheads in the queuing theory block and decrease |

| Parameter | Recommended updates | Comments | Impact on spectrum requirements of input revision |
| --- | --- | --- | --- |
| | | so we have reverted to NGMN and 3GPP values in our analysis. | spectrum requirements. |
| Mean IP packet size | Update to Real Wireless recommended values | Real Wireless values draw on mean packet sizes from recent industry papers. These assume that fragmentation of packets for mobile networks would occur so as not to exceed the MTU for Ethernet in IP networks today of 1500 bytes even with jumbo mode IP packets. Real Wireless recommended values also do not fluctuate over time as was the case in the ITU default settings. | Decreasing the mean packet size relative to the ITU default settings will decrease overheads required in the queuing theory block and decrease spectrum estimates. |
| Second moment of IP packet size | Update to reflect Real Wireless recommended values for mean IP packet size | Our analysis also uses updated packet size variance in line with changes to the mean packet size squared. Note that our recommended values for the second moment of packet size maintain the ITU standard error in packet size across SCs but require further review as we observed that the ITU standard error levels can result in negative packet sizes in some cases. | As above. |
| Market attribute percentages | Update to WINNER suggested values with 2020 values kept constant out to 2030. | Our analysis uses the suggested market attribute percentages from the WINNER study as while these are close to the ITU default settings they have a more consistent trend over time than the ITU default settings. Note that the WINNER study has no suggested values for 2025 and 2030 so we use the 2020 suggestions for both of these as to follow the WINNER trend would result in zero values for average session duration of some SCs by 2030. | Minor as close to ITU default setting. |

**Table 4: Summary of changes to service and market related parameters (Green: ITU default setting, amber: minor changes close to ITU default setting, red: major changes against ITU default settings)**

## 3.4 We have selected technology and network parameters in the ITU model to reflect UK networks

Appendix E provides a detailed review of the technology and network related input parameters to the ITU-R M.1768-1 model. These parameters describe the radio access technologies and networks that are assumed to be available within each service environment to carry the demand density input to the model.

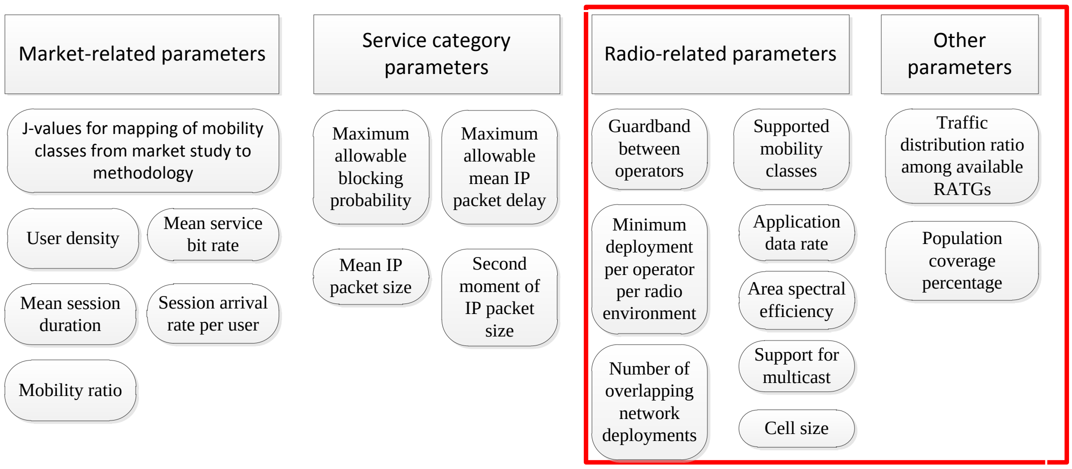



**Figure 46: Input parameters for ITU-R M.1768 model with technology and network related parameters discussed in this chapter highlighted**

Figure 46 highlights the input parameters that we have reviewed in this area to ensure that they:

- Reflect typical site numbers in the UK's cellular networks.
- Reflect the expected capabilities of the UK's cellular networks over time.
- Reflect the UK's appetite for offloading traffic from the wider area macrocellular network via small cellular cells in licensed spectrum and Wi-Fi integration into cellular networks.

Table 5 provides a summary of the changes to technology and network related ITU-R M.1768-1 model parameters recommended in our baseline model settings. The most major of these changes are to the following parameters:

- Minimum deployment per operator per radio environment
- Application data rate
- Area spectral efficiency
- Population coverage percentage

| Parameter | Recommended updates | Comments | Impact on spectrum requirements of input revision |
|---|---|---|---|
| Guard band between operators | Maintain ITU default values | A 0MHz setting as per ITU recommendations assumes that FDD spectrum is dominant which reflects the UK usage of mobile broadband spectrum. Therefore we maintain this at the ITU default value. | No impact |
| Minimum deployment per operator | Update from 20MHz to 5MHz for RATG1 and 2. | We recommend changing this to 5MHz in line with minimum LTE, UMTS and | Spectrum requirements appear slightly reduced due to being produced at a |

| Parameter | Recommended updates | Comments | Impact on spectrum requirements of input revision |
|---|---|---|---|
| per radio environment | | LTE-A deployment bandwidths and the outcome of the UK 4G auction. | finer resolution under the updated setting. |
| Number of overlapping network deployments | Maintain ITU default values | Maintain at 1 for RATG1 and 2 (not needed for RATG3) to obtain the highest resolution spectrum estimate from the model. | No impact |
| Supported mobility classes | Maintain ITU default values | Support ITU assumptions that macrocells address highest speed users, microcells address mobile users and picocells and hotspots are used by pedestrians only. | No impact |
| Application data rate | Update to use:<br>- Cell edge rates for RATG1<br>- Average data rates for RATG2 adjusted for real networks<br>- Average data rates for RATG3 that reflect Wi-Fi standards support over time | Generally ITU recommended application rates appear high and introduce technologies too early (i.e. LTE-A prior to 2020 and RATG3 picocells prior to 2015). Our revised application rates assume RATG1 networks will provide coverage and hence suggest cell edge rates whereas RATG2 and 3 will provide performance and so are based on average supported data rates (adjusted for average performance on real networks). | Reducing application rates in our baseline base relative to the ITU settings reduces support for more demanding SCs and generally should **reduce spectrum requirements**. Although note our sensitivity analysis later shows that this is not always the case. |
| Area spectral efficiency | Update to reduced spectral efficiencies compared with ITU default settings that are more aligned with the WINNER study.<br>New spectral efficiencies added for RATG3. | ITU default settings are generally very high compared against other sources. Our recommended baseline setting reduces the ITU spectral efficiencies to largely align with WINNER suggested values at the assumed year of the RATG's deployment. This spectral efficiency is then grown at a rate in line with our UHF strategy study for Ofcom. New spectral efficiency values are introduced for RATG3 in line with suggested application rates | Our suggested lower spectral efficiencies relative to the ITU default levels will **increase spectrum requirements**. |

| Parameter | Recommended updates | Comments | Impact on spectrum requirements of input revision |
|---|---|---|---|
| | | and assumed average supported bandwidth in LE devices over time. | |
| Support for multicast | Maintain ITU default values | Support ITU suggestion of multicast support across all RATGs. | No impact |
| Cell size | Maintain ITU recommended values for picocells and hotspots in all environments and microcells in suburban and rural areas. Macrocell sector areas in all environments and microcell sector areas in dense urban environments to be updated in line with UK site deployments. | Support the ITU recommended values for picocells and hotspots in all environments and microcells in suburban and rural areas. Suggest an adjustment to the macrocell sector areas in all environments and microcell dense urban sector areas in line with UK microcell deployments. Note this is a reasonably minor adjustment in all cases except rural macrocells where the sector area is increased by 13 times. This is likely due to differences in assumed frequencies and target data rates between our analysis and the ITU's. | Our suggested large increase in rural cell sizes will decrease the spectral efficiency density in this teledensity and **increase rural spectrum requirements.**<br><br>In suburban areas we suggest an increase in macrocell size which would **increase suburban spectrum requirements.**<br><br>In dense urban areas we suggest a decrease in macrocell and microcell cell sizes which would **decrease spectrum estimates in dense urban areas.** |
| Traffic distribution ratio among available RATGs | Maintain ITU traffic distribution between RATG1 and RATG2 but delayed by 5 years. Update the RATG3 to (RATG1 + RATG2) distribution to reflect our Wi-Fi offload analysis i.e. 43% at 2010 and 33% at 2030. | We assume that LTE-A in the UK is not deployed until 2020 which is 5 years later than the ITU default setting. We agree with the ITU assumption of Wi-Fi offload reducing over time but suggest a lower 2010 Wi-Fi offload starting point of 43% compared with 70% in the ITU default. | Our suggested baseline updates to the ITU default settings will have a **mixed impact on spectrum requirements**. Delaying the roll out of LTE-A by 5 years will increase spectrum requirements from 2015 onwards. Our suggested lower Wi-Fi offload level will increase spectrum requirements in early years. However, we do not reduce Wi-Fi offload as aggressively as ITU in our baseline setting so by 2030 the ITU Wi-Fi offload level is much less than our baseline leading to lower spectrum requirements for our baseline settings. |

| Parameter | Recommended updates | Comments | Impact on spectrum requirements of input revision |
|---|---|---|---|
| Population coverage percentage | Minor updates to 2010 coverage levels suggested against ITU recommended values but more much aggressive uptake of small cells anticipated over time. | Our recommended baseline coverage levels largely align with the ITU default settings for macrocells. However, in the case of smaller cells we suggest mostly minor adjustments to the assumed 2010 coverage levels but then assume more aggressive small cell uptakes compared to the ITU recommendations based on forecasts for the small cell market. | Our suggested more aggressive uptake of small cells relative to the ITU default settings will offload more macrocell traffic to more spectrally efficient small cells (if low mobility traffic) and **decrease spectrum requirements.** |

**Table 5: Summary of changes to technology and network related parameters (Green: ITU default setting, amber: minor changes close to ITU default setting, red: major changes against ITU default settings)**

# 4. Sensitivity analysis

Within this study we have examined the sensitivity of our spectrum estimates to input assumptions by generating spectrum requirements for a number of scenarios. The findings for this sensitivity analysis are reported in this chapter.

## 4.1 Key findings from the scenarios investigated in our sensitivity analysis

Within our sensitivity analysis we have set up the ITU-R M.1768-1 model to generate licensed spectrum requirement estimates for a series of scenarios to investigate:

- The impact of small cells only being deployed where essential
- The impact on the upper limit of mobile broadband spectrum requirements for different assumptions on Wi-Fi offload levels and small cell uptake
- The impact on the lower limit of mobile broadband spectrum requirements for varying assumptions on Wi-Fi offload and small cell uptake
- The impact of assumptions regarding the mobility of users in suburban areas (which drives macrocell requirements in this environment and makes it the driver for overall spectrum requirements in many cases)
- The impact of availability of LTE-A hotspots
- The impact of assumptions regarding the application rate in the ITU-R M.1768-1 model inputs
- The impact of assumptions regarding service delivery via circuit switched as opposed to packet switched mechanisms

Note that in the case of LE spectrum estimates we have only investigated the case of varying demand levels (as reported earlier in section 2.5). The other scenarios listed here were not investigated as these are not likely to have a large impact on LE spectrum estimates. Arguably higher Wi-Fi offload levels (which might be linked to a low small cell uptake in licensed spectrum) will impact LE spectrum requirements. However, as cellular offload traffic only makes up a small percentage of overall LE traffic (as discussed in our LE demand estimates in Appendix C) this will only be to a limited extent.

Table 6 summarises our key findings from the scenarios investigated in our sensitivity analysis. Across these the assumed mobility ratio of users in suburban and rural areas was found to be the biggest driver of spectrum requirements. This is because traffic from high mobility users can only be accommodated on macrocells due to handover issues on smaller cells. As macrocells have a larger coverage area than other cell types they have the lowest spectral efficiency density of all cell types and so this high mobility traffic can only be served at relatively low spectral efficiency densities driving up overall spectrum requirements. This limitation of having to serve a fixed amount of high mobility traffic means that our low, medium and high demand spectrum estimates are largely insensitive to:

- Wi-Fi offload levels based on the argument that these limiting high mobility users will not be able to avail of Wi-Fi access points due to handover issues in small cells and limited outdoor coverage of Wi-Fi.
- Licensed small cell uptake levels provided that the combination of LTE-A hotspots and small cell uptake is at a level sufficient to accommodate all low mobility

traffic in suburban environments as is the case for our baseline model settings for the later parts of our study timescales when the existing supply of spectrum starts to become under pressure.

| Scenario | Key findings | Impact |
|---|---|---|
| Small cells (microcells and picocells) only being rolled out where essential | The overall spectrum estimate for the medium demand case with our baseline model settings, which includes LTE-A hotspots, is not greatly impacted by small cell (i.e. microcell and picocells) uptake. Later scenarios investigated also show that this is the case for our low and high demand settings also. This is because overall spectrum requirements are driven by high mobility traffic in suburban areas which cannot be easily be offloaded to smaller cells (see section 2.2.1).<br><br>We note from later scenarios that if LTE-A hotspots are not available that the assumed uptake of small cells becomes more important. However, we view this balance between using LTE-A hotspots and increasing the roll out of picocells and microcells as a deployment trade-off for operators to decide upon rather than a driver for spectrum requirements. | Low |
| Upper limit of mobile broadband spectrum requirements for different assumptions on Wi-Fi offload levels and small cell uptake | Spectrum estimates appear very sensitive to Wi-Fi offload levels but we note that this is due to a limitation of the ITU-R M.1768-1 model not allowing Wi-Fi offload levels to vary across SEs (see model limitations discussed in section 2.1). This sensitivity to Wi-Fi offload is not representative of practical spectrum requirements as in the case of suburban mobile users, who largely drive overall spectrum requirements (see section 2.2.1), there will be a limited opportunity to offload to Wi-Fi due to handover issues and limited support for high velocity users in smaller cells.<br><br>Similar to the previous scenario, spectrum estimates in this high demand scenario are not sensitive to the uptake of small cells (but this again is to be balanced against the availability of LTE-A hotspots). | Medium |
| Lower limit of mobile broadband spectrum requirements for different assumptions on Wi-Fi offload levels and small cell uptake | As in the case of the upper limit of mobile broadband spectrum requirements discussed above, the lower limit on mobile broadband spectrum requirements, based on a low demand setting, appears sensitive to Wi-Fi offload but not to small cell take up. However, the same comments apply re the applicability of higher Wi-Fi offload levels to mobile users and the impact of the availability of LTE-A hotspots on the importance of small cell take up. | Medium |
| Reduced percentage of mobile users in suburban environments | Reducing the percentage of mobile users in suburban areas to 10% (in line with forecasts of indoor to outdoor traffic levels) can reduce spectrum estimates by as much as 28% compared to our medium demand baseline.<br>We note that in the case of 2030 the spectrum requirements of rural mobile users and hence macrocell | High |

| Scenario | Key findings | Impact |
|---|---|---|
| | users start to dominate over suburban mobile users in this scenario but that this can be readdressed by capping the rural high mobility traffic percentage at 10% also. | |
| Availability of LTE-A hotspots | The lack of availability of LTE-A hotspots can have a significant impact on spectrum requirements. This is due to the high spectrum efficiency density of LTE-A hotspots compared to other cell types (as set by model inputs on spectral efficiency and sector area). This can be re-addressed to a certain extent by higher uptakes of other small cell types.<br><br>We note that the overall spectrum requirements return to similar levels to our medium demand original baseline case when:<br>• The percentage of mobile users is capped in suburban and rural areas to levels in line with current estimates of outdoor to indoor traffic<br>• LTE-A hotspots are not available but replaced with a small cell uptake assumption in line with our baseline or higher small cell uptake levels<br><br>In practice, the organisation of small cell spectrum and small cell topologies within their network will be an operator decision to achieve the best balance between cost and performance and so we do not view this as a driver for spectrum requirements. | Medium (due to mitigation via increased small cell uptake) |
| Application rate assumptions in the ITU-R M.1768-1 model inputs | Generally higher application rate assumptions give higher spectrum requirements due to allowing more demanding SCs to be carried by the network. These more demanding SCs have higher overheads, as calculated in the queuing theory block of the model, which leads to higher spectrum requirements.<br><br>However, this impact is not always seen if:<br>• The higher assumed application rates do not cross the boundary of the mean service bit rates of these more demanding services<br>• The higher application rates are set to target more demanding application rates towards more efficient smaller cells<br><br>The results from this sensitivity analysis show that there is a limited impact on overall spectrum requirements in cases where higher application rates are targeted at smaller cell layers, to use this network layer for performance, and lower application rates are targeted at macrocells. This reflects how networks are likely to be used in practice and supports our baseline assumptions for application rates. | Variable |
| The impact of assumptions regarding service | Our initial investigation of changing all conversational and streaming SCs with the exception of SC5 from being delivered via circuit switched mechanisms to packet | Potentially high but requires |

| Scenario | Key findings | Impact |
|---|---|---|
| delivery via circuit switched as opposed to packet switched mechanisms | switched mechanisms indicates that spectrum estimates may be reduced by as much as approximately 20% and delay the requirement for further mobile broadband spectrum allocations until 2030. However, our review of PS parameters for conversational and streaming services has been limited in the study timescales and we suggest further review and investigation in this area. In particular further investigations should consider suitable PS settings for mean packet size and second moment of packet size which unlike the ITU default settings do not lead to negative packet sizes in some cases. Also the queuing theory block in the existing ITU-R M.1768-1 model needs to be reviewed for whether it represents the overhead needed for PS methods delivering guaranteed bit rate services such as VoLTE. | further investigation |

**Table 6: Key findings across sensitivity analysis scenarios**

## 4.2 Summary of input parameters varied in scenarios investigated

The main parameters being varied within the model in our sensitivity scenarios are:

- Wi-Fi offload
- Small cell uptake
- Percentage of high mobility traffic
- Application rate assumptions

### 4.2.1 Wi-Fi offload

Wi-Fi offload percentage is the percentage of the total mobile demand that could have potentially been carried on licensed spectrum but is actually carried or "offloaded" to Wi-Fi networks. Here the total mobile demand that could potentially be carried on licensed spectrum is the demand generated by mobile or portable devices (such as laptops and smartphones) that have a cellular capability and are availing of a service that could have been carried over licensed spectrum. This excludes traffic from devices with Wi-Fi only capability and applications such as Smart TV that are very unlikely to ever make use of cellular spectrum which we class as LE specific traffic rather than offloaded traffic. Note that some studies consider both Wi-Fi offload percentage and the proportion of traffic carried over licensed small cells as a single offload value. In this study we consider the impact of Wi-Fi offload percentage and licensed small cell uptake separately. A high Wi-Fi offload level means more traffic on Wi-Fi networks and less traffic on cellular networks.

Figure 47 shows the low, medium and high settings investigated in our sensitivity analysis for Wi-Fi offload percentage with the rationale behind these discussed further in our detailed assumptions behind the distribution of traffic across RATGs in the model in appendix E.

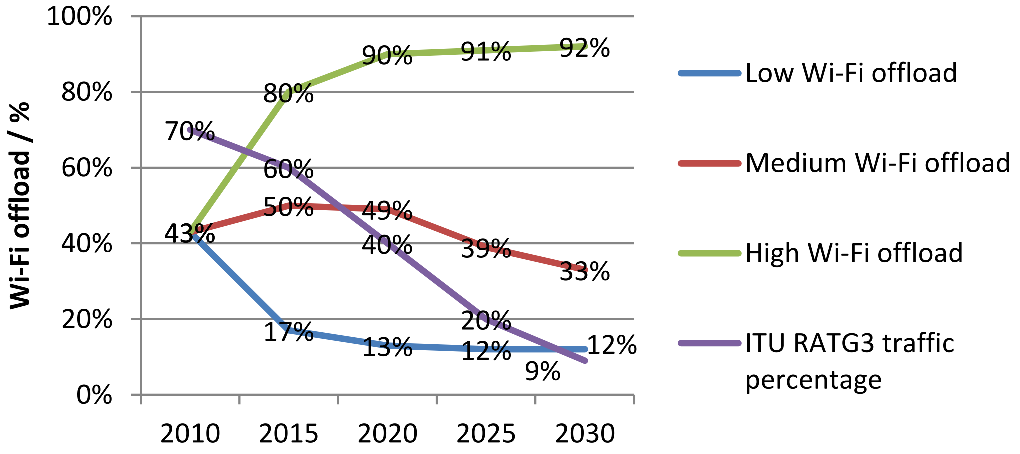



**Figure 47: Low, medium and high Wi-Fi offload percentages of total mobile demand that could have potentially been carried on licensed spectrum investigated in our sensitivity analysis**

### 4.2.2 Small cell uptake

The roll out of small cells and the trade-off between increasing small cell site numbers and acquiring more spectrum is a much debated topic. Small cell uptake is represented in the ITU-R M.1768-1 model by the coverage levels of licensed microcells (including microcells and outdoor small cells or metrocells) and picocells (including enterprise femtocells and residential femtocells). In the sensitivity analysis we vary the coverage levels of licensed microcells and picocells to represent higher or lower numbers of small cells being deployed relative to our baseline model setting (which is the medium small cell uptake level). These small cells will carry a higher or lower level of traffic from the macrocell layer respectively compared to our baseline model settings or medium small cell uptake case.

The hotspot category of cell type is largely used for RATG3 or LE hotspots in the ITU-R M.1768-1 model (although LTE-A hotspots are also included in later years) so we do not include this in our uptake of small cells sensitivity analysis. Any increase in LE hotspot deployment numbers on licensed spectrum will instead be covered by the Wi-Fi offload percentage.

We have, therefore, investigated the change in the spectrum estimate if the deployment of small cells is:

1. Low uptake where small cells are only deployed where essential which we represent by:
    - Microcell coverage levels based on the number of outdoor small cells found to be necessary to be built to meet the medium demand scenario in our UHF strategy study for Ofcom [5]. In this study outdoor small cells were only deployed if all other options for macrocell upgrades were exhausted or too costly or time consuming.
    - Picocell coverage levels in line with the ITU default picocell coverage levels which are less aggressive than the baseline picocell coverage assumptions in our medium scenario. The exception is SE 1 where the baseline coverage

already tracks the ITU default setting so we instead halve coverage levels in the low scenario.

2. Medium uptake in line with our recommended baseline coverage levels in the model for microcells, picocells and hotspots.
3. High uptake assumes revising microcell and picocell coverage levels to the upper end small cell growth levels given by Informa's latest forecast on the small cell market from Q1 2013 [14] and with higher ceilings on coverage percentages in later years to represent small cells being used to enhance user experience rather than just coverage.

The coverage levels in each of the SEs for microcells and picocells that correspond to these small cell uptake scenarios are shown in Figure 48 and Figure 49 with the full basis for these given in the discussion of coverage levels in appendix E.

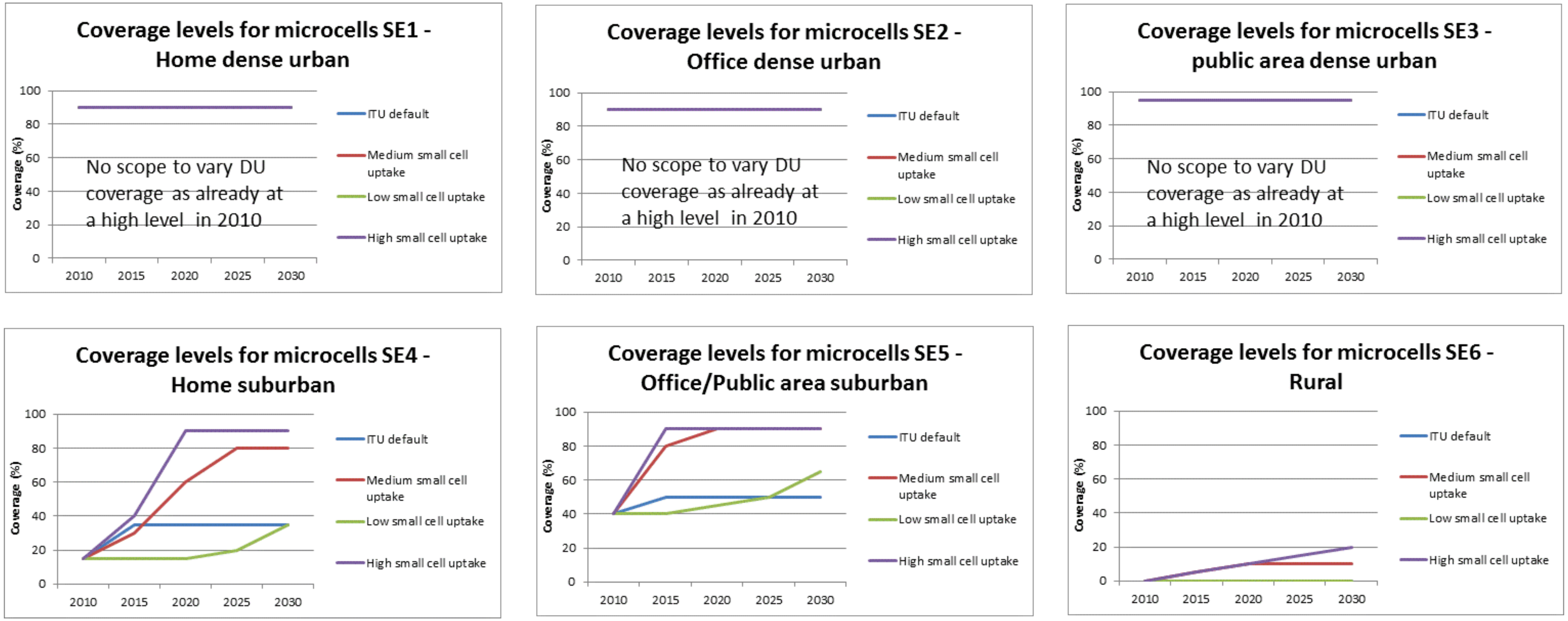



**Figure 48: Low, medium and high microcell uptake levels investigated**

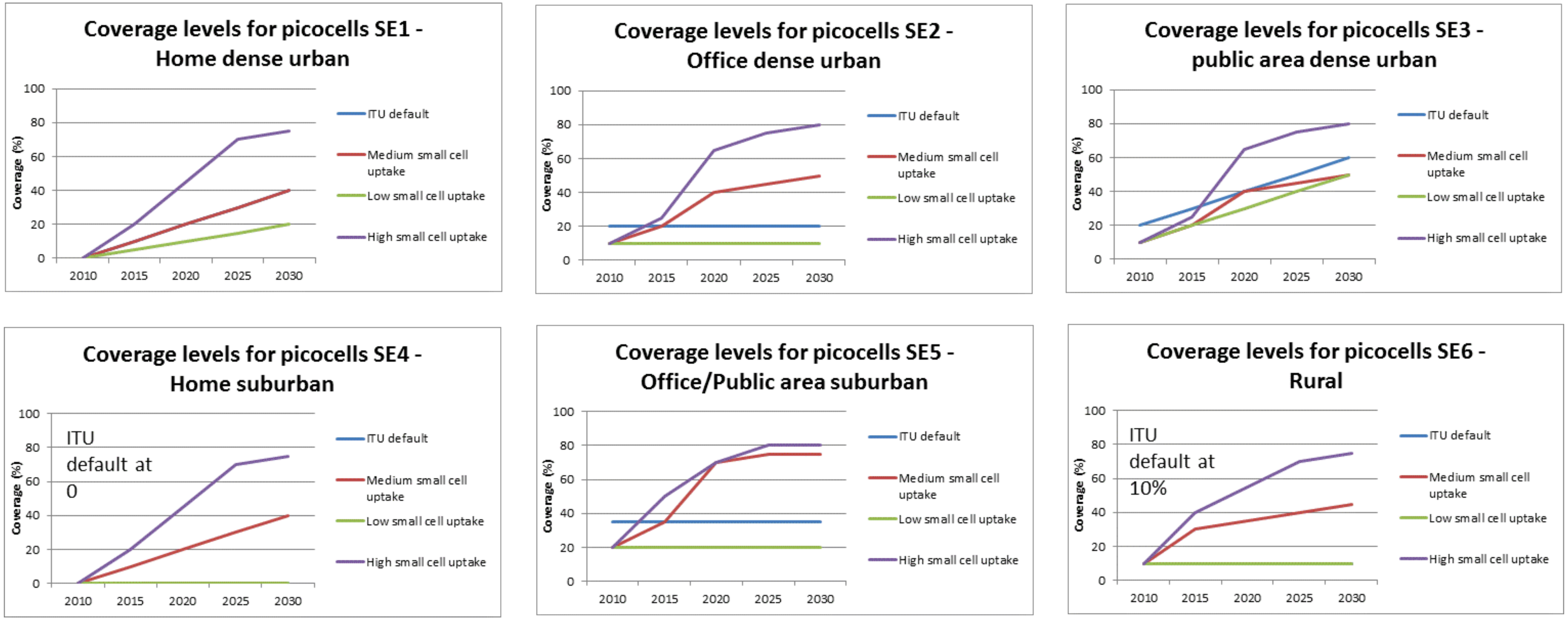



**Figure 49: Low medium and high picocell uptake levels investigated**

### 4.2.3 Percentage of traffic from high mobility users

As noted in section 2.2.1, generally licensed spectrum estimates across the low, medium and high demand settings and using our baseline model settings are driven by the SE5 (suburban office/public area) demand from high mobility users which have to be served by macrocells due to their velocity. In our baseline model settings we follow the ITU recommended values for mobility ratios across traffic and set a maximum of 20% of users across SCs in the SE5 suburban office/public area environment to be high or super high speed users i.e. in cars or on trains.

In our sensitivity analysis we have tested the case where in all SCs in suburban environments the mobility ratio for high or super-high users is capped at a total of 10%. This is based on 90% of traffic estimated to be generated indoors by 2015 by sources such as [15], [16] and [17]. Although not all of this 10% of outdoor traffic will be high velocity users and much will be used by pedestrians on streets we make a worst case assumption that up to this 10% of outdoor traffic will be for high velocity users in our sensitivity analysis.

### 4.2.4 Application rates

As an input to the ITU model an application rate is set per RATG for each year and cell type. This determines the service categories that can be carried by each RATG by being compared against the mean service bit rate for each SC.

It is not clear whether this application rate should be set to:

- Cell edge throughputs
- Average cell throughputs
- Maximum throughputs achievable in the cell

It is also noted that the supported application rate will vary by teledensity with macrocells in dense urban deployments with small sector areas likely to support much higher application rates than those in rural areas with larger sector areas (although the ITU model does not facilitate changing the application rate by teledensity).

The Real Wireless baseline settings in the model assume that RATG1 is used for coverage and so the application rate for RATG1 macrocells is limited to cell edge rates. For RATG2 and RATG3 we assume that these are used for performance and so the application rates here are in line with average cell rates that users could expect from these technologies in the different cell sizes.

We have investigated the sensitivity of results to application rate assumptions via the following three cases:

- Medium demand baseline model settings which assume average data rates for RATG2 and 3 but cell edge rates for RATG1.
- Medium demand baseline model but with ITU application rates used (which are more in line with maximum achievable data rates for each RATG).
- Medium demand baseline model but with average cell edge rates used for the application rate in all RATGs (which is an increase over our baseline but less than the ITU values). This case might be more representative of performance in cells

in dense urban and suburban areas which are capacity rather than coverage limited. This only impacts the RATG1 application rates by increasing them above our baseline setting as RATG2 and RATG3 are already set in the baseline scenario to average data rates based on the average achievable spectral efficiency.

## 4.3 Impact on spectrum requirements if small cell deployment is limited

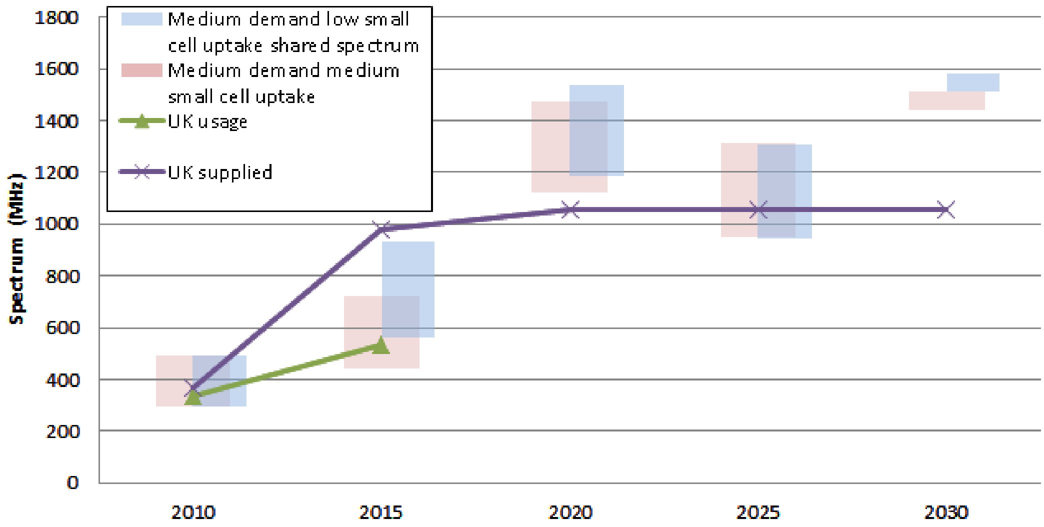
Table 7 highlights the scenarios investigated to understand the impact of a slow uptake of small cells on spectrum requirements where L is low, M is medium, H is high and RW is the Real Wireless baseline ITU-R M.1768-1 model input settings.

| Scenario | Mobile demand total | % licensed targeted demand offloaded to Wi-Fi | Model tech parameters | Small cells |
|---|---|---|---|---|
| Baseline for licensed | M | M | RW | M |
| Small cells only where essential | M | M | RW | L |

**Table 7: Scenarios investigated for impact on spectrum requirements when small cells only deployed where needed**

Figure 50 shows the impact of a slow small cell uptake, where small cells are only deployed where essential, on spectrum requirements for our medium demand scenario. The increased spectrum requirement for the low small cell uptake case in 2015 is due to microcell traffic in dense urban areas, which dominates the overall spectrum requirements for this year only in our baseline medium demand scenario (see section 2.2.1), not being able to migrate onto picocells as quickly as in the baseline scenario due to a slower uptake of picocells and hence reduced picocell coverage levels. However, from 2020 onwards the spectrum estimate is driven by the requirements of high mobility users in suburban and later rural areas which must be accommodated on macrocells due to handover limitations on smaller cells. This limits the opportunity for the offload of traffic from macrocells to small cells and hence the impact of small cells from 2020 onwards.

However, it should be noted that this scenario assumes the inclusion of LTE-A hotspots. Based on results in section 4.7, in the case of LTE-A hotspots being available with high spectral efficiency densities, as in our model baseline settings, low mobility suburban traffic is easily accommodated across the microcell, picocell and hotspot layers and the volume of traffic from high mobility users on less spectrally efficient macrocells drives spectrum requirements. However, if LTE-A hotspots are removed in this medium demand baseline case not all low mobility traffic can be served by microcells and picocells and needs to be carried on the less efficient macrocell layer hence driving up spectrum requirements. Therefore if LTE-A hotspots are not available spectrum estimates do become more sensitive to small cell deployment levels than shown by the scenarios examined here and listed on Table 7. As also discussed in section 4.7, the percentage of high mobility traffic also impacts sensitivity to small cell uptake as this changes the maximum amount of low mobility traffic that can potentially be distributed across small cell layers. Overall this later section concludes that small cell uptake should not be a driver for spectrum requirements and that our low, medium and high spectrum estimates are appropriate provided that the combination of LTE-A hotspots and small cell uptake reaches a capacity level commensurate with our baseline model settings.




| Spectrum (MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| **Medium uptake** | **Shared** | 295 | 440 | 1120 | 950 | 1445 |
| | **Dedicated** | 490 | 720 | 1475 | 1315 | 1515 |
| **Low uptake** | **Shared** | 295 | 560 | 1185 | 945 | 1510 |
| | **Dedicated** | 490 | 930 | 1540 | 1310 | 1580 |

**Figure 50: Licensed spectrum requirements (MHz) for medium baseline scenario vs. medium demand with small cell uptake low (dedicated spectrum estimate at upper end of bars and shared spectrum estimate at lower end of the bars)**

## 4.4 Sensitivity of upper limit on spectrum requirements to Wi-Fi offload and small cell uptake

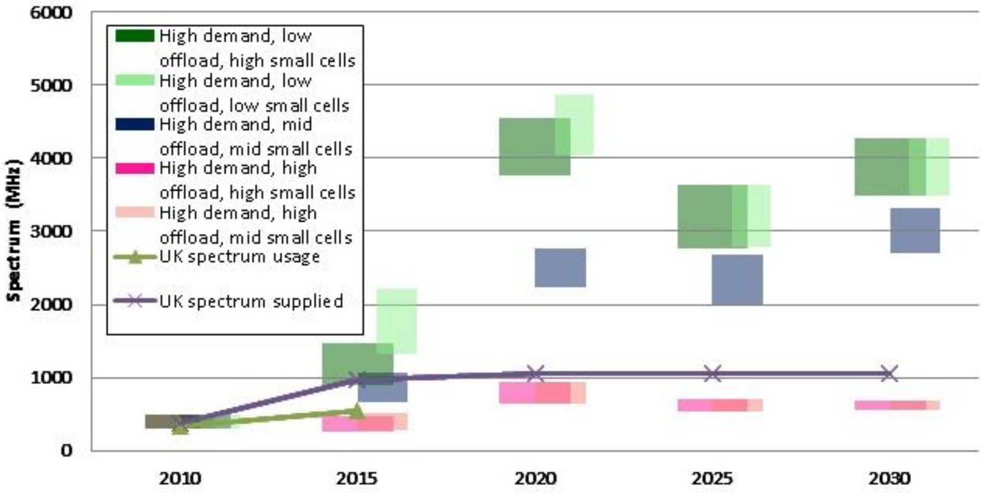
Table 8 highlights the scenarios investigated to understand the impact of various assumed levels of Wi-Fi offload and small cell uptake on the upper limit of spectrum requirements where L is low, M is medium, H is high and RW is the Real Wireless baseline ITU-R M.1768-1 model input settings.

| Scenario | Mobile demand total | % licensed targeted demand offloaded to Wi-Fi | Model tech parameters | Small cells |
|---|---|---|---|---|
| High market setting for licensed spectrum demand | H | M | RW | M |
| High Wi-Fi offload impact on high market setting | H | H | RW | M |
| High Wi-Fi offload and high small cell impact on high market setting | H | H | RW | H |
| Low Wi-Fi offload and high small cell on high market setting | H | L | RW | H |
| Upper limit on licensed spectrum requirements | H | L | RW | L |

**Table 8: Scenarios investigated for the upper limit on spectrum estimates**

The results in Figure 51 indicate that the upper bound on spectrum requirements:

- Appears very sensitive to the assumed Wi-Fi offload level. However, this result will likely over emphasise the impact of Wi-Fi offload on spectrum requirements. This is because, as discussed in section 2.3.1, high mobility suburban users largely drive overall spectrum requirements for our low, medium and high demand spectrum estimates using our baseline model settings. These high mobility users will have a limited opportunity to offload to Wi-Fi due to handover issues in smaller cells and limited outdoor coverage by Wi-Fi hotspots. Therefore only low Wi-Fi offload levels would be applicable to these high mobility users in practice. As the ITU-R M.1768-1 model does not allow Wi-Fi offload levels to vary across SEs (see model limitations discussed in section 2.1) and hence does not allow lower Wi-Fi offload levels to be directed at these mobile users this result may exaggerate the impact of Wi-Fi offload on overall spectrum requirements.
- Is not sensitive to the deployment of small cells but we note that, as discussed in the previous section, that this lack of sensitivity to small cell uptake is dependent on amount of low mobility traffic available in suburban areas (which largely drive overall spectrum requirements) which in turn is related to the availability of LTE-A hotspots and mobility ratio assumptions in suburban areas.




| Spectrum (MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| **High offload, High small cells** | **Shared** | 295 | 250 | 650 | 525 | 555 |
| | **Dedicated** | 490 | 465 | 930 | 705 | 690 |
| **High offload, Mid small cells** | **Shared** | 295 | 285 | 645 | 525 | 555 |
| | **Dedicated** | 490 | 505 | 930 | 705 | 690 |
| **Mid offload, Mid small cells** | **Shared** | 295 | 665 | 2230 | 2010 | 2710 |
| | **Dedicated** | 490 | 1070 | 2770 | 2675 | 3325 |
| **Low offload, High small cells** | **Shared** | 295 | 895 | 3775 | 2775 | 3490 |
| | **Dedicated** | 490 | 1475 | 4555 | 3635 | 4275 |
| **Low offload, Low small cells** | **Shared** | 295 | 1330 | 4045 | 2790 | 3485 |
| | **Dedicated** | 490 | 2210 | 4880 | 3630 | 4270 |

**Figure 51: Upper limit on licensed spectrum requirements (MHz) investigated against Wi-Fi offload and small cell uptake assumptions (dedicated spectrum estimate at upper end of bars and shared spectrum estimate at lower end of the bars)**

## 4.5 Sensitivity of lower limit on spectrum requirements to Wi-Fi offload and small cell uptake

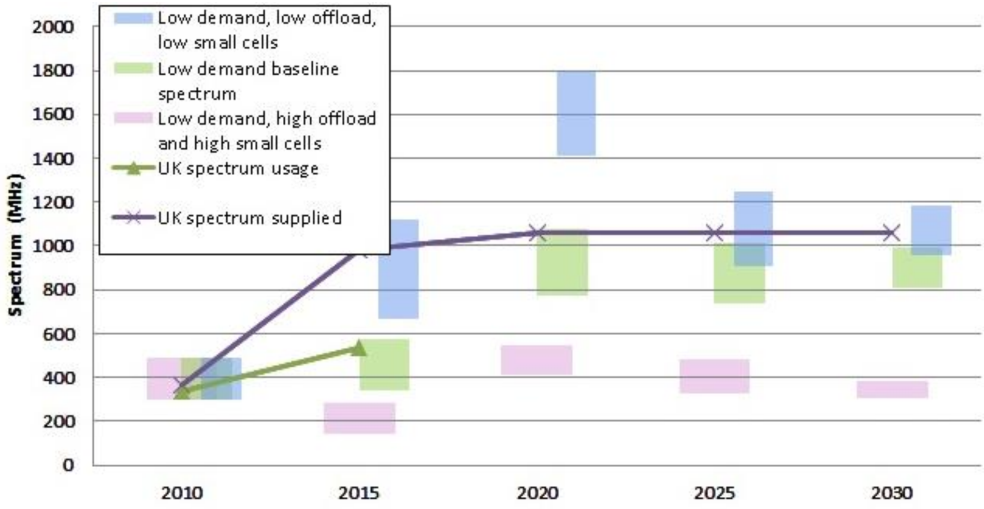
Table 9 highlights the scenarios investigated to understand the impact of various assumed levels of Wi-Fi offload and small cell uptake on the lower limit of spectrum requirements where L is low, M is medium, H is high and RW is the Real Wireless baseline ITU-R M.1768-1 model input settings.

| Scenario | Mobile demand total | % licensed targeted demand offloaded to Wi-Fi | Model tech parameters | Small cells |
|---|---|---|---|---|
| Low market setting for licensed | L | M | RW | M |
| Low offload and small cell impact on low market setting for licensed | L | L | RW | L |
| Lower limit on licensed spectrum requirements | L | H | RW | H |

**Table 9: Scenarios investigated for the lower limit on spectrum estimates**

The results in Figure 52 show that the lower bound on spectrum requirements, as was the case for the upper spectrum limit, is:

- Sensitive to the assumed Wi-Fi offload level. However, we again note that this may be an artefact of the model limitation of not varying Wi-Fi offload levels by SE and that in practice the high mobility users who drive overall spectrum requirements will have a limited opportunity to offload to Wi-Fi.
- Not sensitive to the small cell uptake levels. However, we again note that this lack of sensitivity to small cell uptake is dependent on the amount of low mobility traffic which can be offloaded to small cells in suburban environments which generally drive overall spectrum requirements. This amount of low mobility traffic available to be distributed on small cells is in turn related to the availability of LTE-A hotspots and mobility ratio assumptions as discussed further in section 4.6 and 4.7.




| Spectrum (MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| High offload High small cells | Shared | 295 | 140 | 415 | 330 | 305 |
| | Dedicated | 490 | 285 | 545 | 480 | 380 |
| Base line | Shared | 295 | 340 | 775 | 740 | 805 |
| | Dedicated | 490 | 575 | 1080 | 1015 | 995 |
| Low offload Low small cells | Shared | 295 | 670 | 1410 | 910 | 955 |
| | Dedicated | 490 | 1120 | 1795 | 1250 | 1185 |

**Figure 52: Lower limit on licensed spectrum requirements (MHz) investigated against Wi-Fi offload and small cell uptake assumptions (dedicated spectrum estimate at upper end of bars and shared spectrum estimate at lower end of the bars)**

## 4.6 Sensitivity to mobility assumptions of bottleneck services in suburban environments

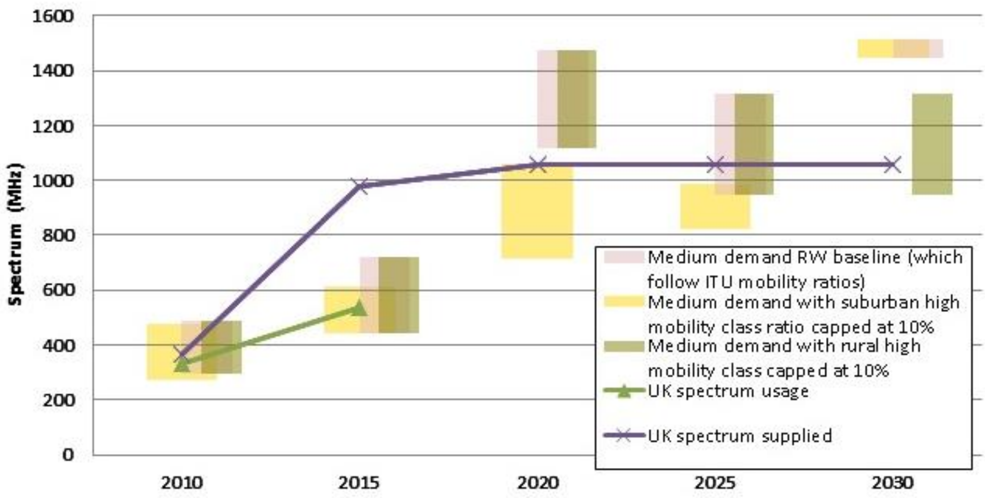
Table 10 highlights the scenarios investigated to understand the impact of mobility assumptions on spectrum requirements where L is low, M is medium, H is high and RW is the Real Wireless baseline ITU-R M.1768-1 model input settings.

| Scenario | Mobile demand total | % licensed targeted demand offloaded to Wi-Fi | Model tech parameters | Small cells |
|---|---|---|---|---|
| Baseline for licensed | M | M | RW | M |
| Sensitivity to mobility assumptions in suburban areas | M | M | RW but suburban SEs mobility ratio for high speed class capped at 10% | M |
| Sensitivity to mobility assumptions in rural areas | M | M | RW but rural SEs mobility ratio for high speed class capped at 10% | M |

**Table 10: Scenarios investigated for sensitivity to mobility in suburban areas**

As discussed in section 4.2.3, we have examined reducing limiting the percentage of traffic consumed by high mobility users in suburban areas to a maximum of 10% across SCs in line with recent forecasts of indoor to outdoor traffic levels.

Figure 53 shows the resulting spectrum requirements with this reduction in mobility percentage in suburban areas included against our baseline model settings which follow the higher ITU mobility percentages. This shows that for a reduced mobility ratio in suburban areas spectrum requirements are reduced as a higher proportion of traffic is non-mobile and can be carried by more spectrally efficient small cells.




| Spectrum (MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| Suburban cap | Shared | 275 | 440 | 715 | 825 | 1445 |
| | Dedicated | 475 | 615 | 1060 | 985 | 1515 |
| No cap | Shared | 295 | 440 | 1120 | 950 | 1445 |
| | Dedicated | 490 | 720 | 1475 | 1315 | 1515 |
| Rural cap | Shared | 295 | 440 | 1120 | 950 | 950 |
| | Dedicated | 490 | 720 | 1475 | 1315 | 1315 |

**Figure 53: Overall licensed spectrum results (MHz) with default ITU mobility in suburban areas vs. a reduced percentage of suburban high mobility users capped at 10% (dedicated spectrum estimate at upper end of bars and shared spectrum estimate at lower end of the bars)**

In both cases overall spectrum requirements are still driven by the suburban environment but in the reduced mobility ratio case the total spectrum requirements across all layers between dense urban and suburban areas become much more comparable.

Note that in 2030 the spectrum requirement between our medium demand baseline case and medium demand case with the reduced suburban mobility setting does not change. This is because high mobility users in rural areas now start to dominate the overall spectrum requirement.

The third scenario on Table 10 examines the impact on spectrum requirements if mobility percentages in rural areas are also capped at 10% in line with estimates of indoor to outdoor traffic levels. As shown on Figure 53, in this case the overall spectrum requirement in 2030 does reduce relative to the our baseline scenario as 2030 spectrum requirements become driven by suburban rather than rural high mobility users.

Examining the impact of the reduced mobility assumption in suburban areas in more detail in Figure 54 we see a trend in 2010 and 2015 of traffic moving towards microcells in the reduced mobility setting case. From 2020 onwards the macrocell spectrum requirements continue to be less in the reduced mobility case as more low mobility macrocell traffic is available to be offloaded to other network layers. However, we also see spectrum requirements for microcells reducing which is due to the introduction of LTE-A hotspots with extremely high spectrum efficiency densities which take traffic from the microcell layer and deliver this with very low spectrum requirements. There is also a small increase in picocell spectrum needed between the two cases from 2020 onwards showing that some of the microcell spectrum reduction is also due to increased availability and use of picocells.

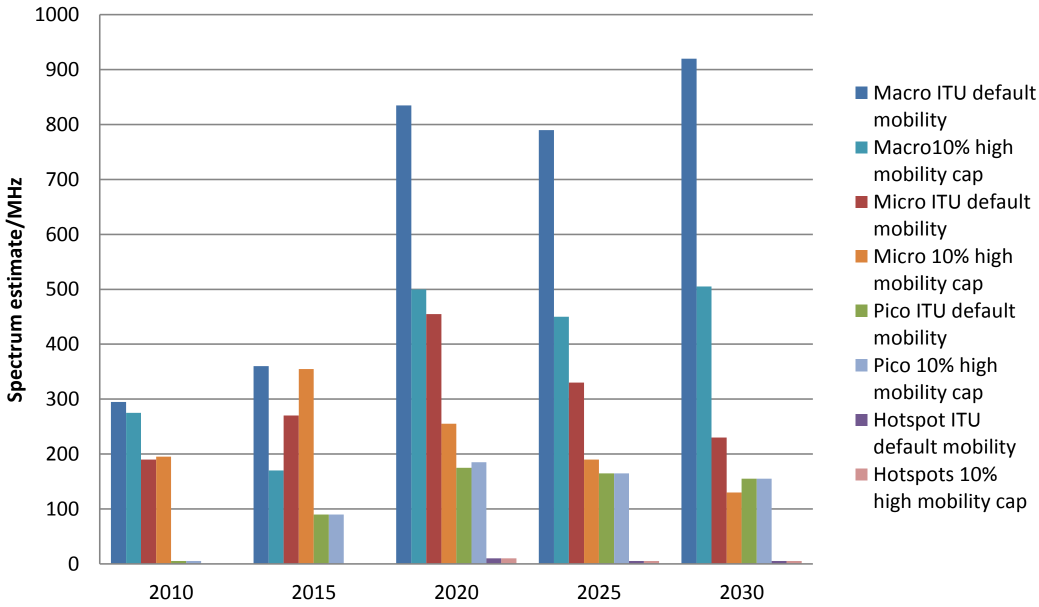



**Figure 54: Suburban licensed spectrum result (MHz) with default ITU mobility in suburban areas vs. a reduced percentage of suburban high mobility users capped at 10%**

## 4.7 Sensitivity to assumptions regarding the availability of LTE-A hotspots

Table 11 highlights the scenarios investigated to understand the impact of assumptions on the availability of LTE-A hotspots on spectrum requirements where L is low, M is medium, H is high and RW is the Real Wireless baseline ITU-R M.1768-1 model input settings.

| Scenario | Mobile demand total | % licensed targeted demand offloaded to Wi-Fi | Model tech parameters | Small cells |
|---|---|---|---|---|
| Baseline for licensed | M | M | RW | M |
| Impact of LTE-A hotspots | M | M | RW but LTE-A hotspots removed – only LE hotspots considered | M |

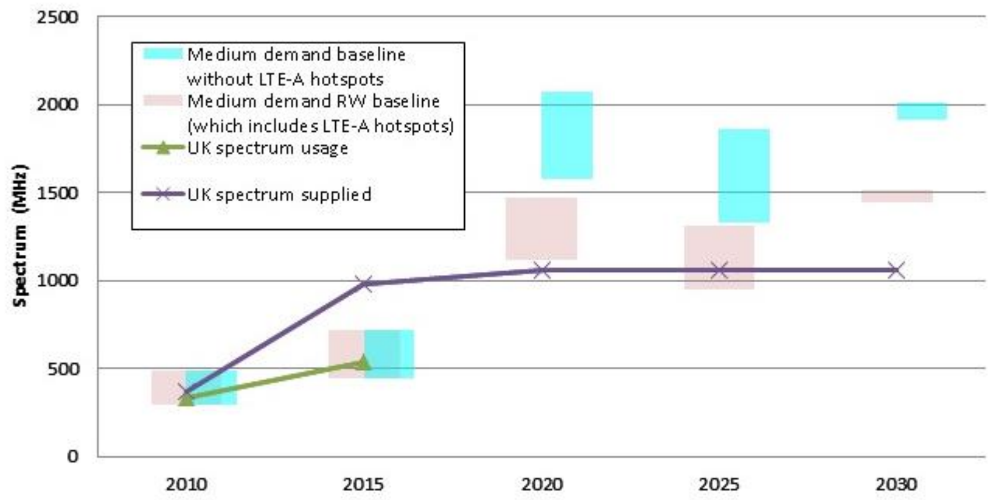
**Table 11**: **Scenarios investigated for sensitivity to roll out of LTE-A hotspots**

Our baseline model settings include application rates for LTE-A hotspots in line with the ITU default values (but adjusted down in some cases as ITU default application rates went beyond spectral efficiencies at the time) and LTE-A hotspot coverage levels which track LE hotspot coverage levels as in the ITU default model. These represent very high frequency LTE-A small cells which may have restricted sector areas similar to hotspots rather than picocells.

The ITU-R M.1768-1 model assumes that the hotspot population coverage percentage is uniform across all RATGs but it is unlikely that LTE-A hotspots would immediately reach the coverage levels of Wi-Fi hotspots or even reach significant coverage levels by 2030. Therefore we examine the case when only LE hotspots are included and there is assumed to be no impact from LTE-A hotspots.

As shown by the overall spectrum result in Figure 55 this does not impact the 2010 or 2015 result as we assume that LTE-A only becomes available in 2020. However, from 2020 onwards there is a large difference in the overall spectrum requirement because of the lack of LTE-A hotpots which due to their small sector areas have very high spectral efficiency densities.

Examining this result in more detail in the suburban environment, see Figure 56, which drives overall spectrum requirements (as discussed in section 2.2.1), in the case of LTE-A hotspots being available with high spectral efficiency densities low mobility suburban traffic is easily accommodated across the micro, picocell and hotspot layers and the volume of traffic from mobile users on less spectrally efficient macrocells drives spectrum requirements. In the case without LTE-A hotspots not all low mobility traffic can be served by microcells and picocells and needs to be carried on the less efficient macrocell layer hence driving up spectrum requirements. In the case without LTE-A hotspots we would therefore expect spectrum estimates to become more sensitive to small cell roll out assumptions.




| Spectrum MHz | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| With hotspots | Shared | 295 | 440 | 1120 | 950 | 1445 |
| | Dedicated | 490 | 720 | 1475 | 1315 | 1515 |
| Without hotspots | Shared | 295 | 440 | 1580 | 1330 | 1915 |
| | Dedicated | 490 | 720 | 2070 | 1865 | 2010 |

**Figure 55: Overall licensed spectrum estimate (MHz) for the medium demand baseline scenario with and without LTE-A hotspots included (dedicated spectrum estimate at upper end of bars and shared spectrum estimate at lower end of the bars)**

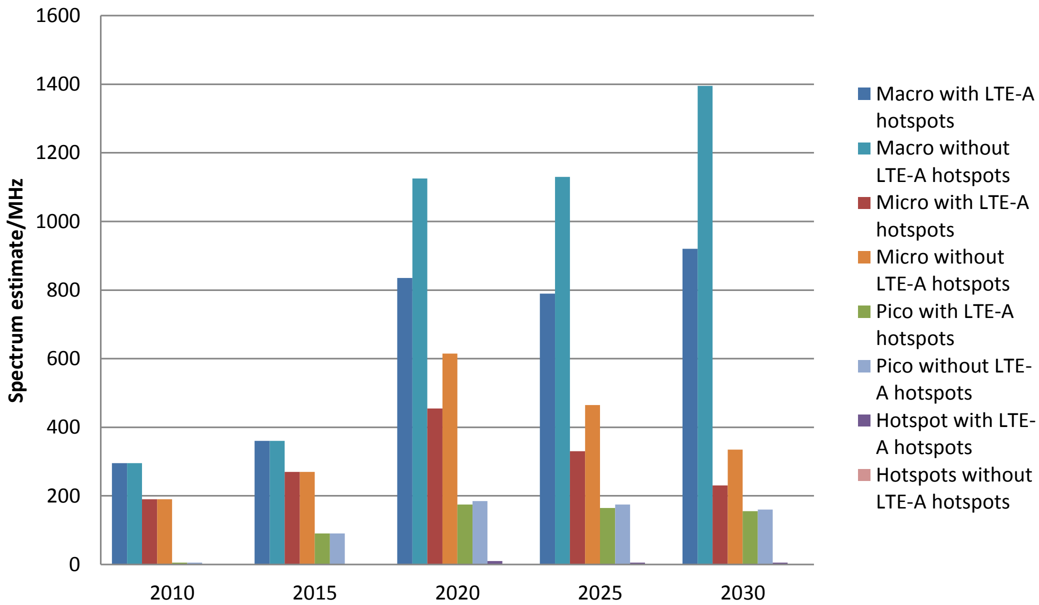



**Figure 56: Licensed spectrum estimate (MHz) for the medium demand baseline scenario with and without LTE-A hotspots included for suburban areas with distribution of spectrum requirements across network layers shown**

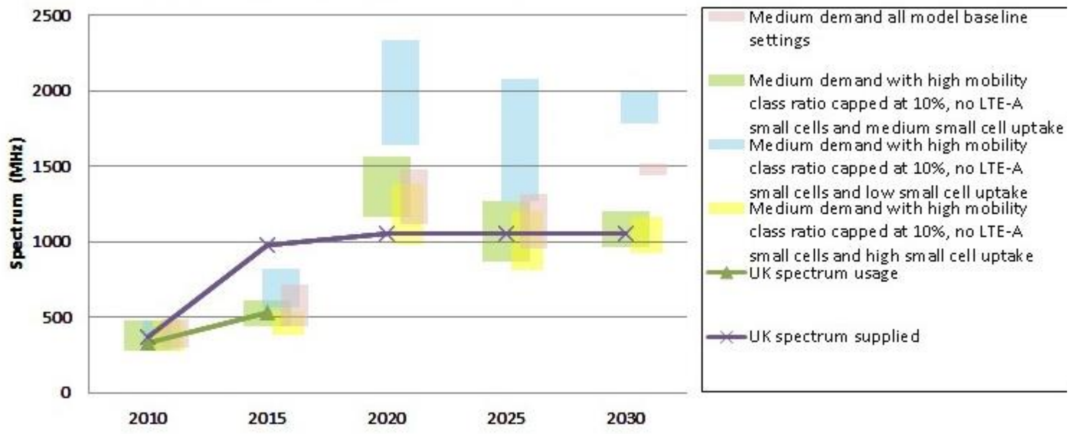
Given the high impact of the assumed percentage of traffic from mobile users in suburban and rural areas as highlighted in section 4.6 and the potential high impact of LTE-A hotspot availability, we have examined additional scenarios that combine assuming no availability of LTE-A hotspots with a reduced quantity of high mobility traffic (see Table 12).

| Scenario | Mobile demand total | % licensed targeted demand offloaded to Wi-Fi | Model tech parameters | Small cells |
|---|---|---|---|---|
| Baseline for licensed | M | M | RW | M |
| Impact of small cells when no LTE-A hotspots | M | M | RW but LTE-A hotspots removed – only LE hotspots considered<br>SE 5 high mobility traffic capped at 10% and SE4 set to 0, SE6 at 10% | M |
| Impact of small cells when no LTE-A hotspots | M | M | RW but LTE-A hotspots removed – only LE hotspots considered<br>SE 5 high mobility traffic capped at 10% and SE4 set to 0, SE6 at 10% | L |
| Impact of small cells when no LTE-A hotspots | M | M | RW but LTE-A hotspots removed – only LE hotspots considered<br>SE 5 high mobility traffic capped at 10% and SE4 set to 0, SE6 at 10% | H |

**Table 12: Scenarios investigating the combined impact of reduced mobility percentage, no LTE-A hotpots and varying small cell uptake levels**

The results across these are shown in Figure 57. These results show that for medium demand levels and even in cases of reduced mobility percentages, where the small cell layer will be required to absorb more low mobility traffic from macrocells, a lack of LTE-A hotspots can be re-addressed by uptakes of other small cell types in line with our medium or high small cell uptake levels. This finding should also apply to our low demand scenario where demand levels are lower than the medium demand level investigated here and hence we would expect the combinations of LTE-A hotspots and small cell uptakes investigated to also be adequate to accommodate all low mobility traffic in the low demand case. In the high demand case the relative insensitivity of spectrum estimates to small cell uptake (except in the case of 2015 where dense urban microcell requirements drive spectrum requirements) reported in sections 4.4 implies that all low mobility traffic has also been accommodated across the combination of microcells, picocells and hotspots for our baseline model settings at least.

This implies that across our low, medium and high demand settings that spectrum estimates are insensitive to small cell uptake levels provided capacity has been arranged across the microcell, picocell and hotspot layers to be commensurate to our baseline model settings and hence able to accommodate all low mobility traffic in the suburban environments which largely drive overall spectrum requirements. In practice, this trade-off between the deployment of LTE-A hotspots and small cell uptake levels and the distribution of traffic amongst these will be an operator decision to achieve the best balance between cost and performance and should not be taken as a driver for spectrum requirements.




| | Spectrum (MHz) | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| Medium demand with high mobility class ratio capped at 10%, no LTE-A small cells and medium small cell uptake. | Shared | 275 | 440 | 1160 | 865 | 960 |
| | Dedicated | 475 | 615 | 1565 | 1270 | 1205 |
| Medium demand with high mobility class ratio capped at 10%, no LTE-A small cells and low small cell uptake. | Shared | 275 | 560 | 1645 | 1265 | 1785 |
| | Dedicated | 475 | 820 | 2340 | 2080 | 2000 |
| Medium demand with high mobility class ratio capped at 10%, no LTE-A small cells and high small cell uptake. | Shared | 275 | 380 | 980 | 815 | 930 |
| | Dedicated | 475 | 530 | 1380 | 1200 | 1160 |
| Base line | Shared | 295 | 440 | 1120 | 950 | 1445 |
| | Dedicated | 490 | 720 | 1475 | 1315 | 1515 |

**Figure 57: Licensed spectrum estimates (MHz) for varying combinations of LTE-hotspot availability, reduced high mobility class ratios and small cell uptake (dedicated spectrum estimate at upper end of bars and shared spectrum estimate at lower end of the bars)**

We note that in the case where the percentage of mobile users is capped in suburban and rural areas to levels more in line with current estimates of outdoor to indoor traffic and LTE-A hotspots are replaced with a medium or higher small cell uptake assumption that the overall spectrum requirements return to similar levels to our medium demand original baseline case. This is because:

- The higher small cell uptake level (of microcells and picocells) is needed to carry the low mobility traffic that LTE-A hotspots would have carried. These have a lower spectral efficiency density than LTE-A hotspots and therefore require more spectrum for the same volume of traffic as the hotspots.
- However, adjusting the percentage of high mobility traffic down to 10% means that there is less high mobility traffic required to be carried at the lowest spectral efficiency density of the macrocell layer. This means that the macrocell layer can offload more low mobility traffic to the more efficient microcells and picocells and save on spectrum requirements.

So the impact of requiring more spectrum due to losing the LTE-A hotspots largely cancels out the impact of being able to offload more low mobility traffic onto the smaller cell layer due to the reduced percentage of high mobility traffic.

Arguably taking account of the results across all our sensitivity analysis scenarios our baseline model settings should be adjusted to allow for:

- Percentages of high mobility traffic in suburban and rural areas more in line with forecasts of indoor to outdoor traffic levels
- A more pessimistic future for LTE-A hotspots

However, the results from this last set of scenarios show that the combined impact of these leaves the spectrum estimates presented in section 2 largely unchanged provided small cell uptake levels are enough to accommodate all low mobility traffic in the suburban environments which largely drive overall spectrum requirements.

## 4.8 Sensitivity to assumptions whether the application rate within the ITU-R M.1768-1 model should be based on maximum, average or cell edge data rates

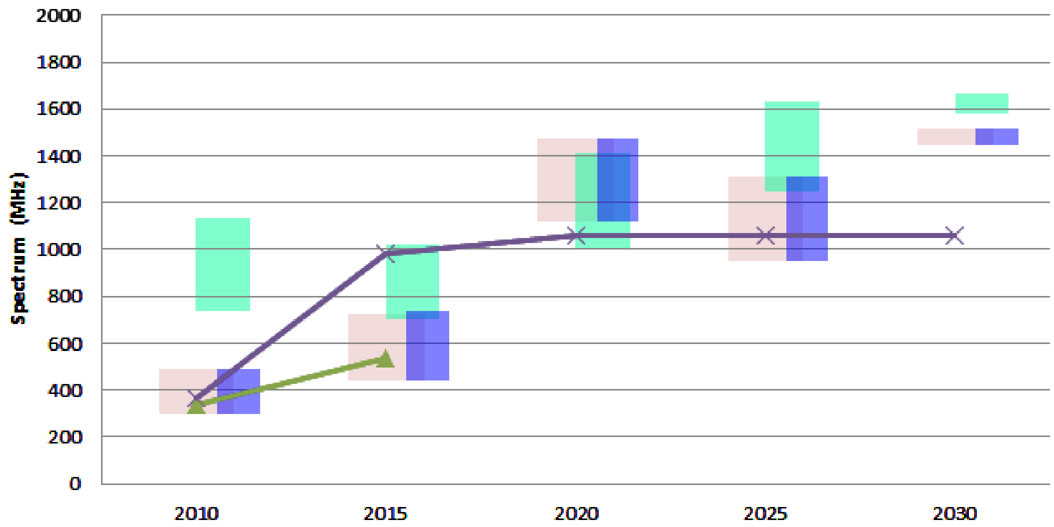
Table 13 highlights the scenarios investigated to understand the impact of assumptions on application rates on spectrum requirements where L is low, M is medium, H is high and RW is the Real Wireless baseline ITU-R M.1768-1 model input settings.

Results are compared in Figure 58 showing that generally as the supported application rate increases the spectrum requirement also increases as more demanding SCs can be supported by more RATGs. These more demanding SCs have, however, stricter service requirements which create more overhead in the queuing theory block of the model and hence drive higher spectrum requirements.

| Scenario | Mobile demand total | % licensed targeted demand offloaded to Wi-Fi | Model tech parameters | Small cells |
|---|---|---|---|---|
| Baseline for licensed | M | M | RW | M |
| Impact of application rate assumptions (ITU default) | M | M | RW but ITU application rates | M |
| Impact of application rate assumptions (average data rates) | M | M | RW but application rates revised to average data rates | M |

**Table 13: Scenarios investigated for the lower limit on spectrum estimates**

In 2020 this trend is not followed and the spectrum requirements with the higher ITU application rates produces a lower spectrum requirement compared to our baseline model settings and our sensitivity case using average data rates. This is because in 2020 particularly high application rates are applied to hotspots and picocells in the ITU default settings. This means that these smaller cells with very high spectral efficiencies attract the traffic of the more demanding SCs and deliver these more efficiently than in the other scenarios where the overall traffic level remains the same but the distribution of traffic across SCs is more equally spread across cell types and hence delivered less efficiently. This shows that the most efficient way to meet demand across a range of SCs is to target more demanding services towards small cells and keep the macrocell layer for coverage and basic SCs. This supports the approach taken to application rates in our baseline model settings.




| | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| Base line | Shared | 295 | 440 | 1120 | 950 | 1445 |
| | Dedicated | 490 | 720 | 1475 | 1315 | 1515 |
| ITU rates | Shared | 735 | 705 | 1010 | 1250 | 1580 |
| | Dedicated | 1135 | 1020 | 1410 | 1630 | 1665 |
| All average | Shared | 295 | 440 | 1120 | 950 | 1445 |
| | Dedicated | 490 | 735 | 1475 | 1315 | 1520 |

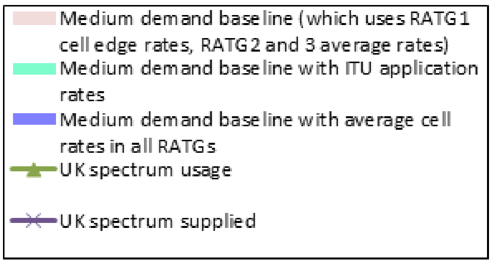
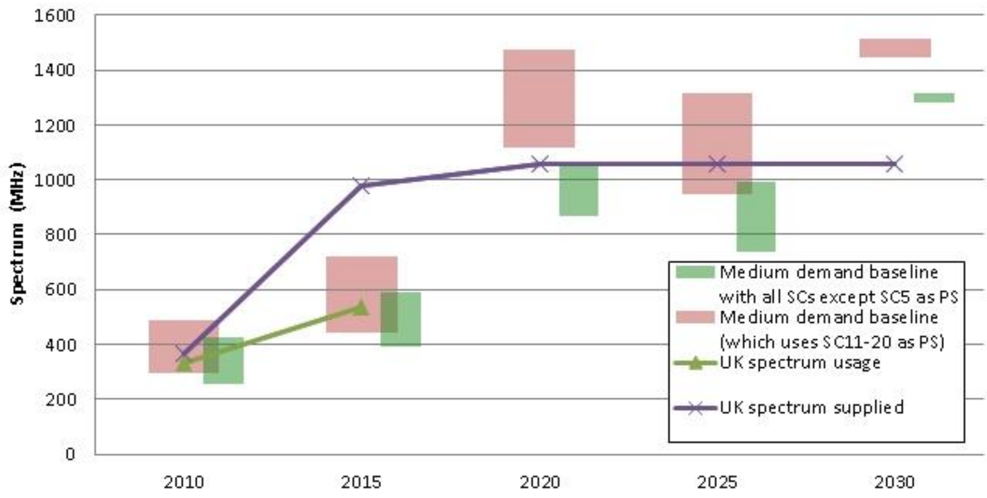



**Figure 58: Licensed spectrum estimate (MHz) for varying application rate assumptions (dedicated spectrum estimate at upper end of bars and shared spectrum estimate at lower end of the bars)**

## 4.9 Sensitivity to packet switched vs. circuit switched assumptions across SCs

As indicated in appendix D which provides our critique of services related parameters within the ITU-R M.1768-1 model, in our baseline model settings we have maintained the ITU recommended assumption that all conversational and streaming services are CS. However, in Figure 59 we compare spectrum estimates if this assumption is revised and SC1-4 (most conversational service categories) and SC6-10 (all streaming service categories) are assumed to be PS services rather than CS services and use the mean packet sizes, second moment of packet sizes and mean tolerable IP packet delay values for these SCs that we recommend in appendix D. This shows that changing these SCs to PS services reduces spectrum estimates to the extent that existing planned releases of spectrum in the UK could be enough to serve our medium demand case out to 2025 with further bands not needing to be identified beyond this until 2030.




| Spectrum (MHz) | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| **Base line** | **Shared** | 295 | 440 | 1120 | 950 | 1445 |
| | **Dedicated** | 490 | 720 | 1475 | 1315 | 1515 |
| **All PS but SC5** | **Shared** | 255 | 390 | 870 | 740 | 1280 |
| | **Dedicated** | 425 | 590 | 1050 | 995 | 1315 |

**Figure 59: Comparison of assuming PS vs. CS for conversational and streaming SCs**

In appendix D we note that our review of suitable PS parameters including the mean packet sizes, second moment of packet sizes and mean tolerable IP packet delay values across SCs have been limited due to the timescales of this study. In particular we have selected second moment of packet size values that maintain ITU recommended values for standard errors in packet size but have noted that in some cases this can lead to negative packet sizes and so requires a more detailed review than has been possible in the timescales of this study. However, this sensitivity analysis case highlights the importance of assumptions on whether SCs are delivered via PS or CS networks and suggests that this more detailed review would be worth pursuing.

# 5. Conclusions and Recommendations

This chapter summarises our key findings from this study and recommendations to Ofcom for further investigations which would enhance the spectrum estimates presented and overcome some of the limitations of the ITU-R M.1768-1 model.

## 5.1 Our licensed spectrum requirement estimates for our medium and high demand forecasts predict pressure on mobile broadband licensed spectrum from 2020 onwards

In summary our licensed spectrum estimates indicate that:

- By 2020 currently awarded and planned awards of mobile broadband spectrum in the UK may not be sufficient to keep pace with demand if our medium and high estimates of UK mobile broadband demand and baseline model settings are realised in practice.
- Only if UK mobile broadband demand follows our low demand forecasts and baseline model settings will the current planned level of UK spectrum awards be potentially enough to keep pace with increases in demand out to 2030.
- In the high demand case mobile broadband spectrum requirements up to and including 2015 are commensurate with current UK spectrum availability and future release plans but rely on all awarded spectrum becoming fully utilised. Given that this includes a number of TDD bands and UK cellular networks are currently deployed around FDD networks it may be challenging to realise this higher utilisation in practice.
- The difference between our medium and high forecasts UK mobile broadband demand being realised in practice can cause as much as a doubling in spectrum requirements.

These results are based on our baseline model settings also being realised which include our assumptions on medium Wi-Fi offload and small cell uptake levels.

We have performed a sensitivity analysis to determine the impact of changing input assumptions in our baseline model settings on the above headline conclusions. This has shown that:

- Assumptions on the percentage of high mobility traffic in suburban and rural areas are crucial to overall spectrum requirements. This is because this high mobility traffic must be carried on macrocells due to the limited ability of small cells to support handover for high velocity users. As macrocells have a lower spectral efficiency than all other network layers the spectrum requirements of these high mobility users become the largest contribution towards overall spectrum requirements across network layers and environments. The assumed percentage of high mobility traffic in suburban and rural areas in the ITU recommended values, which we maintain in our baseline settings are high compared to current sources on the split between indoor and outdoor traffic levels. Reducing the percentage of high mobility traffic in suburban and rural environments to a maximum of 10% in line with these sources has the impact of reducing spectrum requirements by as much as 28%.

- The impact of small cell uptake on spectrum requirements is linked to the availability of LTE-A hotspots. Within our spectrum estimates we have followed the ITU's assumption that LTE-A hotspot devices (which we assume to be short range access points operating at high frequencies and wide bandwidths) will be available to provide a very high spectral efficiency density layer to LTE-A networks in capacity constrained areas. In the case where LTE-A hotspots are available in our baseline model settings and for our low, medium and high demand estimates the uptake of other small cell types such as microcells and picocells does not have a large impact on overall spectrum requirements. This is because all low mobility traffic is easily accommodated across microcells, picocells and hotspots due to the very high spectral efficiency densities of LTE-A hotspots. However, if LTE-A hotspots are not deployed this needs to be compensated for by a higher uptake of other small cell types (microcells and picocells) so that the overall capacity across the small cell layers is still commensurate with our baseline model settings. In practice the balance between the deployment of LTE-A hotspots and the uptake of other small cell types such as picocells and microcells will be an operator decision and overall spectrum requirements remain driven by high mobility user spectrum requirements on macrocells and as such insensitive to small cell uptake provided the small cell layers provide a capacity level commensurate to our baseline model settings. Increasing small cell uptake beyond this point does not decrease overall spectrum requirements.
- Wi-Fi offload levels, when applied equally across all users types, have a large impact on overall spectrum requirements. However, we note that overall spectrum requirements are largely driven by the requirements of high mobility users who will have a limited opportunity to offload to Wi-Fi in practice and hence should be subject to lower Wi-Fi offload levels. A limitation of the ITU-R M.1768-1 model is that it does not allow Wi-Fi offload levels to vary across different service types and hence the results of our sensitivity analysis around Wi-Fi offload are likely to exaggerate the impact of Wi-Fi offload.
- Assumptions on whether a SC should be delivered via a packet switched (PS) or circuit switched (CS) network can have a significant impact on spectrum estimates and potentially delay additional requirements for spectrum releases until 2030 (under of medium demand case investigated). In our sensitivity analysis we have examined the impact of modifying the ITU recommended assumption that all streaming and conversational services are delivered via circuit switched mechanisms to only very low rate voice services being delivered over CS networks. This reduces spectrum estimates for our medium demand case by up to approximately 20% and can potentially delay further requirements for further spectrum releases until 2030. We therefore recommend that the ITU assumptions in this area are revisited.

Overall, our sensitivity analysis indicates that arguably a lower percentage of high mobility traffic and a more pessimistic view on LTE-A hotspots should be applied to our baseline model settings. However, exploring the combined effect of these we find that these two changes largely cancel each other in terms of impact on spectrum requirements and lead back to spectrum estimates aligned with our baseline model settings. Our investigation of sensitivity to application rate assumptions also supports the choices made in our baseline model settings.

## 5.2 Our spectrum estimates are based on baseline model settings which challenge ITU recommended model settings

In the course of this project we have reviewed all inputs to the ITU-R M.1768-1 model. Our starting point for model settings has been the input values recommended by ITU-R working party 5D in their work in progress response to JTG 4-5-6-7 in response to WRC-15 agenda item 1.1. However, we have recommended updates to these ITU recommended model settings in our analysis to bring these up to date with current mobile broadband service requirements, in line with practical mobile broadband network capabilities and in line with UK mobile broadband network deployments. The main areas where we have suggested revisions which are likely to have the biggest impact on overall spectrum requirements are:

- Maximum allowable mean IP packet delay
- Mean IP packet size
- Application rates
- Spectrum efficiency
- Coverage levels

## 5.3 Summary of conclusions against JTG 4-5-6-7 requirements

In line with JTG 4-5-6-7 requests we have examined spectrum requirements in terms of:

- Coverage
- Capacity
- Performance
- High and low market conditions (already discussed in section 5.1)
- Asymmetry in demand and potential implications for spectrum requirements

We note that the spectrum requirements for coverage, capacity and performance are not independently generated by the ITU-R M.1768-1 model and instead these requirements are intertwined in the overall spectrum estimates generated by the model. For example, although the model generates spectrum estimates based on demand densities and hence capacity requirements these are based on initially achieving a baseline coverage level at given performance levels for each service category determined by the model input settings and then increasing this spectrum estimate for higher user densities in line with the capacity requirements of each service category.

Given that the ITU-R M.1768-1 model has been developed to target spectrum requirements for capacity our results indicate for this area that:

- The driver for overall spectrum requirements has moved from intensive dense urban scenarios with the highest overall demand densities to suburban environments where the capacity requirements of mobile users, who must be served on macrocells due to handover limitations on smaller cell types, drive overall spectrum requirements.
- While dense urban areas are traditionally the areas where capacity requirements and hence spectrum requirements are highest this is no longer likely to be the case due to the intensive use of small cells alongside already dense deployments of macrocells in these dense urban areas. This means that these high demand

densities in dense urban areas will be served with relatively high spectral efficiency densities and so spectrum requirements will not necessarily be the highest across all environments.

- The intensive use of small cells in dense urban deployments is worth noting in terms of spectrum requirements for capacity as these rely on relatively high coverage levels across macrocells, microcells and picocells in the near future. As small cells increase in density this may lead to an added requirement in these areas for a small cell spectrum layer to meet capacity and performance requirements of networks and drive spectrum requirements more towards our dedicated rather than shared spectrum estimates.

The ITU-R M.1768-1 model takes account of user experience expectations and hence required network performance levels to meet these via the service and market related parameters for each SC and SE combination within the model. Parameters within this such as mean service bit rates and maximum tolerable packet delays can be interpreted as setting a performance benchmark that spectrum requirements are calculated against. Therefore the findings above related to capacity requirements can also be interpreted as the spectrum requirements to meet the performance levels specified by our model inputs for each SC which we have reviewed and selected to be representative of applications within these SCs today and out to 2030.

In terms of coverage requirements we note that contributions to ITU working party 5D have suggested that rural macrocell spectrum requirements estimated by the ITU-R M.1768-1 model may be representative of spectrum for coverage requirements. However, we note that this may not be representative of coverage spectrum requirements in practice due to:

- Spectrum for coverage requirements being driven by local site locations, terrain and carrier frequency limitations whereas the ITU-R M.1768-1 model determines spectrum requirements based on average demand and capacity densities.
- Capturing spectrum requirements for macrocells alone not taking into account the use of small cells such as femtocells to address coverage black spots which may require their own dedicated carrier.
- The ITU-R M.1768-1 model giving no indication of spectrum requirements by frequency range whereas for coverage requirements a knowledge of the amount of sub 1GHz spectrum required will be crucial.
- The ITU-R M.1768-1 model generating spectrum estimates per RATG but in practice coverage will need to be provided for multiple air interfaces within each RATG to support legacy terminals.
- The spectrum calculated by the ITU model being driven by average demand levels across SEs. However, in practice in rural areas peak demand levels will likely occur around villages where carriers at higher frequency bands could be used alongside lower frequency carriers to boost capacity in these localised demand peaks.

Overall we conclude that the ITU-R M.1768-1 is not a suitable platform to assess spectrum requirements for coverage and that a more detailed coverage analysis is instead needed.

In terms of asymmetry of uplink and downlink demand our analysis shows that:

- The ratio of downlink to uplink demand varies by SE, due to the selection of services used in each environment, and over time it can range from 8 to 0.7 when following the ITU recommended distribution of traffic across SCs and SEs and calibrating against our own UK specific uplink and downlink demand estimates.

- Translating uplink and downlink demand in to uplink and downlink spectrum requirements for RATG1 and RATG2 shows that using FDD spectrum assignments instead of more efficient TDD spectrum assignments (without allowances for guard bands) could lead to as much as a 50% overhead in spectrum requirements.
- The environments where downlink traffic is anticipated to be at least double that of uplink traffic were identified as SE2 dense urban office users, SE5 suburban office and public area users and SE6 rural users , within the model structure and baseline input settings. SE6, being a rural environment, is unlikely to drive spectrum requirements on the basis of capacity and so the choice between FDD and TDD spectrum is less critical here. However, significant demand levels could be seen in dense urban and suburban office environments and there may be a case for considering a TDD indoor small cell channel that could potentially be shared across operators to make more efficient usage of spectrum in these environments.
- While we assume different downlink to uplink traffic ratios across device types in our demand analysis and the mixture of device types vary in the device population over time this only appears to generate a slight downward trend in overall downlink to uplink demand ratios and hence spectrum requirement ratios out to 2030 which is not significant.

## 5.4 LE spectrum requirements results indicate that the 5GHz band will ease immediate congestion for LE hotspot spectrum but further releases need to be planned for

Our analysis of LE spectrum requirements has investigated the impact of:

- LE demand levels
- Practical deployment limitations of LE technologies

Of these we have found that LE spectrum requirements are heavily driven by the practicalities of deploying LE systems and ensuring good frequency reuse rather than the demand density directly. For example in 2020 the spectrum requirements for LE hotspots in the medium and very high demand cases examined with the practicalities on bandwidth and frequency reuse applied are commensurate. However, prior to applying these adjustments the very high demand case required approximately twice as much spectrum as the medium demand case.

We have examined LE spectrum estimates across short range hotspots and longer range picocells.

Overall our LE spectrum estimates for short range hotspots have shown that:

- Of the home, office and public area environments considered the requirements of the home environment drive LE hotspot requirements due to the high usage of demanding video services such as Smart TV and home multimedia systems. This is despite being at lower user densities compared to busy public areas such as transport hubs.

- Existing allocations at 5GHz will ease immediate congestion in the 2.4GHz band out to 2020 based on results across our low, medium and very high demand scenarios.
- From 2020 onwards there is a strong case for the extension of the 5GHz band as proposed for WRC-15 based on results across our low, medium and very high demand scenarios.
- In the case of our very high demand scenario is it likely that further LE hotspot spectrum allocations beyond the extension of the 5GHz band as proposed for WRC-15 will be needed by 2030.

We note that spectrum requirements for wider range LE picocells, while much less than those of LE hotspots, could become significant (between 125MHz and 165MHz in the timescales of this study for very high user density scenarios such as those found in busy transport hubs) and much higher than the amounts of TVWS spectrum identified for these types of cells in dense urban and suburban areas in the UK so far. Also it should be noted that the extension of the 5GHz band under current LE conditions will not address requirements for these longer range LE picocells and hence new bands will need to be identified for these that are either at lower frequencies or allow higher transmit power levels to accommodate these longer range access points.

## 5.5 Limitations of the ITU-R M.1768-1 model and recommendations for further investigation

This study aims to produce mobile broadband spectrum requirement estimates to support Ofcom's contribution to the ITU working party 5D response to JTG 4-5-6-7 in preparation for agenda item 1.1 at WRC-15. The spectrum estimates produced within this study therefore need to support the ITU process and as such be based around the ITU-R M.1768-1 spectrum requirements model.

However, as noted in section 2.1, there are apparent deficiencies which are important to note in the current ITU-R M.1768-1 model. We have sought wherever possible to address these via appropriate choice of inputs and via modifications to the model as summarised in Table 14. However, despite these mitigating steps to produce the most credible spectrum estimates possible these apparent limitations in the ITU model should still be noted when interpreting our results.

| Description of limitation | Mitigating action taken in this study | Recommended next steps |
|---|---|---|
| The modelled sector areas across cell types does not vary with:<br><br>• Frequency band<br>• Technology or RATG[18] | Included sector sizes based on deployments of UK cellular sites today which will represent the mix of spectrum available in the UK today. While this means that results are more representative of UK networks, this sector size could still vary over time with the introduction of other | Further expand the ITU model to allow sector sizes to vary over time to represent changing spectrum allocations and site numbers and also to vary by RATG. |

[18] Noting that for different RATGs supporting different coding and modulation combinations, levels of MIMO etc. there will be a different signal to noise requirement to meet the same target cell edge performance level and hence cell sizes could be different.

| Description of limitation | Mitigating action taken in this study | Recommended next steps |
|---|---|---|
| | frequency bands and more sites. Therefore this does not entirely address the model deficiency of sector sizes not varying with frequency band or RATG. | |
| Spectrum requirements across frequency bands are not reported by the model | None feasible in the study timescales | Reviewing other coverage focused studies such as our 800MHz coverage obligation study for Ofcom [11] against the results of this study to draw conclusions on sub 1GHz spectrum requirements |
| Coverage percentages assumed do not vary with radio access technology group (RATG) | None feasible in the study timescales | Expand model to vary coverage levels by RATG so that lower coverage levels for less mature RATGs can be considered and their introduction more accurately represented over time. |
| Results are limited to spectrum requirements across RATGs as a whole rather than specific networks. | None feasible in the study timescales | Further develop the ITU-R M.1768-1 model to represent all cellular air interfaces active in the UK i.e. GSM, UMTS, LTE individually rather than collectively under RATG1. |
| Application rates, which describe the supported service levels in particular cell types and RATGs, do not vary with environment. | None feasible in the study timescales | Further develop ITU-R M.1768-1 model to allow application rates to vary by service environment. |
| The relative extent and density of the different layers of the network (macrocells relative to small cells) are inputs to the model rather than an outcome of determining the most efficient network topology. | None feasible in the study timescales | Re-examine spectrum requirements using a model such as the one used in our UHF strategy study for Ofcom [5] which includes deploying cell types in the most efficient manner to meet growing capacity requirements over time. |
| The model does not consider the fine-grained local spatial and temporal structure of the demand, which can significantly impact the required peak network capacity density. | In the case of LE spectrum estimates we calibrate the user densities in each SE in line with our demand density estimates for each SE which represents quite localised demand levels. The queuing theory block in model also allows some overhead for demand peaks. | Update the ITU-R M.1768-1 model to calibrate user densities driving demand densities on a per service and environment basis as used in our LE spectrum analysis rather than on a per teledensity basis as used in our licensed spectrum analysis. Also consider traffic peaks as in our UHF strategy study for Ofcom [5]. |

| Description of limitation | Mitigating action taken in this study | Recommended next steps |
|---|---|---|
| The model in its unmodified form does not compute the requirements for licence-exempt spectrum. | We have updated the model to include RATG3 spectrum requirements but note that the ITU model is generally not well suited to the highly localised demand levels of LE hotspots. | Developing a different approach to LE spectrum estimates which examines spectrum requirements and the practical limitations of meeting these in highly localised scenarios such as an apartment block. |
| The model does not facilitate considering different levels of Wi-Fi offload to different user types and SEs | None feasible in the study timescales | Update the ITU-R M.1768-1 model so that the impact of different assumed Wi-Fi offload levels across SEs and user types can be investigated. In particular the impact of a limited offload opportunity for high mobility users on overall spectrum estimates should be investigated. |
| The demand levels input to the model through market settings are not necessarily all distributed and contributing to spectrum requirements in the model. | We address the deficiency of undistributed traffic in the model by calibrating our UK specific demand densities per teledensity against the demand densities in the model once distributed across RATGs and cell types to ensure that all demand in our forecasts is included in spectrum estimates. | Further analyse demand inputs and the distribution of traffic in the model and refine this so that no demand is generated without a cell type and RATG combination being available to serve it. |
| Deployment cost is not considered in the model even though there is a fundamental link between the demand generated in a network and whether it is economical for an operator to provide high end services which drive demand up. | When selecting model input settings we have drawn heavily on our UHF strategy study which examined the most economical capacity enhancements options for operators in given demand and spectrum supply scenarios. | Examin how a more economics based model such as the one used in our UHF strategy study for Ofcom [5] could be used to understand spectrum estimates with network costs kept in mind. |
| The setting for whether a service category is circuit switched or packet switched does not vary with time in the model. This means services cannot migrate to being packet switched rather than circuit switched over time in line with expected cellular network evolutions. We also note that the ITU recommended values assume all conversational | We have carried out a sensitivity analysis to determine the importance of assumptions on whether SCs are PS or CS. This has shown that this can have a significant impact on spectrum estimates and potentially delay the date for additional spectrum requirements until 2030 as opposed to 2020 for our medium demand case. | Update ITU-R M.1768-1 model to allow CS and PS assumptions to vary over time and across RATGs, review more fully the appropriateness of assuming PS delivery mechanisms for all SCs and appropriate PS service related parameters for these and whether the overheads for PS mechanisms in the model currently are |

| Description of limitation | Mitigating action taken in this study | Recommended next steps |
|---|---|---|
| and streaming services are delivered via circuit switched networks which may not be a true reflection of today's cellular networks. | | appropriate for guaranteed bit rate services. |

**Table 14: Summary of model limitations, mitigating actions taken in this study and recommended next steps to address these limitations**

Additionally there were areas not included in our sensitivity analysis but identified within our study as having a potential impact on results which could be investigated further as follows:

- Investigating the practical performance and impact on spectral efficiencies of small cells in different shared spectrum arrangements.
- The impact on different assumptions on requirements for fixed amounts of bandwidth to be maintained to support legacy networks and devices over time.
- Considering the impact of licencing models which are intermediate between conventional licensed and licence-exempt approaches, such as licensed shared access (LSA).
- Investigating increasing rather than decreasing mean session duration over time
- Investigating the impact of assuming packet fragmentation for cellular networks and hence assuming minimum rather than mid to max packet sizes in service parameters.
- Investigating the packet size distribution for the applications in the ITU SCs further to determine more robust standard error and second moment of packet size values that do not lead to negative packet sizes as is the case with the ITU recommended standard error values. We also suggest reviewing applying PS settings to more SCs than in the ITU recommended model settings as this could have a significant impact on spectrum estimates and potentially delay additional spectrum requirements until 2030.

# Abbreviations

| | |
|---|---|
| CFI | Call for Inputs |
| CoMP | Co-ordinated Multi-Point |
| CS | Circuit Switched |
| DL | Downlink |
| DTT | Digital Terrestrial Television |
| eMBMS | Evolved Multimedia Broadcast Multicast Service |
| IMT | International Mobile Telecommunications |
| ITU-R | International Telecommunications Union Radiocommunications |
| LE | Licence exempt |
| LOS | Line of Sight |
| LTE | Long Term Evolution |
| LTE-A | Long Term Evolution Advanced |
| LSPD | Large Screen Portable Devices |
| MIMO | Multiple Input Multiple Output |
| MNO | Mobile Network Operator |
| PS | Packet Switched |
| PTP | Peer to Peer |
| RATG | Radio Access Technology Group |
| SC | Service Category |
| SE | Service Environment |
| UE | User Equipment |
| UL | Uplink |
| UMTS | Universally Mobile Telecommunications System |
| VoLTE | Voice over LTE |

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