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Examining the current assignment and usage of mobile spectrum

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About Plum

Plum offers strategy, policy and regulatory advice on telecoms, spectrum, online and audio-visual media issues. We draw on economics and engineering, our knowledge of the sector and our clients' understanding and perspective to shape and respond to convergence.

About this study

This study for the Global Satellite Operators Association (GSOA) examines the current allocations and assignment of spectrum to mobile services across the world. It looks first at allocation – how is spectrum provided to the industry at an international level – before considering how these designated bands are being assigned and used by mobile network operators.

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Summary

Ever since the introduction of mobile telephony in the 1980s, and particularly with the lower cost and increased availability provided by 2G in the early 1990s, usage of these services has increased at a very rapid rate, both in terms of the number of users and the demand for connectivity per user. New services, such as picture messaging, Internet access, and app store access, have all led to demand from consumers for higher quality connections and greater capacity. To meet this increased demand, new technologies have been developed to increase service capabilities, improve spectrum efficiency, and reduce costs. At the same time, the mobile sector has had large and increasing spectrum allocations identified at World Radio Conferences (WRCs). In this paper we have investigated the extent to which these allocations are being used.

Spectrum identified to IMT

Identifying exactly how much spectrum can be used by mobile is made complex due to differences between International Telecommunication Union (ITU) regions, changes in technology, and the suitability of spectrum for the deployment of mobile networks. However, the ITU has, at a number of WRCs, identified specific bands for International Mobile Telecommunications (IMT), with the expectation that mobile networks will be able to make use of spectrum within these bands. This provides a maximum amount of spectrum which mobile network operators should expect to be able to access.

Figure 1.1: Total spectrum identified for IMT globally (below 7 GHz)

Frequencies	Bandwidth (MHz)	Notes
450 – 470 MHz	20	Often assigned as FDD with 2×7.5 MHz bandwidth
470 – 608 MHz	138	Lower portion of this is sometimes used for television broadcasting so is subject to footnotes and exemptions. Generally only used outside Region 1.
608 – 614 MHz	6	This is generally used for radio astronomy and medical equipment but is identified for IMT and used in select countries in Asia Pacific.
614 – 698 MHz	84	Generally used for IMT in Region 2.
694 – 960 MHz	266	Note overlap with 698 MHz above. 700 MHz was harmonised at WRC-15.
1427 – 1518 MHz	91	Identified for supplementary downlink (SDL).
1710 – 2025 MHz	315	Variety of band configurations available, including AWS in Region 2.
2110 – 2200 MHz	90	Often used alongside spectrum in 1900 MHz to provide paired bandwidth
2300 – 2400 MHz	100	Usually assigned as TDD spectrum.
2500 – 2690 MHz	190	
3300 – 3400 MHz	100	Identified to add to 3400 MHz bands, but limited take-up as used for radiolocation in many countries. Only identified on a secondary basis in Region 2.
3400 – 3600 MHz	200	Core C-band frequencies for 5G.
3600 – 3700 MHz	100	
4800 – 4990 MHz	190	
Total	**1886**	**Removing 4 MHz from the total to account for overlap at 694 – 698 MHz.**

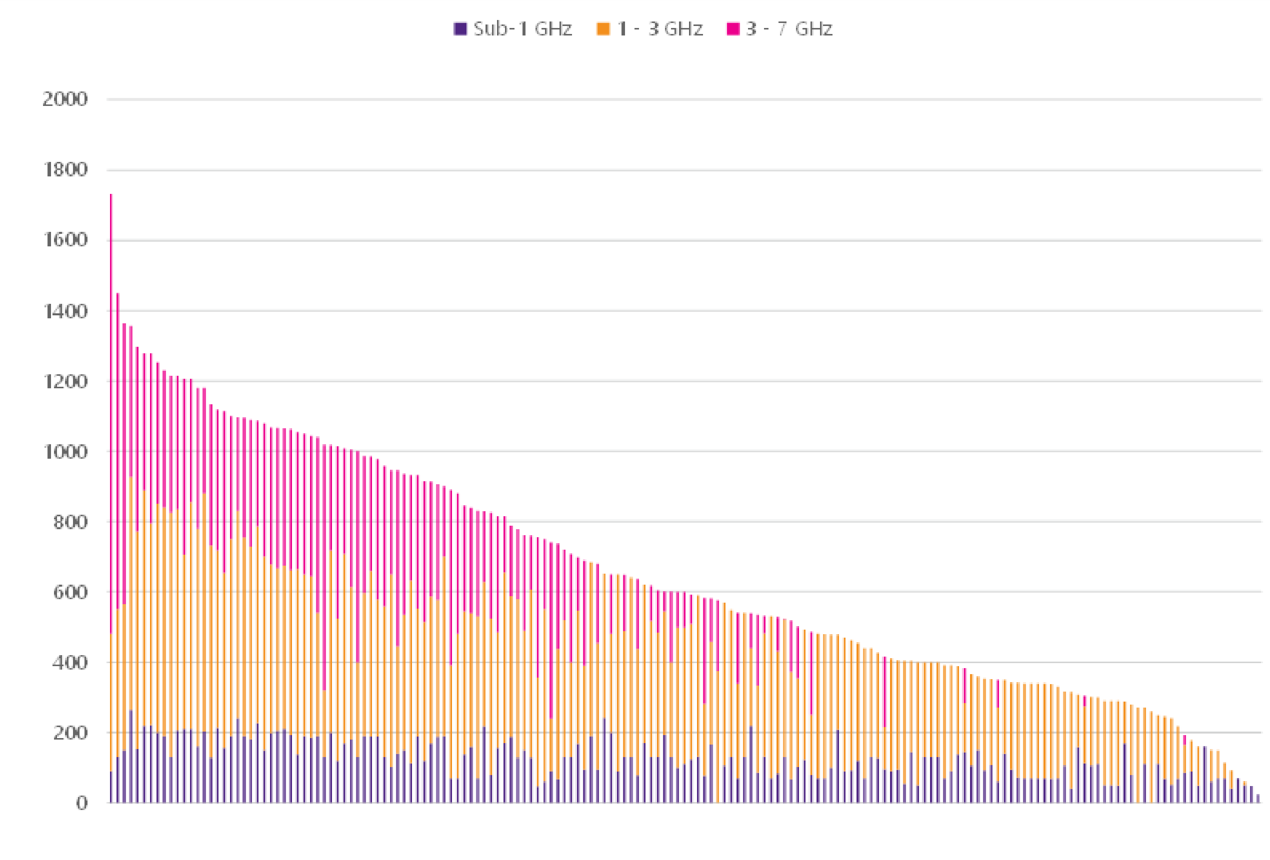
As well as the spectrum listed above, the mmWave frequencies (at 24.25-27.5 GHz, 37-43.5 GHz, 45.5-47 GHz, 47.2-48.2 GHz, and 66-71 GHz) were identified at WRC-19, and add an additional 17.25 GHz of bandwidth to the total available for IMT. These have been requested to add high-speed, low latency services, and are not necessarily direct substitutes for spectrum below 7 GHz. However, the availability of this spectrum for future services should not be ignored.

Outside of these identified bands, there are existing assignments of spectrum for public mobile network operators in the 4 GHz, 6 GHz and 7 GHz bands in individual countries. There are further allocations at sub-regional levels; for example, South Africa has awarded significant spectrum holdings in the 2000 MHz range, which is also awarded by China. Even if assuming that 6 GHz and 7 GHz bands are not useful given current ecosystem availability, it is clear, from the above table, that there is almost 2 GHz of spectrum which is harmonised and allocated to mobile broadband[1], in addition to the spectrum available in mmWave frequencies.

Spectrum assigned to mobile operators below 7 GHz

This total spectrum allocation can be compared against the current assignments and awards to operators. The figure below illustrates the total spectrum assigned in three frequency range categories for each country for which information was available (approximately 160 observations). There is a very wide diversity of spectrum assignments, with the least developed countries tending to be (but not restricted to) the right side of this chart, and assignments for spectrum above 3 GHz tending to be in countries with the most spectrum in other bands.

Figure 2: Current spectrum assignments (MHz)[2]



[1] This accords with a statement from the ITU, which states that there was 1.9 GHz of spectrum allocated to mobile, before the mmWave allocations and other smaller allocations at WRC-19. See https://www.itu.int/hub/2020/01/wrc-19-identifies-additional-frequency-bands-for-5g/

[2] Each bar represents one country. Note that countries are not listed on the x-axis, full results can be found in Appendix B.

The relative newness of spectrum in the 3500 MHz bands is reflected in the fact that many countries have not progressed to these assignments yet. There is generally a relatively constant ratio of sub-1 GHz and 1-3 GHz spectrum assignments, other than in countries with the lowest spectrum availability.

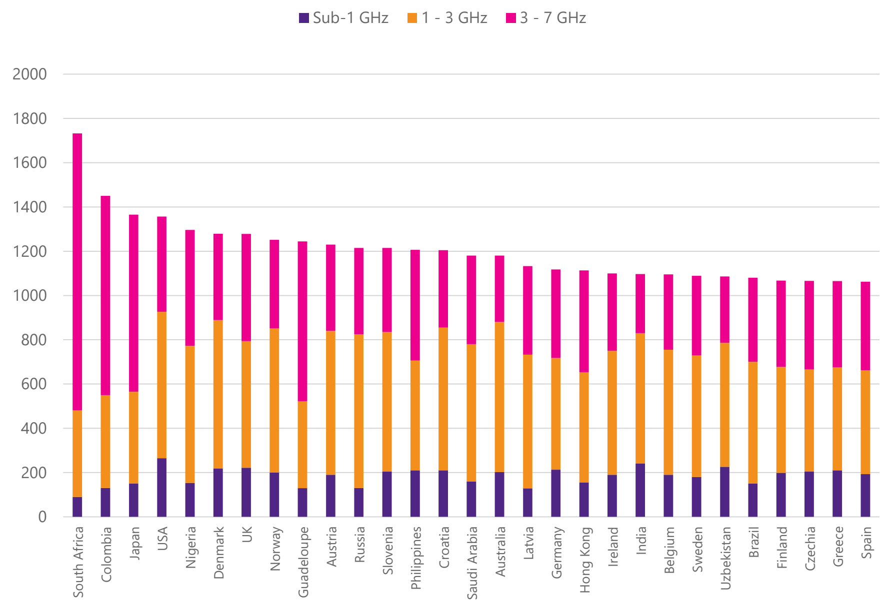
No country has assigned all spectrum allocated to mobile services. As shown above, there is almost 2 GHz of spectrum currently identified for IMT below 7 GHz, but the highest assignment, in South Africa, is only 1732.4 MHz – and this outlier is caused by large assignments in the 2000 MHz, 4900 MHz and 6 GHz bands (which are not assigned by any other country, and indeed in some cases lie outside the spectrum bands which are globally identified for IMT). Although in practice there is less than 2 GHz of spectrum available due to differences in allocations for ITU regions and some spectrum identified via footnotes for a limited number of countries, the total assignments for all countries fall short of the possible maximum.

There are various reasons for spectrum not being allocated, including:

- Lack of demand from operators;
- Lack of regulatory expertise;
- Legacy services being unable to clear bands;
- Uncertainty over future band use; and
- Legal challenges to award mechanisms.

It is useful to consider those countries who have assigned the most spectrum to mobile broadband, as these will be those countries where additional identified spectrum is most in demand.

Figure 3: Current spectrum assignments: countries with the most spectrum assigned



Investigation into consultations in some of these countries indicates there is a common theme that regulators recognise a fast-growing demand for data from mobile operators, and are looking to accommodate this for the benefit of consumers. However, regulators in some countries are looking to support developments in ways other than simply awarding additional spectrum. For example, in December 2022, Ofcom stated[3]:

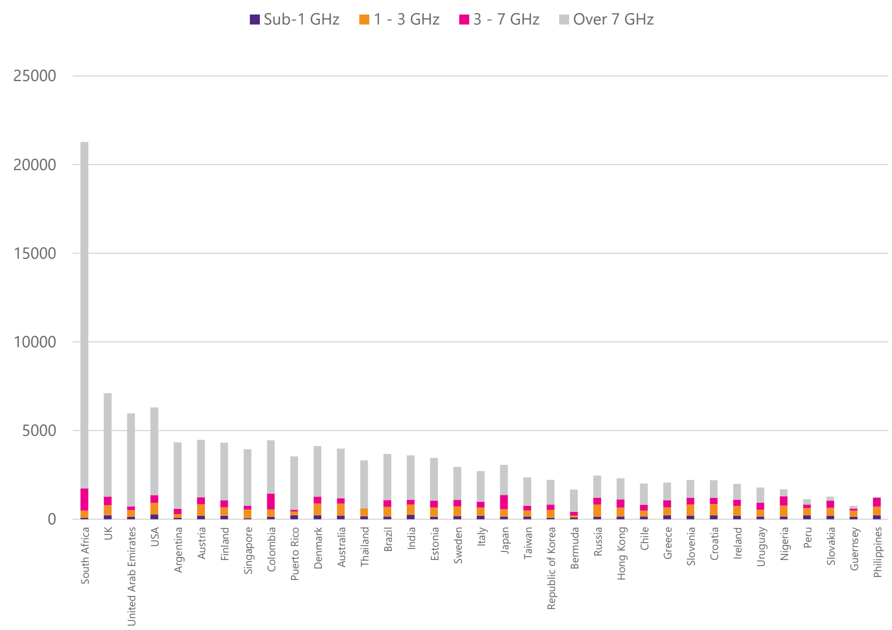
> **“[W]e expect technology upgrades and densification, including the use of mmWave and small cells, to play an important role in enabling MNOs to meet future demand for mobile data, both up to 2030 and beyond, as well as creating the potential for innovation; and we will consider where and when additional spectrum may be needed and will take other competing uses into account in our future spectrum management decisions. We are currently evaluating the best use of the upper 6 GHz band, and favour a ‘no change’ outcome […] at WRC-23.”**

In all countries, it appears that there is some spectrum, identified by the ITU, which has not yet been awarded or assigned to operators. Even in countries which are well advanced in spectrum assignment, there is still further work that can be done in ensuring that mobile operators have access to the spectrum that has been allocated to them. In order to meet the demands of consumers, this should be a focus for regulators.

Spectrum assigned to mobile operators in mmWave frequencies

This lack of assignment is even more pronounced when looking at spectrum above 7 GHz, particularly in the mmWave bands. Only 35 countries in our analysis have assigned spectrum above 7 GHz[4], and there is a wide variety of types of assignment. There are several assignments in the 26 GHz band, particularly in Regions 1 and 3, and a few assignments in the 28 GHz band[5], such as in Japan, Singapore, Taiwan, and the US.

Figure 4: Current spectrum assignments: countries with the most spectrum assigned above 7 GHz



Although the lack of assignment at 6 GHz and 7 GHz is almost certainly due to a lack of international harmonisation and agreement, the fact that interest around these bands is so limited does indicate that regulators are not convinced that there is a heavy demand for additional spectrum. This is reinforced by the low

[3] See https://www.ofcom.org.uk/__data/assets/pdf_file/0036/248769/conclusions-mobile-spectrum-demand-and-markets.pdf

[4] Other than a few legacy awards in bands such as 10 GHz, these awards are generally significantly higher than 7 GHz (above 24 GHz), to allow for large contiguous bandwidths.

[5] It should be noted that there is no IMT identification between 27.5 GHz and 37.0 GHz, meaning that these assignments at 28 GHz are not in line with WRC outcomes.

number of 26 GHz assignments, which would be expected to be more prevalent if regulators recognised demand for large bandwidth spectrum[6].

Spectrum used by mobile networks

Finally, it is unclear from public information how much of the spectrum assigned for mobile broadband is actually used by mobile networks. There is some circumstantial evidence that not all spectrum is used in all regions it is available, and further we note that there have been some occasions where spectrum has been returned to regulators or operators have decided against taking part in award processes. This all indicates that there is not necessarily a large demand for additional mobile spectrum bands.

Conclusions

This paper notes that there is a significant amount of spectrum that has been identified for use by IMT, both below 7 GHz and in the mmWave bands. Of this, no country has assigned all available spectrum to mobile networks, with the majority providing less than half of identified spectrum. Future growth in demand for mobile services is uncertain, but the current low uptake of mmWave spectrum indicates that there is scope for growth in this area. Regulators and governments should be encouraged to focus on assigning spectrum in existing identified bands, and making most efficient use of this, before considering identifying and allocating greater amounts of spectrum to IMT and withdrawing it from the use of other services.

[6] Lack of demand for mmWave bands may be due to lack of availability of equipment as the identification of spectrum in the millimetric bands happened much earlier than the mobile industry was expecting.

1 Introduction

This paper has been commissioned by GSOA to examine the extent to which spectrum has been allocated to mobile broadband by the International Telecommunication Union (ITU) Radio Regulations, following decisions made at the global World Radio Conferences (WRCs), and then to examine how this allocation is reflected by the awards and assignments made by national and regional regulatory bodies.

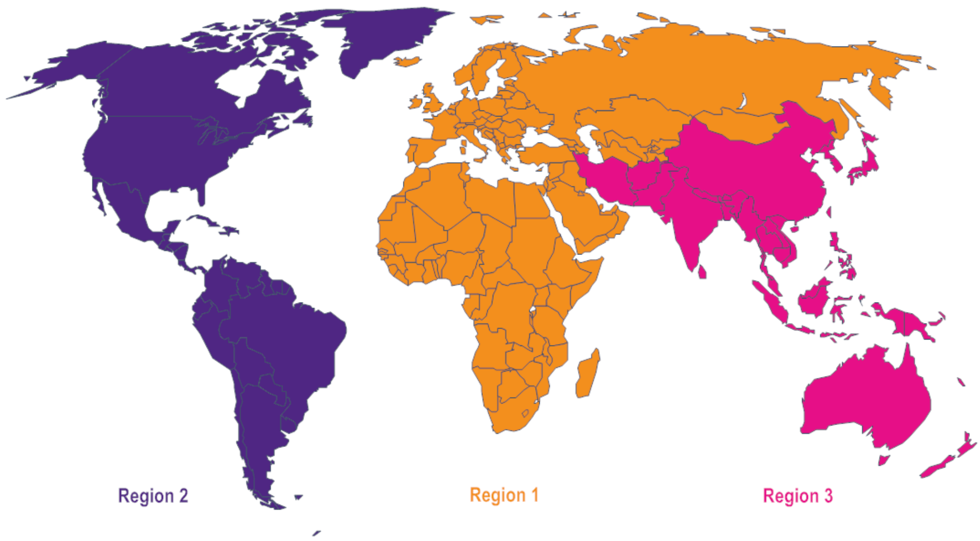
Ever since the introduction of mobile telephony in the 1980s, and particularly with the lower cost and increased availability brought in by 2G in the early 1990s, usage of these services has increased at a very rapid rate, both in terms of the number of users and the demand for connectivity per user. New services, such as picture messaging, Internet access, and app store access, have all led to demand from consumers for higher quality connections and greater capacity.

To meet this increased demand, new technologies have been developed to increase service capabilities, reduce costs, and improve spectrum efficiency. At the same time, national regulators have assigned large amounts of spectrum to the mobile industry, enabled by changing allocations of spectrum at every WRC since 2000. This spectrum allocation or identification for International Mobile Telecommunications (IMT) has often removed existing spectrum allocations from other industries, such as broadcasting (in the UHF bands), fixed links and fixed satellite (in the C-band), or fixed and mobile satellite communications (in the 26 GHz and 28 GHz band). These other industries, however, are also seeing increased growth in demand, with need for greater backhaul capacity, new services over satellite, and new networks launching.

Ahead of WRC-23 and WRC-27, discussions are being held over the next generation of mobile technologies (IMT-2030), and spectrum needs for these technologies. In particular, stakeholders are examining the usage of the 7 – 24 GHz bands, which are currently extensively used by a total of sixteen ITU-R radio services, including satellite. Alongside these investigations, however, it is important to assess whether there is justification for new spectrum allocations.

This paper first considers the current allocation of spectrum to mobile services. Broadly speaking, spectrum allocation decisions are made across the three ITU Regions of the world, as shown in Figure 1.1. We look at the history of mobile spectrum assignments across these regions and determine the current status of spectrum bands.

Figure 1.1: ITU Regions for spectrum allocation decisions



Once the amount of spectrum available to the mobile service is understood, we then examine how this has been assigned or awarded to operators by national governments or regulators. We consider spectrum in four categories:

- Sub-1 GHz;
- 1 – 3 GHz;
- 3 – 7 GHz; and
- Above 7 GHz.

We look at countries which have the most and least spectrum assigned to mobile operators, and countries which have high proportions of one of these categories. We look at all countries which have assigned spectrum above 7 GHz, since there have been relatively few assignments in this category.

1.1 Structure of this report

The remainder of the report is structured as follows.

- Section 2 examines the allocation of spectrum at an international level, identifying which bands have been allocated and the total spectrum availability in each band.
- Section 3 analyses data on national spectrum assignments in over 160 countries to see where these allocations have been assigned and the spare capacity that already exists in the bands.
- Section 4 considers whether there is evidence that spectrum assignments are being used efficiently by operators.
- Section 5 concludes.

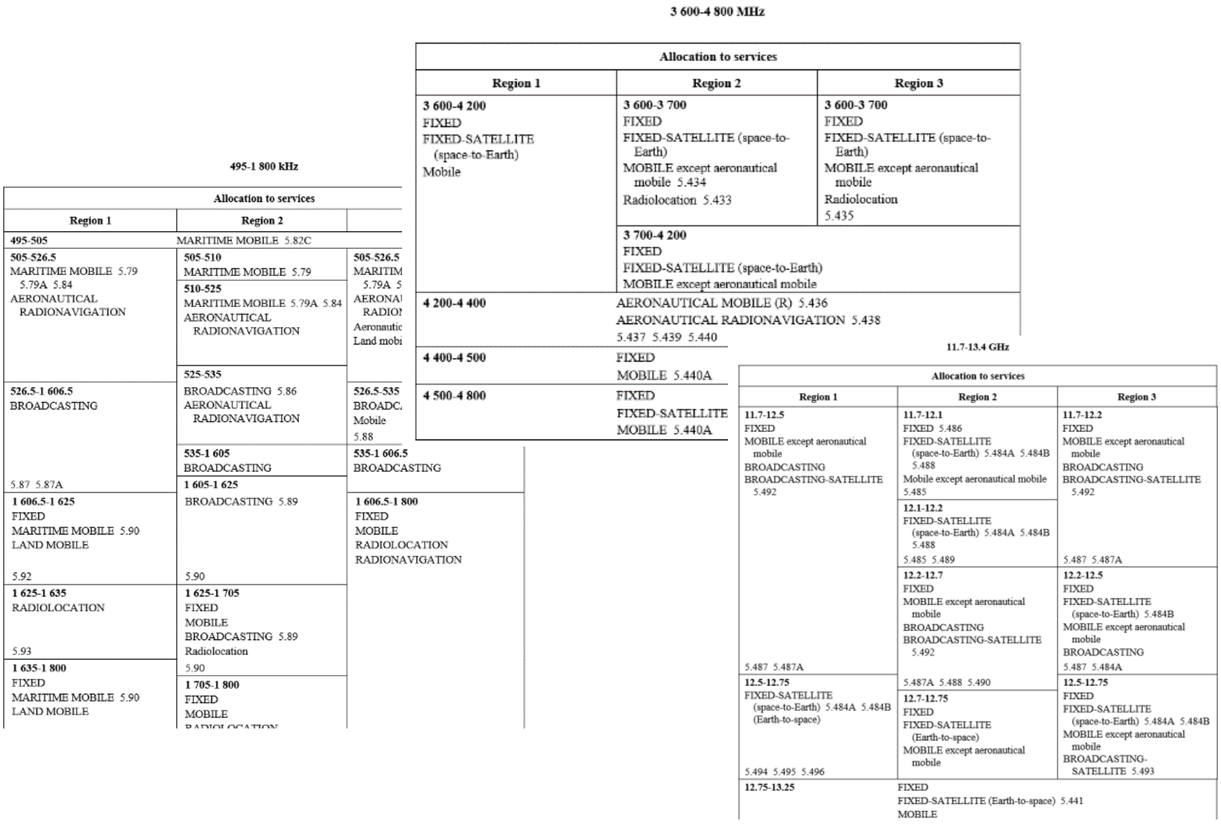
In addition, appendices include a full list of LTE and 5G band numbers, and show the full details of spectrum assignments in countries worldwide.

2 Spectrum allocated to mobile services

Spectrum is allocated to different uses by the International Telecommunications Union (ITU), with most work done in conjunction with the four-year cycle of the World Radio Conferences (WRCs). At these Conferences changes to the Radio Regulations, published by ITU-R, are discussed and agreed, and a new version of the Radio Regulations is published shortly after the conclusion of the conference[7].

The objective for this international agreement on spectrum use is to enable harmonisation and reduce harmful interference. Radio waves do not stop at national borders, and lower frequencies can travel significant distances. While it is possible for technologies to manage interference between networks, it is much more difficult to overcome interference between services. For example, the 3570-3640 MHz band in France is assigned to Bouygues Telecom, while 3560-3610 MHz in Germany is assigned to T-Mobile. It is possible for these two networks to coordinate on locations and pointing directions of base stations to minimise interference. However, if the band was instead used for broadcast services in one country, this would be more difficult.

Figure 2.1: Illustration of spectrum allocation in ITU Radio Regulations



Spectrum is allocated to a number of categories of use; for the purposes of this paper, we are interested in the allocations to the Mobile Service. However, this spans a very wide range of spectrum across many different bands and is not all specific to public mobile broadband networks deployed by network operators. There are allocations to the Mobile Service within the Radio Regulations, for example, ranging from 1.6 MHz in Region 3 to 275 GHz worldwide, as can be seen above. In many of these bands spectrum is allocated on a co-primary basis (that is, there is more than one service which may use the spectrum and further international, regional and

[7] The current 2020 version of the Radio Regulations is available on the ITU website at https://www.itu.int/hub/publication/r-reg-rr-2020/.

national agreements and arrangements should be made to determine which service is enabled); in some bands there are specific provisions applicable to a Region, a group of Regions or to some countries through footnotes.

A large proportion of the spectrum allocated to the Mobile Services within the Radio Regulations is not, therefore, available exclusively for use by public mobile broadband networks, and there are instead specific bands which are identified as being the key harmonised bands for IMT. While these allocations are treated individually in the three ITU regions, the need for equipment ecosystems and the international roaming nature of mobile devices dictates that there are necessarily significant frequency overlaps in the spectrum available in the regions. This is achieved through the use of regional and country-specific footnotes, where globally identified spectrum is noted as being unavailable for assignment in specific areas.

2.1 A history of spectrum use by mobile

The increasing demand for spectrum by public mobile networks has coincided with increasing use in many other areas, such as satellite communications and WiFi. While initial spectrum assignments were relatively ad hoc (with low bandwidth requirements and limited competition allowing regulators to offer direct awards and cleared spectrum), with the advent of GSM 2G networks, increased numbers of operators, and greatly increased demand, there was very quickly a requirement for additional spectrum to be released.

The first mobile networks, running on analogue technologies, tended to use spectrum above or below existing television broadcasts – countries tended to award licences in the 450-470 MHz band, or the 800 MHz or 900 MHz bands, depending on where television was located. This led to significant incompatibilities between handsets and networks, but the small size of the market and the expense of international use meant that there was little demand for cross-compatibility or roaming.

Nevertheless, by the time that 2G was developed, there was an increased call for standardisation, to enable operators and users to benefit from economies of scale. Regional bodies attempted to harmonise spectrum use, with European regulators converging around spectrum at 900 MHz (with expansion into the 1800 MHz band) and American regulators using 850 MHz and PCS[8] (1900 MHz) bands. Incompatible technologies (GSM and CDMA) meant that roaming was still limited, and indeed many handsets were only able to use a single band. For example, in the UK, the Nokia 5110 handset used the 900 MHz carrier, and could be used only on Cellnet and Vodafone, while the Nokia 5130 and 5146 handsets operated on 1800 MHz frequencies, used on Orange and One 2 One networks respectively. Later handsets started to introduce dual band technology, but were still limited by region.

The move to 3G saw a greater convergence in technologies, although UMTS (W-CDMA) and CDMA2000 continued to compete across regions. Spectrum allocation was again divided by region, with Region 1 tending to assign 2100 MHz spectrum as an additional band for 3G, while Region 2 upgraded to CDMA2000 in many of the existing spectrum bands but with an inclusion of the AWS[9] band. Sales of 2100 MHz spectrum were particularly high-profile, with many regulators seeing an opportunity to introduce new operators to the market, and auctions fetching very high prices.

The next generation[10] saw a consolidation in technologies, with Qualcomm ending development of the CDMA UMB standard, and networks moving to LTE instead. LTE required allocations of a number of 5 MHz lots, and with a limited opportunity to refarm, there was a further requirement for spectrum award, including as new services gave rise to even greater demand. Regulators released further lots in existing bands, but also provided additional spectrum under 1 GHz (at 700 MHz in Regions 1, 2 and 3, and at 600 MHz in Region 2) and at higher

[8] Personal Communications Service
[9] Advanced Wireless Services
[10] Although commonly termed as "4G", the first releases of LTE technologies did not meet the requirements specified by the ITU for defining the new generation; these standards were not met until the first major evolution of LTE, to LTE-Advanced. However, there was a general relaxation of the definition over time, and this paper will use 4G to mean any LTE technology.

bands – including supplementary downlink at 1400 MHz, extensive bands at 2500 MHz and 2600 MHz, and some limited award of 2300 MHz.

With the introduction of 5G, the mobile industry sought the allocation of further spectrum, with focus in three areas – the sub-1 GHz bands (also termed "low-band"), spectrum in the C-band (the "mid band"), and mmWave spectrum[11]. These allocations, alongside spectrum refarmed from previous generations[12], could be used to allow mobile operators to run high-capacity and high-speed networks, without constraints on throughput However, this spectrum, particularly in the mmWave bands, has not yet been used to its full extent, as will be examined in later sections.

2.2 Spectrum identification and consolidation

As described above, while spectrum had been allocated for Mobile Service in the ITU's Radio Regulations, to ensure international harmonisation of bands there have been defined frequencies identified at WRCs for IMT. In recent years, these identifications have been made ahead of the introduction of technologies which use them, but for early generations of mobile networks there was no such identification in place – leading to the situations described above where different regions (and countries) used different frequencies. For these frequencies, identification for IMT has been made in later years, again to encourage harmonisation.

Figure 2.2: Spectrum identification for mobile at WRCs

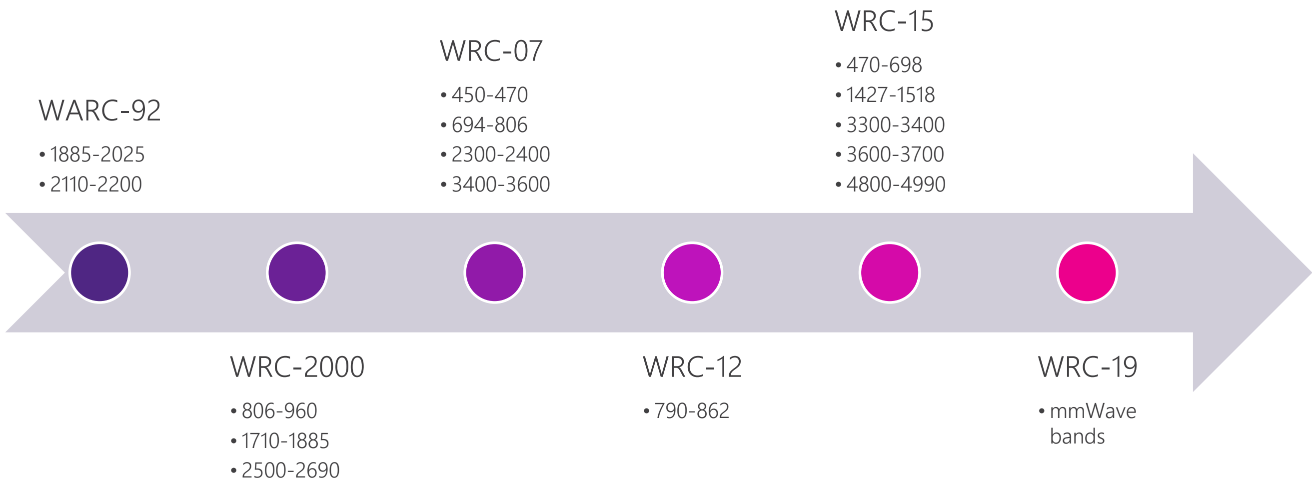


Figure 2.2 above provides a high-level overview of the identification of different bands; it can be seen that spectrum for LTE technologies was agreed at WRC-07, while the spectrum that had been used by 2G technologies was not formally identified until the year 2000. Spectrum required for LTE expansion, and the low-bands and mid-bands for 5G, were identified at WRC-15, with mmWave spectrum identified in 2019.

[11] See 'Spectrum Considerations for 5G Mobile Communications Systems, at https://www.sciencedirect.com/science/article/pii/S1877050917301679

[12] For example, China Unicom is seeking to refarm its 900 MHz spectrum for 5G (see https://www.commsupdate.com/articles/2022/11/04/china-unicom-given-green-light-to-refarm-900mhz-band-for-5g/) while Ofcom in the UK has varied spectrum licences for O2 and Vodafone to allow spectrum to be used on 5G networks (see https://telecoms.com/515474/ofcom-wants-to-let-vodafone-and-o2-refarm-4g-spectrum-for-5g/)

Overall, over 1880 MHz of spectrum has been identified for IMT outside of the mmWave bands[13], as shown in Figure 2.3 below.

Figure 2.3: Total spectrum identified for IMT globally

Frequencies	Bandwidth (MHz)	Notes
450 – 470 MHz	20	Often assigned as FDD with 2×7.5 MHz bandwidth
470 – 608 MHz	138	Lower portion of this is sometimes used for television broadcasting so is subject to footnotes and exemptions. Generally only used outside Region 1.
608 – 614 MHz	6	This is generally used for radio astronomy and medical equipment but is identified for IMT and used in select countries in Asia Pacific.
614 – 698 MHz	84	Generally used for IMT in Region 2.
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1710 – 2025 MHz	315	Variety of band configurations available.
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3400 – 3600 MHz	200	Core C-band frequencies for 5G.
3600 – 3700 MHz	100	
4800 – 4990 MHz	190	
Total	**1886**	**Removing 4 MHz from the total to account for overlap at 694 – 698 MHz.**

The mmWave frequencies (at 24.25-27.5 GHz, 37-43.5 GHz, 45.5-47 GHz, 47.2-48.2 GHz, and 66-71 GHz) were identified at WRC-19, and add an additional 17.25 GHz of bandwidth to the total available for IMT. These have been requested to add high-speed, low latency services, and are not necessarily direct substitutes for spectrum below 7 GHz. However, the availability of this spectrum for future services should not be ignored.

2.2.1 Comparison of global and regional identification

While this provides a comprehensive view of the amount of spectrum identified for IMT, it should be noted that not all this spectrum is fully available in every country or in every region. Many identifications have footnotes which restrict IMT access to spectrum in certain countries. Further, the Radio Regulations are specified separately for the three ITU regions, and historically some of these spectrum bands have not been included in

[13] This accords with a statement from the ITU, which states that there was 1.9 GHz of spectrum allocated to mobile, before the mmWave allocations and other smaller allocations at WRC-19. See https://www.itu.int/hub/2020/01/wrc-19-identifies-additional-frequency-bands-for-5g/

certain regions (for example, the 470 – 608 MHz band in Regions 1 and 2, or the 790 – 862 MHz band in Region 1 which was only identified at WRC-12)[14].

Therefore, to have a comprehensive picture of the spectrum currently allocated to Mobile Service and that identified for public mobile broadband, we would need to draw on a number of resources:

- ITU frequency allocation tables, along with WRC outcomes;
- Historical assignments; and
- Mobile band plans used by regulators worldwide.

The overlap between bands, along with national decisions over which band plans to use[15], means that it is difficult to provide a single list of how much spectrum has been allocated to mobile broadband worldwide. However, there is a general trend towards harmonisation of all identified spectrum, and regional and area-wide bodies (such as CEPT, APT and CITEL) continue to recommend licenced bands within these identified frequencies. The above list of identified spectrum should therefore be taken as a maximum which countries and regions should aspire to.

Outside of these global identifications, there are further assignments at regional levels; for example, South Africa has awarded significant spectrum holdings in the 2000 MHz range outside of the identified frequencies listed above; various countries have also assigned some spectrum in 6 GHz, 7 GHz, 10 GHz and 12 GHz bands[16]. However, given the lack of a global ecosystem for equipment in these bands we do not believe it is reasonable to consider these as universally accepted.

2.3 Substitutability of bands

Although the analysis above has considered spectrum as a whole, it is worth commenting on the fact that different bands have different characteristics, and thus different uses.

- Sub-1 GHz spectrum has long propagation and is suitable for networks that need to reach inside buildings. However, the smaller bandwidths available can lead to low data speeds or network quality.
- Spectrum between 1 and 3 GHz does not travel as far, meaning that networks need to be denser, but it provides adequate in-building coverage and can offer higher bandwidth, giving a better experience.
- Spectrum between 3 and 7 GHz[17] can provide very large bandwidths, with high network speeds, but the networks may be more expensive due to the reduced distance the signals travel and resulting reduction in cell size.
- Spectrum above 7 GHz can be used for very high speeds and low latencies, but the power requirements and the short propagation mean it is mainly suitable for very high capacity communications.

The nature of these spectrum bands, along with historical precedent, has led to competing demands. Spectrum between 470 and 800 MHz has been used around the world for terrestrial television broadcasts, and any

[14] The ITU noted in 2008 that only six bands were identified across all three ITU regions: 450 – 470 MHz, 790 – 960 MHz, 1710 – 2025 MHz, 2110 – 2200 MHz , 2300 – 2400 MHz and 2500 – 2690 MHz. Further details and discussion of identification can be seen at https://www.itu.int/ITU-D/tech/MobileCommunications/Spectrum-IMT.pdf

[15] A comprehensive view of potential band plans can be found in ITU-R Recommendation M.1036-6, available at https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.1036-6-201910-I!!PDF-E.pdf

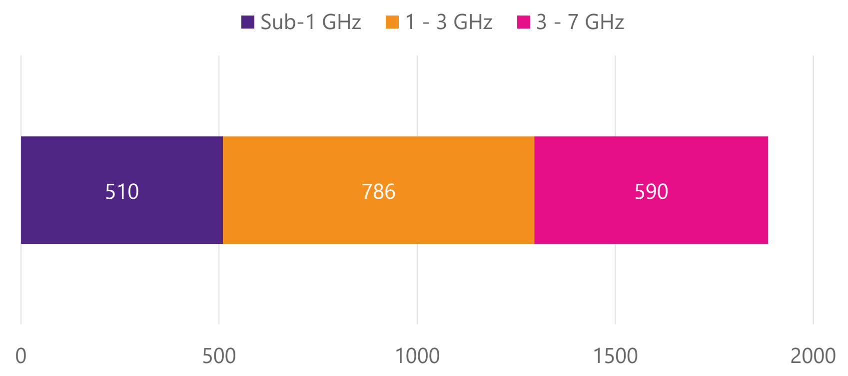
[16] See, for example, https://techblog.comsoc.org/2020/10/28/big-names-clash-over-12-ghz-for-5g-despite-it-not-being-included-in-itu-1036-frequency-arrangements-for-imt/

[17] Agenda item for WRC-23

expansion of mobile use in this area has required television's spectrum footprint to decrease. Spectrum in the 1400 MHz band has traditionally been used for supplemental downlink only. Most countries continue to run at least some 2G mobile network in the 850 MHz or 900 MHz bands. Nevertheless, our analysis of the data collected indicates that there are sizeable amounts of spectrum identified for IMT around the world, even without considering allocations above 7 GHz.

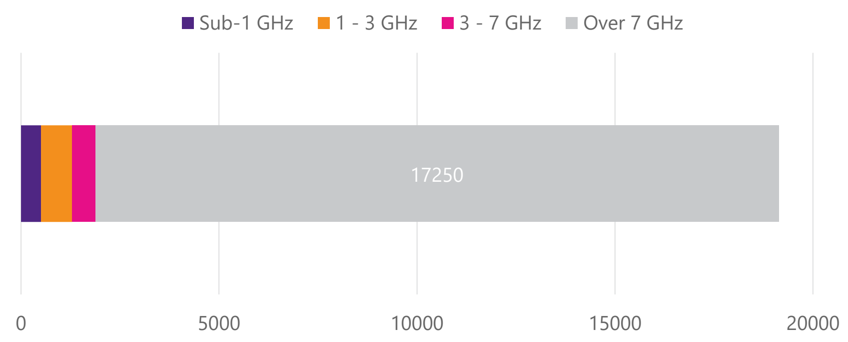
When categorising the spectrum identified for IMT as shown in Figure 2.3 in this way, we can see the total bandwidths identified are as shown below.

Figure 2.4: Total bandwidth (in MHz) of spectrum identified for IMT below 7 GHz, by category



In addition to this, as discussed above, there is 17.25 GHz of spectrum identified to IMT in the mmWave bands. If this is included in our diagram, it overshadows other allocations considerably.

Figure 2.5: Total bandwidth (in MHz) of spectrum identified for IMT, by category



In the next section we consider how countries around the world have assigned spectrum in each of these categories, and compare it to this overall availability of identified spectrum.

3 Spectrum assigned to mobile broadband

Although it is difficult to compare data across regions when looking at allocation of spectrum at the ITU level, there is some level of harmonisation which is expected. However, even where spectrum has been identified to mobile broadband, this does not automatically give mobile operators the right to use it on their networks.

For this to happen, national regulators or governments must assign a licence for the right to use blocks of frequencies to public mobile broadband operators, on an exclusive or shared basis[18]. These licences may include conditions such as coverage, quality of service, and deployment speed. There may also be constraints on how regulators are able to assign spectrum, including the design of the award mechanism. Implementing these licences, and carrying out complex awards, mean that spectrum assignment may be delayed from the time of spectrum being allocated, or they may not happen at all, due to regulatory inertia.

Even if there were no friction delaying the assignment of spectrum, the full identified band may not be available. Each country has its own frequency allocation table, which may differ slightly from the table of frequency allocations provided in Article 5 of the Radio Regulations. Where there is a legacy scientific use, for example, regulators may not be able to assign the entirety of a band which has been identified to public mobile broadband. In other cases, legacy uses may be able to be cleared, but this could be a costly, time consuming and complicated exercise.

Given these issues, it is not surprising that no country has assigned the full allocation of spectrum to mobile that is available to it. In this section we examine how much spectrum has been assigned, and compare this to the potential maximum derived in Section 2.2.

3.1 Data collection

For this study we have collected data on spectrum awards and assignments across around 160 countries, from a variety of sources:

- Super-national organisations, such as CEPT and APT;
- National regulators;
- Plum's spectrum auction database;
- Analyst reports;
- GSMA reports; and
- The GSA GAMBoD database.

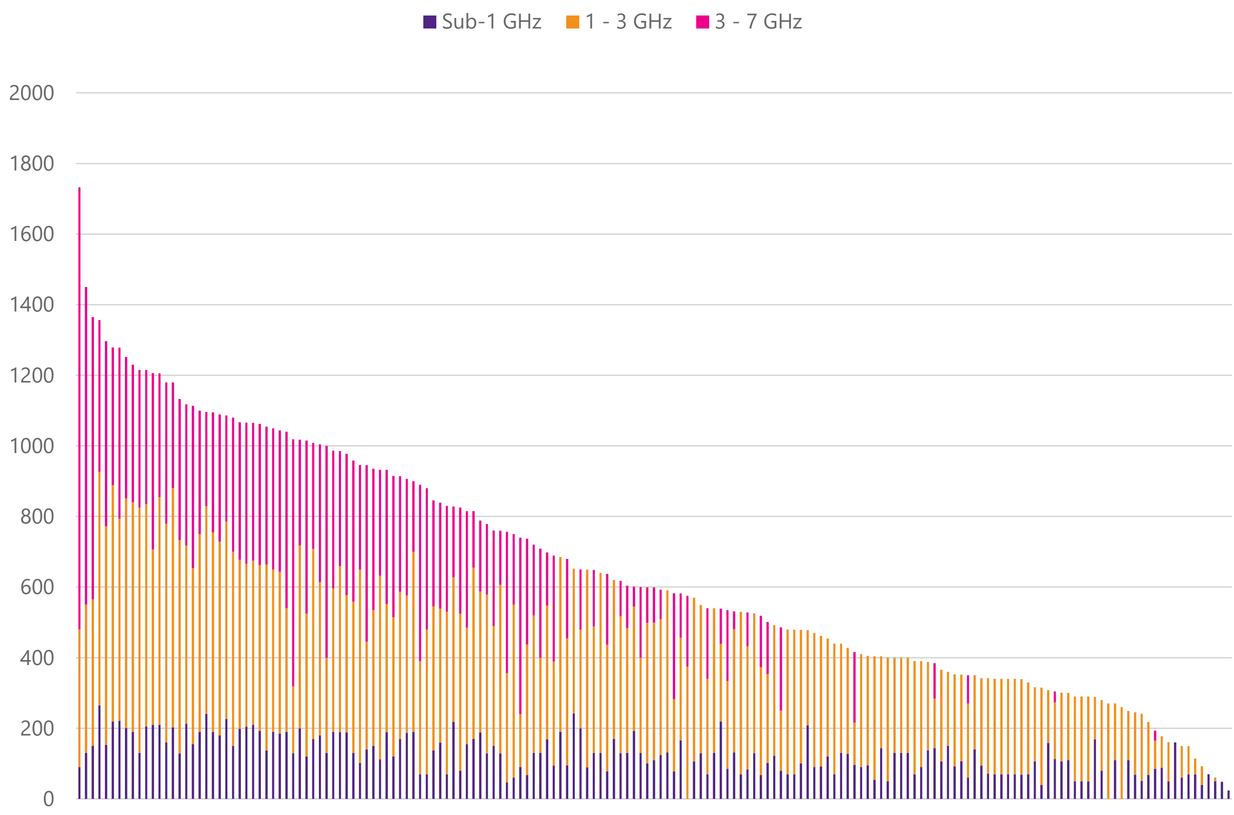
In many cases some of these sources did not agree, and we have reconciled the values as best as possible, placing preference on more direct sources of data. We have attempted to ensure that all information is current, with lapsed licences removed. Where information is uncertain, so as to be conservative we have not included it or have partially included it.

[18] Due to the desire for technology neutrality, regulators may not determine that spectrum is to be awarded to IMT operators; however, the design of the band plan and requirements for coverage or service mean that other users are effectively excluded. In this section all data are derived based on IMT or IMT-like assignments.

3.2 Overall international comparisons

The figure below illustrates how different countries have assigned spectrum in three categories of spectrum. In this initial analysis we have not included mmWave spectrum since the size of the bandwidth identified for these bands would overshadow all other analysis; the mmWave bands are discussed in more detail in Section 3.8.

Figure 3.1: Current spectrum assignments (MHz)[19]



It is clear that there has been a considerable amount of spectrum assigned across the world. The relative newness of spectrum in the 3500 MHz bands is reflected in the fact that this is often the most recent spectrum assigned, and many countries have not progressed to these assignments yet. There is generally a relatively constant ratio of sub-1 GHz and 1 – 3 GHz spectrum assignments, other than in countries with the lowest spectrum availability.

No country has assigned all spectrum identified for public mobile broadband. As shown in Section 2.2, there is almost 2 GHz of spectrum currently allocated to mobile below 7 GHz, but the highest assignment, in South Africa, is only 1732.4 MHz – and this outlier is caused by large assignments in the 2000 MHz and 6 GHz bands (which are not included in the IMT identifications considered in Section 2). There are various reasons for spectrum not being assigned, including:

- Lack of demand from operators including lack of appetite to invest in more spectrum, particularly given falling revenue;
- Lack of regulatory expertise, including the huge task of designing the award structure, conditions and so on;

[19] Each bar represents one country. Note that countries are not listed on the x-axis, full results can be found in Appendix B.

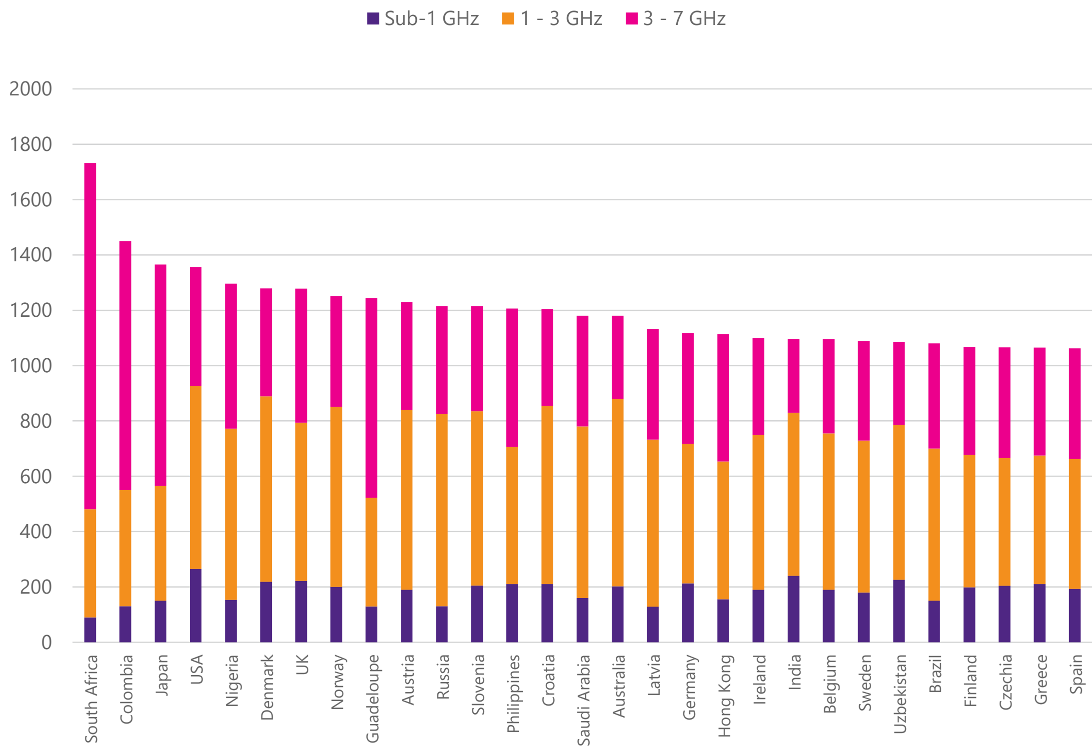
- Legacy services being unable to clear bands;
- Uncertainty over future band use; and
- Legal challenges to award mechanisms.

3.3 Countries with the most spectrum assigned

While the overall picture shown in Figure 3.1 is useful to illustrate the range in assignments around the world, it is useful to consider a number of different cohorts to understand if there are any common factors leading to spectrum assignment.

We start first by examining those countries who have assigned the most spectrum to mobile broadband.

Figure 3.2: Current spectrum assignments: countries with the most spectrum assigned



As previously mentioned, South Africa appears as an outlier here due to its high-bandwidth awards in 3600 MHz, 4900 MHz and 6GHz bands. Of the remaining countries, there is little commonality. Many of the most developed countries are included on this list, although there are notable exceptions – this may be a factor of countries assigning some spectrum on a regional basis, which reduces its general availability (and is given a lower weighting in our analysis). None of the United Nations's Least Developed Countries[20] are included here. Countries exist from Regions 1, 2 and 3; from every continent; large and small, with varying population distribution. The amount of each category of spectrum assigned is also not consistent – not all countries have

[20] See https://www.un.org/ohrlls/content/list-ldcs

assigned full amounts of the sub-1 GHz bands, and in some countries there are significant portions of the 1-3 GHz bands yet to be assigned.

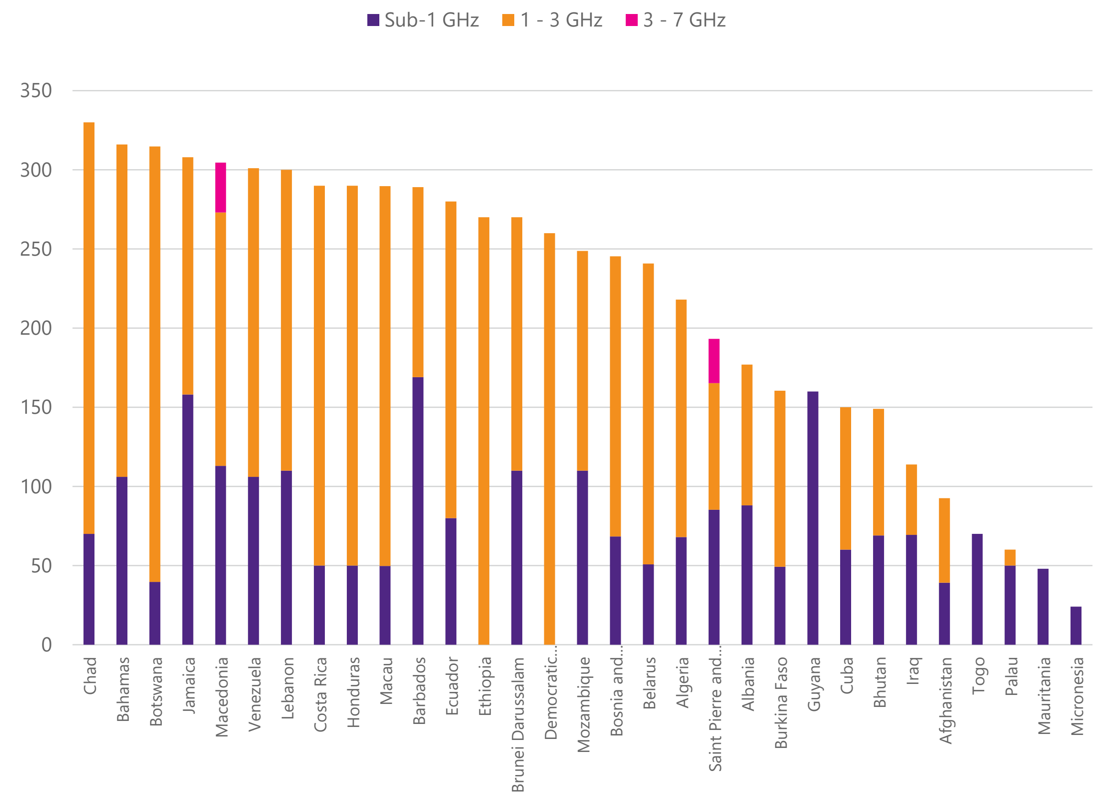
Investigation into consultations in some of these countries indicates there is a common theme that regulators recognise a fast-growing demand for data from mobile operators, and are looking to accommodate this for the benefit of consumers. However, regulators in some countries are looking to support developments in ways other than simply assigning additional spectrum. For example, in December 2022, Ofcom stated[21]:

> **“[W]e expect technology upgrades and densification, including the use of mmWave and small cells, to play an important role in enabling MNOs to meet future demand for mobile data, both up to 2030 and beyond, as well as creating the potential for innovation; and we will consider where and when additional spectrum may be needed and will take other competing uses into account in our future spectrum management decisions. We are currently evaluating the best use of the upper 6 GHz band, and favour a ‘no change’ outcome in relation to a potential IMT identification of the band at WRC-23.”**

3.4 Countries with the least spectrum assigned

At the other end of the scale, there are a large number of countries with little spectrum assigned for mobile use, as shown in Figure 3.3. Most of these countries are either on the UN’s Least Developed Countries list or have similarly low income levels.

Figure 3.3: Current spectrum assignments: countries with the least spectrum assigned



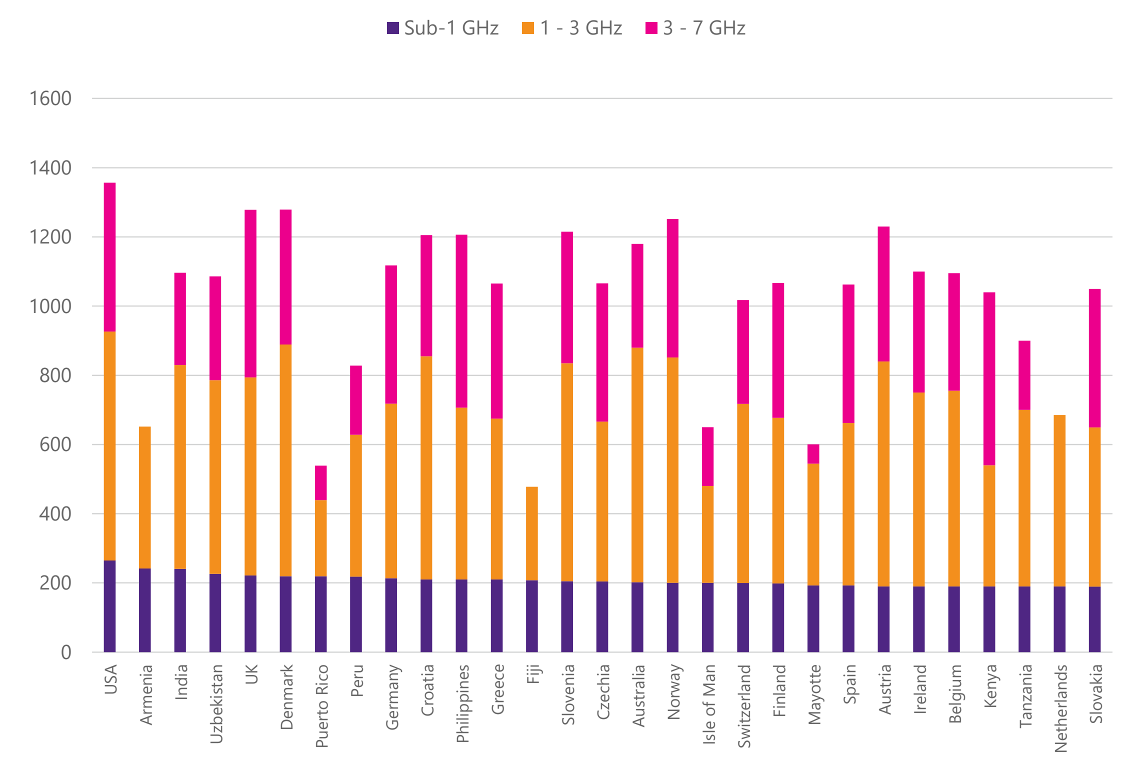
21 See https://www.ofcom.org.uk/__data/assets/pdf_file/0036/248769/conclusions-mobile-spectrum-demand-and-markets.pdf

It is clear that the vast majority of these countries have not yet assigned any spectrum above 3 GHz for mobile broadband, and in a few cases there have not been any assignments over 1 GHz. In some cases, it appears that this low spectrum assignment is deliberate, where countries have low populations and little chance of network congestion – for example, in Barbados and the Bahamas, the small population of the islands leads to a limited market for data. Other countries have only recently liberalised telecommunications markets (such as Ethiopia) or are in the process of national redevelopment (such as Iraq or Afghanistan).

3.5 Countries with the most sub-1 GHz spectrum

As stated above, those countries with the most spectrum overall are not consistent across all categories of spectrum. As such it is useful to look at the different categories of spectrum separately.

Figure 3.4: Current spectrum assignments: countries with the most sub-1 GHz spectrum assigned



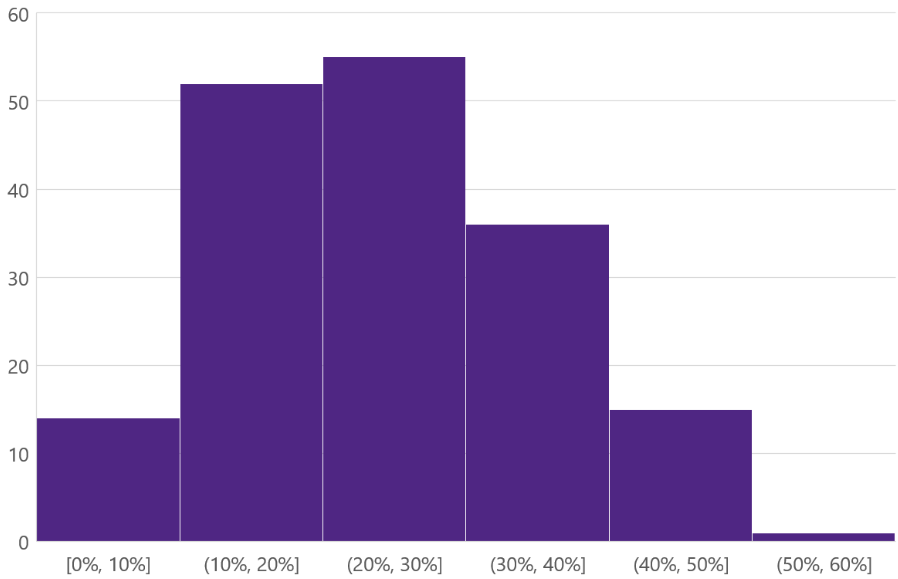
There is little difference in the amount of 1 GHz spectrum assigned in these countries, which is largely because they are at the limits of what can be assigned given the legacy band plans which were followed when 2G and 3G technologies were introduced. The small variations may be due to other legacy issues (such as the need to rearrange the 850 MHz band following the closure of CDMA networks, or some legacy users needing to be protected).

Sub-1 GHz spectrum is particularly useful for mobile networks looking to provide greater coverage – while the bandwidth may be limited, it enables services to be spread over a much wider area. For this reason, as networks are decommissioned or reduced, the sub-1 GHz spectrum is usually the last to be available for refarming.

If we consider the distribution over all countries of the proportion of sub-1 GHz spectrum assigned, we see that all countries still have parts of the identified bands available. The countries shown in Figure 3.4 all have almost

50% of the allocated sub-1 GHz spectrum assigned, but the majority of countries actually have less than 30% assigned.

Figure 3.5: Proportion of the sub-1GHz bands assigned – distribution graph[22]



This low proportion is likely due to non-assignment of newer bands such as the 700 MHz spectrum in Regions 1 and 3, and the 600 MHz band in Region 2; there may also be significant issues with incompatibilities between older band plans and newer configurations, which require licencing changes to resolve. Use of FDD band plans will also introduce unassigned spectrum in duplex gaps, and the need for several band plans to be combined to cover the sub-1 GHz identification leads to further logistical issues[23]. Finally, a large number of countries will have legacy services such as television broadcasting that cannot yet be cleared. In any case, for many countries a primary focus should be on awarding the spectrum that is identified but not yet assigned.

3.6 Countries with the most spectrum between 1 GHz and 3 GHz

Moving to the next spectrum category, this is often considered advantageous for LTE technologies, balancing larger bandwidths against reasonable propagation.

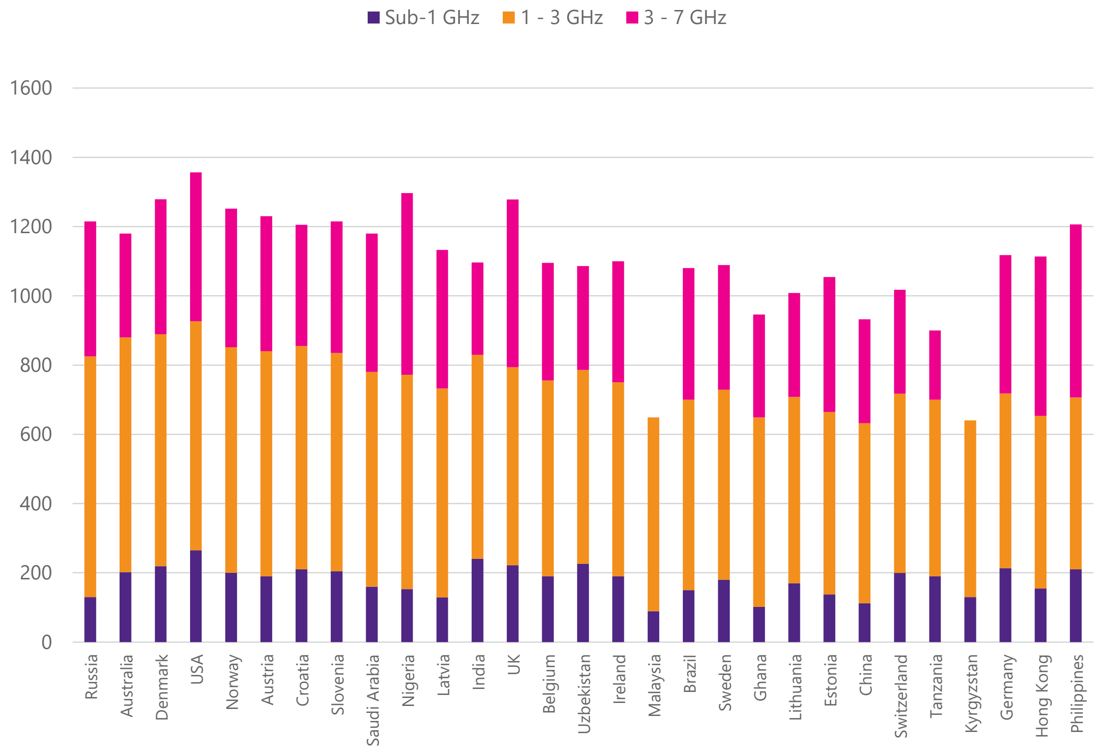
A number of the bands in this category have legacies from 2G and 3G, particularly:

- 1800 MHz, which was used as a 2G band when 900 MHz was occupied and regulators wished to assign more licences to either increase capacity or increase competition;
- PCS (1900 MHz), which was analogous in Region 2 to 1800 MHz in other regions, but which had slightly more bandwidth available;
- 2100 MHz, which was introduced as the main band for 3G networks across Europe (and later Africa), despite smaller cell sizes; and
- AWS, which pairs bands in 1700 MHz and 2100 MHz, again used for 3G services.

[22] This graph shows the number of countries included in each set, defined by the proportion of the sub-1 GHz spectrum which has been awarded.
[23] Some information on how band plans relate to identified spectrum can be seen in Appendix A.

With the advent of LTE and the reduction in demand for 2G – along with delays to LTE spectrum assignments in some countries – 1800 MHz was often refarmed for use by the new LTE networks[24], continuing to run alongside new spectrum assignments when they were possible.

Figure 3.6: Current spectrum assignments: countries with the most spectrum assigned between 1 and 3 GHz

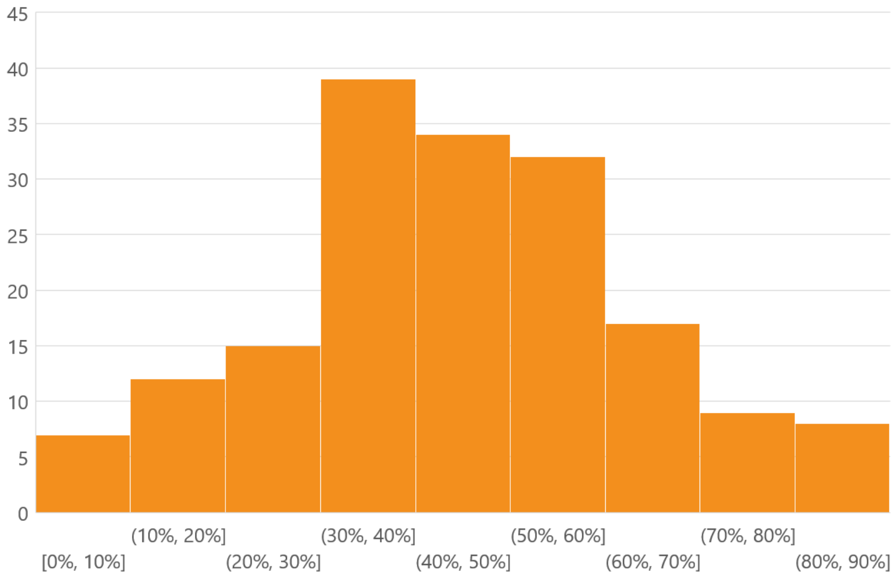


There, again, is little commonality between the countries included on this list, other than the fact that the majority have already assigned spectrum above 3 GHz, indicating that the regulators saw there was an excess demand for spectrum.

When looking over the whole dataset, the spectrum in these bands generally seems to be a little more utilised, with just over half the countries examined having assigned more than half the identified spectrum bands. .

[24] For example, in the UK, LTE services were launched on Everything Everywhere's 1800 MHz spectrum holdings ahead of the 800 MHz and 2600 MHz auctions, in an effort to be first to market.

Figure 3.7: Proportion of the bands between 1 and 3 GHz assigned – distribution graph[25]



Although many countries have assigned more than half the spectrum in this category to operators, there is still a long way to go before this spectrum is fully assigned and utilised.

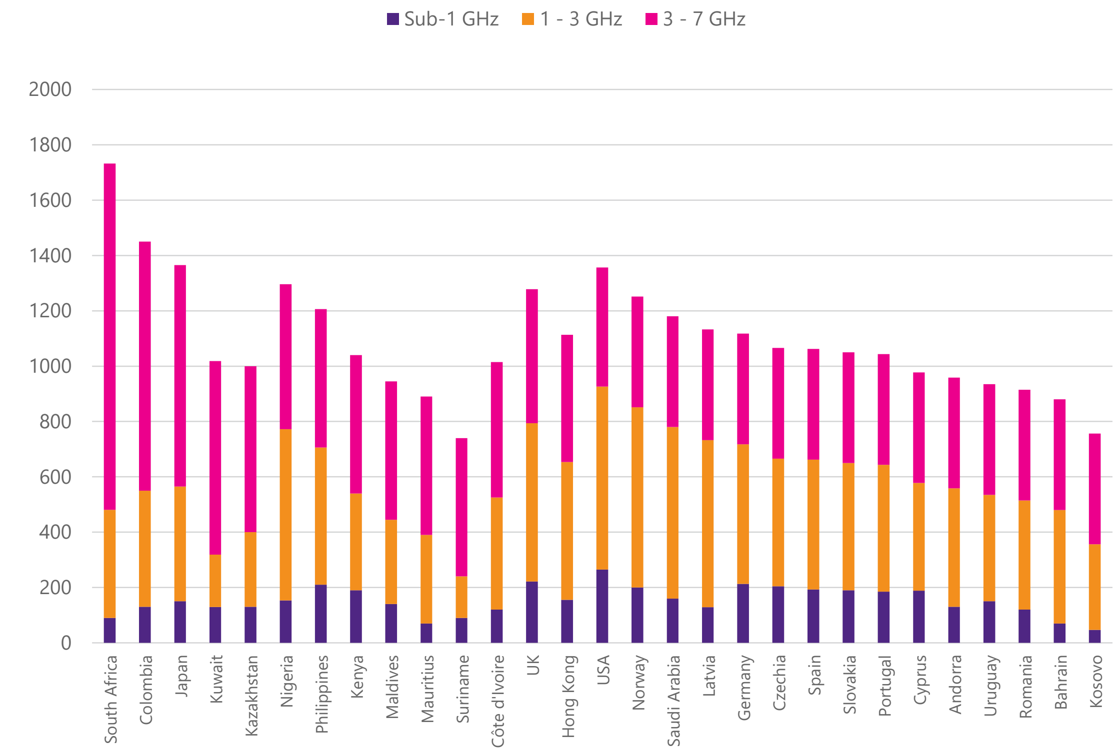
3.7 Countries with the most spectrum between 3 GHz and 7 GHz

When looking at the spectrum assigned above 3 GHz, it is important to consider how it has been awarded and for what purposes. In a large number of countries, spectrum in the 3500 MHz range was previously used for fixed wireless access or wireless backhaul, but where this was awarded with a service-neutral and technology-neutral licence this can now be used for mobile broadband. This may explain why there are a number of countries with large spectrum assignments between 3 and 7 GHz which have comparatively small assignments in other bands.

The amount of spectrum available between 3 and 7 GHz is significantly greater than in the previous categories, and where countries have assigned the full bandwidth between 3400 MHz and 3800 MHz this would often overshadow the lower frequency bands. Indeed, including spectrum at 3300 MHz[26] and also the 3800 to 4200 MHz spectrum has the potential to more than double operators' holdings.

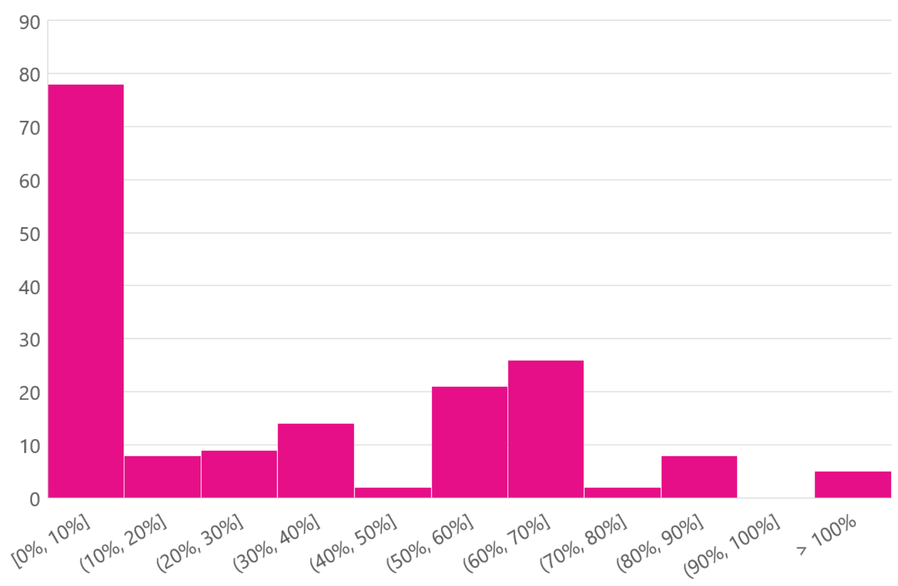
[25] This graph shows the number of countries included in each set, defined by the proportion of the spectrum between 1 and 3 GHz which has been awarded.
[26] Subject to protecting radiolocation services

Figure 3.8: Current spectrum assignments: countries with the most spectrum assigned between 3 and 7 GHz



While there appears to be a significant amount of spectrum in the 3 – 7 GHz bands assigned in these countries, this is not repeated in most countries around the world. In fact, the majority of countries have assigned very little spectrum in these bands.

Figure 3.9: Proportion of the bands between 3 and 7 GHz assigned – distribution graph[27]



[27] This graph shows the number of countries included in each set, defined by the proportion of the spectrum between 3 and 7 GHz awarded.

A few countries have assigned more than the total identified spectrum (by marginal levels), due to national agreements and a lack of interference with existing services. This again raises an interesting point, whereby the identification of spectrum to mobile at the ITU is not always harmonised across all countries in terms of assignment.

There is some recency bias here; the 3500 MHz spectrum is the most recent to be widely adopted, and so countries where 5G networks are not yet rolled out may not have assigned any spectrum in this range. However, this itself is indicative of the need for greater use of the existing spectrum allocations. The assignment of parts of this spectrum band may also be delayed due to the need to clear legacy users, or concerns over the issue of sharing with radio altimeters.

There are only fifteen countries where more than 400 MHz of this category of spectrum are being used. In these countries a manual examination shows that there is spectrum already identified that could be utilised – for example, in Japan, the 4800 MHz spectrum is unused; in Colombia the 3300-3700 MHz spectrum is being awarded in 2023 but there are no plans for any spectrum above at 4800 MHz.

That such a low amount of this spectrum has been assigned indicates there is a lack of demand from operators, or there is a lack of urgency from regulators. As shown in Section 3.3, Ofcom in the UK has recently stated[28] that they do not intend to argue that the 6 GHz band should be allocated to IMT:

> **“We highlight that the case between licence exemption (to support uses such as Wi-Fi) and commercial mobile is finely balanced. There is uncertainty around future developments that could shift the balance towards either approach. To keep options open, we favour a ‘no change’ outcome which would better support either use. We will consider international developments and engage with relevant stakeholders as needed, prior to consulting on the proposals for the future use of the band in the UK.”**

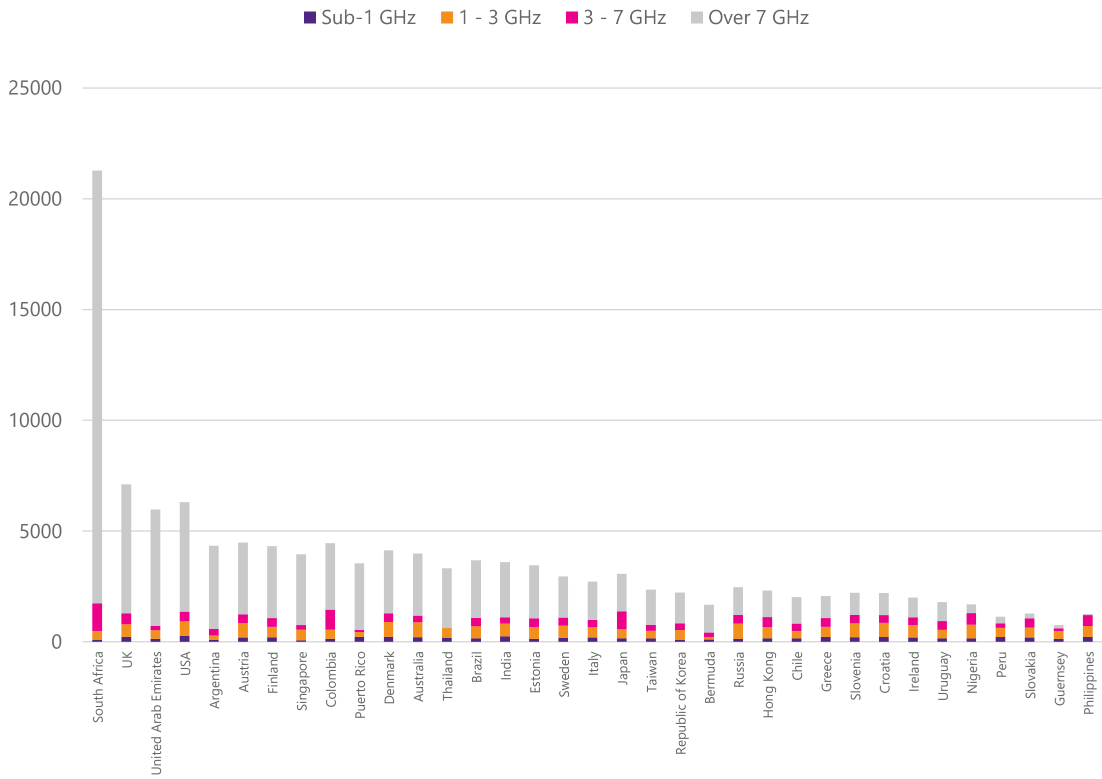
3.8 Countries with the most spectrum above 7 GHz

This lack of assignment is even more pronounced when looking at spectrum above 7 GHz. Only 35 countries in our analysis have assigned spectrum in these bands, and there is a wide variety of types of assignment.

- Spectrum at 10 GHz has been assigned in countries including Nigeria and Peru[29], apparently resulting from legacy assignments.
- There are several assignments in the 26 GHz band, particularly in Regions 1 and 3, and a few assignments in the 28 GHz band[30], such as in Japan, Singapore, Taiwan, and the US.
- A few assignments have been made at 40 GHz, or at 32 GHz[31].

[28] See paragraph 1.19 of https://www.ofcom.org.uk/__data/assets/pdf_file/0036/248769/conclusions-mobile-spectrum-demand-and-markets.pdf
[29] WRC agenda item
[30] It should be noted that there is no IMT identification between 27.5 GHz and 37.0 GHz, meaning that these assignments at 28 GHz are not in line with WRC outcomes.
[31] There have been no awards in Europe as ECC Decision relating to 40 GHz has only just been approved and 32 GHz not supported in Europe

Figure 3.10: Current spectrum assignments: countries with the most spectrum assigned above 7 GHz



Although the lack of assignment at 10 GHz is primarily due to a lack of international harmonisation and agreement, the fact that interest around these bands is so limited does indicate that regulators are not convinced that there is a heavy demand for additional spectrum. This is reinforced by the low number of 26 GHz assignments, which would be expected to be more prevalent if regulators recognised demand for large bandwidth spectrum[32].

When compared to the total identification in the mmWave bands of 17.25 GHz, it is clear that (with the exception of South Africa) the vast majority of spectrum is unassigned.

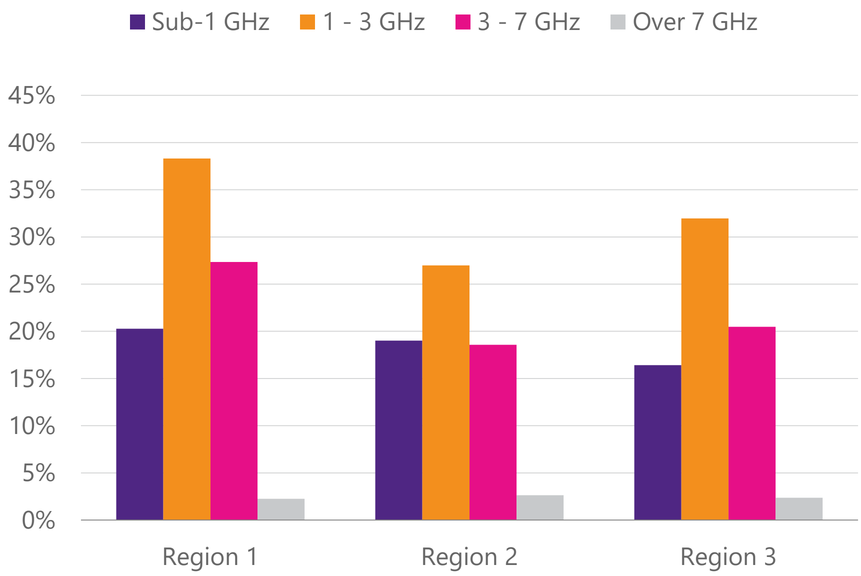
3.9 Summary

When looking at all countries in our sample, it is clear that there is a significant amount of spectrum that has been identified for IMT that has not yet been assigned or awarded.

It is natural that there will be greater demand for spectrum in some countries than in others – caused by higher incomes, greater population density, greater technological advance – but even in these countries not all spectrum has been assigned. This is particularly true of higher frequencies, specifically above 7 GHz, where there appears to be little urgency from regulators in assigning this spectrum. Spectrum in the range of 3 to 7 GHz is also still in the process of award.

[32] Lack of demand for mmWave bands may be due to lack of availability of equipment, as the identification of spectrum in the millimetric bands happened much earlier than the mobile industry was expecting.

Figure 3.11: Average proportion of identified spectrum which has been assigned



Given this analysis, it is clear that regulators must be urged to assign spectrum for public mobile broadband services in the bands where it is currently identified for IMT, so that capacity demands can be met without the need for identifying further IMT spectrum which will reduce the amount available for other services. The ITU has allocated a significant amount of spectrum to the mobile service, and this has not been reflected in the assignments and awards in many countries.

4 Spectrum used by mobile networks

While there is a lot of information available on how spectrum has been assigned across the globe, there is less data on its actual use. Understanding the amount of spectrum which has been deployed on any particular operator's network is difficult as this is commercially-sensitive information, and it is rarely released even to regulators, other than where licence obligations require it.

Nevertheless, there are some pieces of evidence which can be used to consider whether the full spectrum assignments which have been examined above are being used efficiently.

4.1 Geotype analysis

The GSMA has noted a number of times the importance of operators holding a portfolio of spectrum licences, with different frequencies having varying advantages and disadvantages. In lobbying for 5G assignments, they recommend that operators are assigned spectrum in the low-band (sub-1 GHz), the mid-band (generally the C-band), and in mmWave frequencies. This is because of the ways in which this spectrum is used; mmWave is crucial for providing very high bandwidths and capacity, but its limited propagation means that it is unsuitable for use in rural areas; this is where low-band spectrum is needed.

This analysis is consistent with other examples of mobile operators seeking to use spectrum bands in different ways.

- When rolling out LTE networks, initially 1800 MHz spectrum was often used as this could be refarmed from 2G services. However, rural coverage was often delayed until after the 800 MHz spectrum was assigned, as this was preferable for wide coverage, and made the deployment of network profitable given the comparatively lower revenues expected.

- Operators in Region 1 generally acquired spectrum at 800 MHz and 2600 MHz for LTE networks, since the capacity of 800 MHz was insufficient for urban areas.

- In the early days of 2G competition, operators who were granted spectrum at 1800 MHz or in the PCS band often claimed they were at a disadvantage in terms of rural coverage.

- When 3G services were launched in the UK, the new operator (3UK) was offered national roaming on an existing network. When Orange and T-Mobile merged to become Everything Everywhere, 3UK (successfully) argued that the merged entity should be required to sell some of its low-band spectrum to enable the smaller operator to compete.

Plum has built many network models for operators and regulators, and we consider the spectrum use separately for different geotypes – this then informs the expected cell radius and capacity of base stations. This is a standard modelling methodology, and can be found, for example, in the MTR models released by PTS (Sweden) and Ofcom (UK), as well as the general LRIC models released by Telzed.

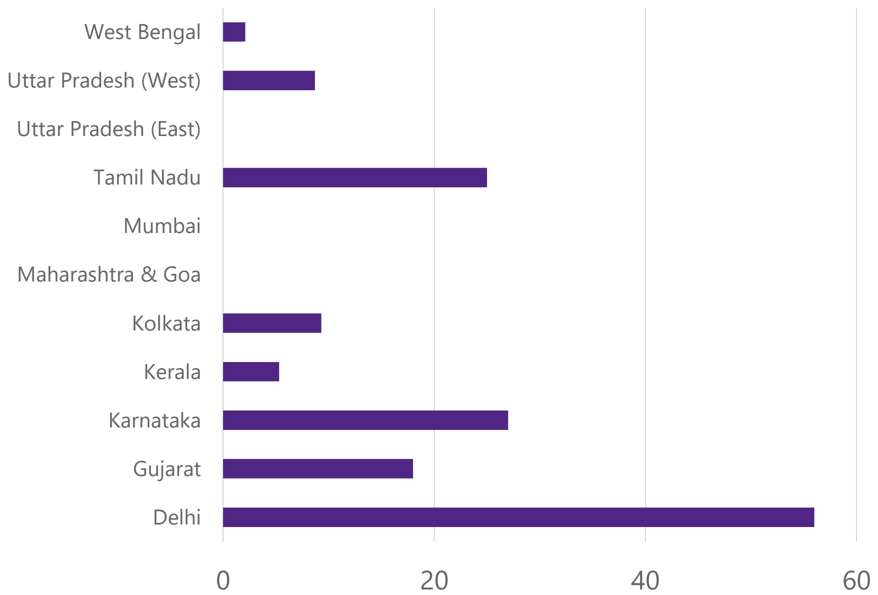
However, such use of spectrum highlights that there is an innate inefficiency in the way that spectrum is assigned. Although licences are issued on a national basis, operators will not use all spectrum bands nationally. Higher frequencies – particularly those in mmWave but also in bands such as 3400 MHz – will only be deployed in urban areas and where population is denser. At the same time, these areas are those where alternative technologies can be used to reduce the load on a mobile network – WiFi offload, fibre connections, or peer-to-peer connections. Further, to some extent these capacity constraints can be met by increased network densification instead of additional spectrum, which will be financially viable due to the high demand in these areas.

It is clear that there are significant portions of a country where higher frequencies of mobile spectrum are not being used, but the usual exclusive nature of the licence prevents other services sharing the spectrum. There have been moves to reduce this inefficiency – mandated sharing such as CBRS in the US has had some success – but these are comparatively rare. Higher frequencies will see an increasingly fragmented geographic footprint when used by mobile networks.

4.2 Regional licence variation

In some countries mobile spectrum is not assigned on a national basis, but instead regional licences are awarded. This is most common in larger countries, such as Canada, India and Australia, and for higher frequency bands where the propagation is less favourable (meaning there will be less interference between regions). In such regional auctions, the prices paid in different areas can vary considerably, as shown in Figure 4.1 – indeed, in this auction there were some areas in which spectrum did not sell at all[33].

Figure 4.1: Prices paid per block (in USD million) in the 2013 Indian auction[34]



This pattern is repeated in all regional auctions – with spectrum being more valuable in some regions, and sometimes unsold in others. The value here is derived from use, which – as explained above in Section 4.1 – varies by geotype, depending on population density, demand and income.

Again, this indicates that there is no uniform use of spectrum across countries, and there will be some areas where there is no excess demand for spectrum. It would be unreasonable to assign further spectrum in these areas, preventing alternative use.

[33] It is important to note that this auction was not considered successful; the reserve price was set at too high a level meaning there was limited participation. Despite this, the differing values of spectrum and the lack of sales in some regions shown how a national allocation of a specific spectrum band can lead to underutilisation in many regions.
[34] Source: TRAI

4.3 Return of existing holdings and no participation in awards

In the past few years there have been a few examples of operators either failing to renew spectrum licences, or returning them to regulators. The most high profile example of this has been in Korea, where all three operators effectively returned their 28 GHz spectrum (which was awarded at an auction in 2018) by failing to meet the rollout obligations included in their licences. Reports[35] indicated that the regulator had given operators clear notice on how the licences could be retained, but operators decided against this.

> **“[T]he ministry said the government had continuously encouraged the three operators to build more radio stations for 28GHz but the companies have failed to comply. The operators failed to even build the minimum number of 28GHz radio stations and offered no smartphones that supported the spectrum to consumers, the ministry said in its rebuke.”**

A lack of demand from operators can also be seen in a number of awards where incumbents have refused to take part in auctions. In the Indian auction described above, all but one operator declined to bid – although this was largely due to overly high reserve prices, it is illustrative that operators were not desperate for new bandwidth. In the auction in Paraguay in 2015, two of the four operators opted to not acquire additional spectrum in the AWS bands[36], again indicating that they could use existing frequencies to meet demand.

[35] See https://www.zdnet.com/article/south-korea-cancels-5g-28ghz-spectrum-allocation-to-telcos-due-to-lack-of-spending/, https://www.lightreading.com/5g/korean-govt-falls-for-5g-fallacy-over-28ghz/d/d-id/783031 and https://www.telecompaper.com/news/south-korean-government-cancels-sk-telecoms-28-ghz-spectrum-license-on-lack-of-investment--1463212 for details. The full decision can be found at https://www.msit.go.kr/eng/bbs/view.do?sCode=eng&mId=4&mPid=2&pageIndex=3&bbsSeqNo=42&nttSeqNo=753

[36] See https://www.bnamericas.com/en/news/claro-and-tigo-the-only-bidders-for-paraguay-4g-spectrum

5 Conclusions

This paper has examined the allocation of spectrum to Mobile Service (and the identification to IMT), the assignment and award of spectrum to mobile network operators, and the use of spectrum on these mobile networks.

5.1 A large amount of spectrum has been identified for IMT

We have shown that, driven by new technologies and increasing demand for data traffic, mobile operators have required larger bandwidths of spectrum in a variety of bands, which have been identified by the ITU at World Radio Conferences during the 20th and 21st centuries. The precise demands of spectrum have changed over time, moving from low bandwidth allocations in lower frequency bands, to additional bandwidths in the mid-band C-band (and even higher bandwidths in mmWave). This has led to the current situation where there is a large amount of spectrum identified for IMT in every ITU region, across a variety of frequency bands. Moving to 5G networks, IMT has been allocated additional bandwidths to accommodate demands for increased data, but there has also been a move to refarm existing spectrum away from legacy technologies. This refarming – particularly in the lower frequency bands which are used for coverage – will help operators to use existing network equipment and more efficiently use spectrum that is assigned.

The total amount of spectrum identified for IMT below 7 GHz is currently just over 1880 MHz; this varies slightly by region and country. There are some bands which are harmonised across all ITU regions, although these may not necessarily currently be configured with the same (or compatible) band plans. Other bands are restricted to smaller areas, although the need for ecosystem and equipment means that there is a minimum size requirement for any identification.

This spectrum below 7 GHz is accompanied by large bandwidths in the mmWave bands – at WRC-19 an additional 17.25 GHz of spectrum was identified for IMT, although, as discussed below, this remains largely underutilised.

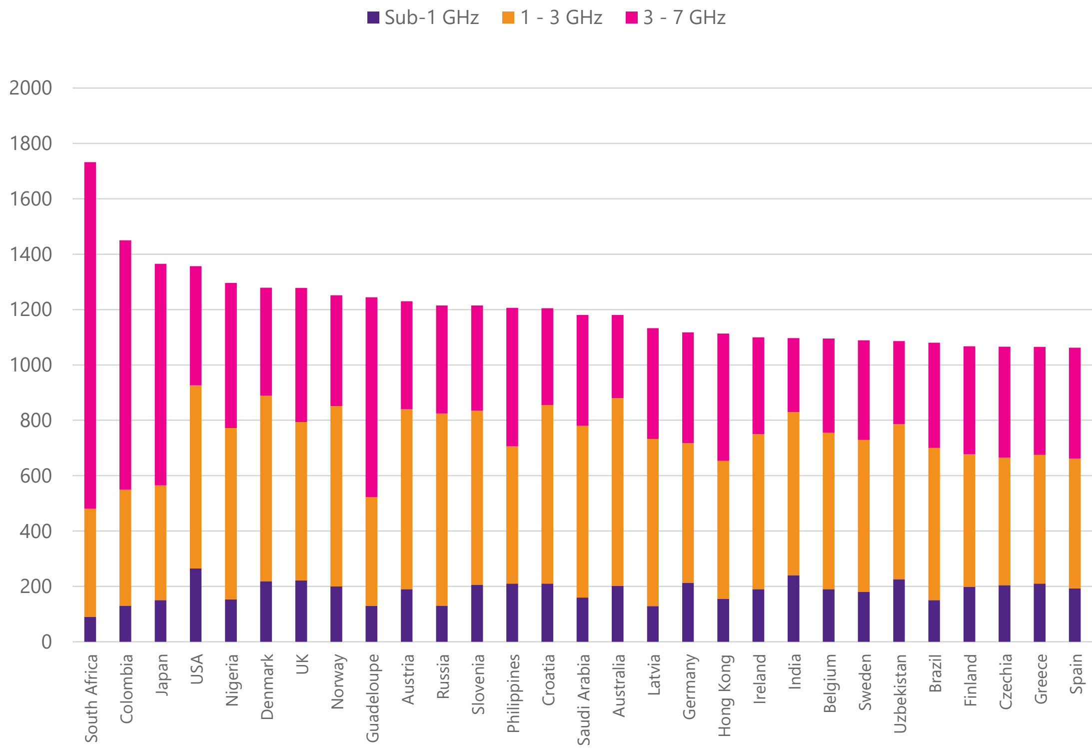
5.2 Spectrum assignment is more limited

Despite the accelerating demand for mobile broadband leading to this high level of spectrum identification, the majority of countries in the world have assigned less than half the identified spectrum to mobile operators. Our analysis has shown that even those countries with the largest amount of spectrum below 7 GHz assigned, shown below, have large amounts of identified spectrum which are yet to be assigned to operators.

These thirty countries have, typically, been the most advanced in assigning newly-identified spectrum, following efficient and transparent processes for award. Despite this, there remain a number of identified bands which are underutilised, due to inefficient band plans, legacy users in the bands leading to interference or clearance issues, or an inertia to assign spectrum.

Instead of advocating for more spectrum to be identified for IMT, it is clear that regulators and governments should be encouraged to first make sure that they are assigning all currently identified spectrum to mobile operators. This would provide networks with large amounts of harmonised spectrum, at ideal frequencies, with an established ecosystem already available.

Figure 5.1: Current spectrum assignments: countries with the most spectrum assigned



This conclusion is even more stark when looking at higher frequency spectrum in the mmWave bands. Of the 17.25 GHz identified above 7 GHz, only 35 countries have assigned any spectrum at all, and only four countries (South Africa, the UK, the UAE, and the US) have assigned more than 5 GHz. This low assignment level contrasts to the potential demand for high bandwidth services which was presumed ahead of 5G rollout. The mobile industry have yet to overcome the challenges of rolling out networks using this high frequency spectrum, such as low propagation, the need for high power levels, and the lower reliability of connection. However, solving these operational difficulties in the mmWave can offer benefits to mobile operators, such as obtaining large continuous spectrum at relatively low prices during auctions and enjoying already globally harmonized frequencies for economies of scales, without jeopardising other wireless industries. This is particularly important since those geographical areas in which capacity is most likely to be constrained are those areas where mmWave bandwidth may be most suitable.

5.3 Future demand for mobile data is uncertain

When considering spectrum for 6G and beyond, the mobile industry is again stating that large bandwidths are required, to serve an increasing number of services. There have been discussions around the use of the sub-THz range, from 90 GHz to 300 GHz, as well as potential expansions in the 6 GHz band and bands between 7 GHz and 24 GHz.

The uptake of 5G has been muted, particularly outside the traditional mobile broadband applications, and as seen above there has been little demand for spectrum in the mmWave frequencies which would be required for higher speed and lower latency technologies. Given this, the current requirements for 6G technology are uncertain and still subject to further study, and it is likely that even where there is a demand for high bandwidths this could be accommodated in the existing mmWave identification. Indeed, given current usage by various services[37] in the bands between 7 GHz and 24 GHz, there would be a limited amount of contiguous spectrum available for identification in any case. Mobile equipment manufacturers are mooting the need for an additional 750 MHz of spectrum for each operator for 6G network rollout, but this would lead to requirements of over 2 GHz in most countries, which would not be possible given the existing congestion in these bands. Instead, as discussed previously, the existing unused identification in the mmWave bands can be brought into service.

With the increase in spectrum refarming, and the availability of large existing bandwidths at mmWave, regulatory bodies and ITU study groups should be cautious against considering the possibility of recommending that future WRCs identify significantly large additional bandwidths for IMT. Even where spectrum is unused, an identification for IMT prevents other international services – such as science research, broadcast, or satellite – from using this spectrum.

Instead, as data traffic grows and network operators require greater capacity, regulators can focus on assigning existing spectrum which has already been identified (particularly in the mmWave bands) and encouraging more efficient network deployments, including the use of small cells and dense urban networks. Reducing the costs of this network deployment – through greater access to sites, improved infrastructure sharing, and more certainty on licencing – can lead to better outcomes for consumers and network operators alike, while not requiring further spectrum to be withheld from other users.

[37] There are a total of sixteen ITU radio services with allocations in the 7 – 24 GHz band.

Appendix A 3GPP band plans

In a further attempt to harmonise spectrum allocations, 3GPP defined a number of LTE spectrum bands, drawing on both previous generations' spectrum and the newly allocated bands. It is useful to compare these to the spectrum bands identified in Section 2.2, as the band plans included show how historic use of spectrum by mobile technologies leads to inefficiencies.

The LTE bands are illustrated below, overlaid with an indication of the globally identified spectrum frequencies.

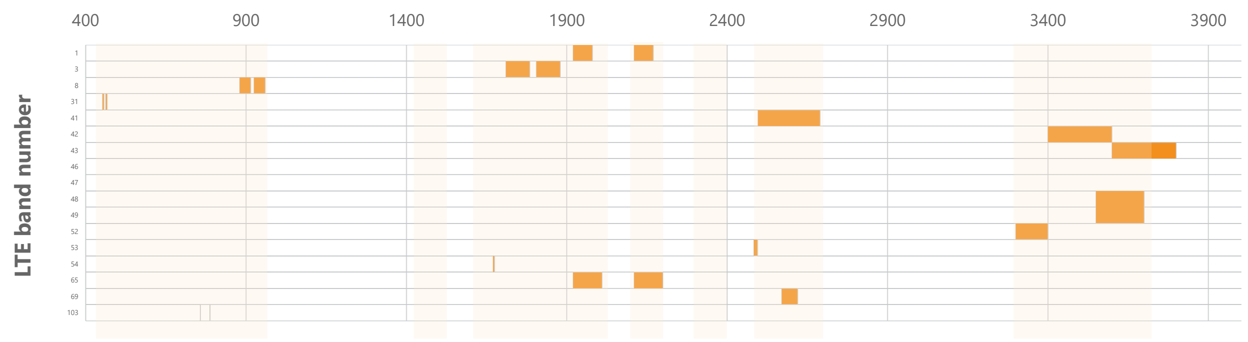
Figure A.1: Spectrum allocated to LTE band numbers

As can be seen, spectrum listed by 3GPP for IMT (LTE) is spread across a wide range of frequencies, although there are three main groupings: spectrum under 1 GHz, between 1400 MHz and 2600 MHz, and above 3300 MHz. This figure is truncated at 4000 MHz; there are further LTE bands at higher frequencies.

It is clear that the majority of band plans do not make full efficient use of the identified spectrum. FDD spectrum use necessarily includes a duplex gap which cannot be used by IMT; other band plans are focussed on only part of any particular identified band. While it is possible to combine LTE bands to make better use of the identified spectrum, only certain combinations are viable. It should also be noted that there are some LTE bands which make use of spectrum which has not as yet been identified for IMT.

This is further complicated by the fact that not every band is recognised in every region. Very few bands are harmonised globally; filtering the figure above to look only at global bands (as shown below) we can see a significant decrease in spectrum available globally. This does not give a good illustration of mobile use of spectrum, however, since every region has its own allocations.

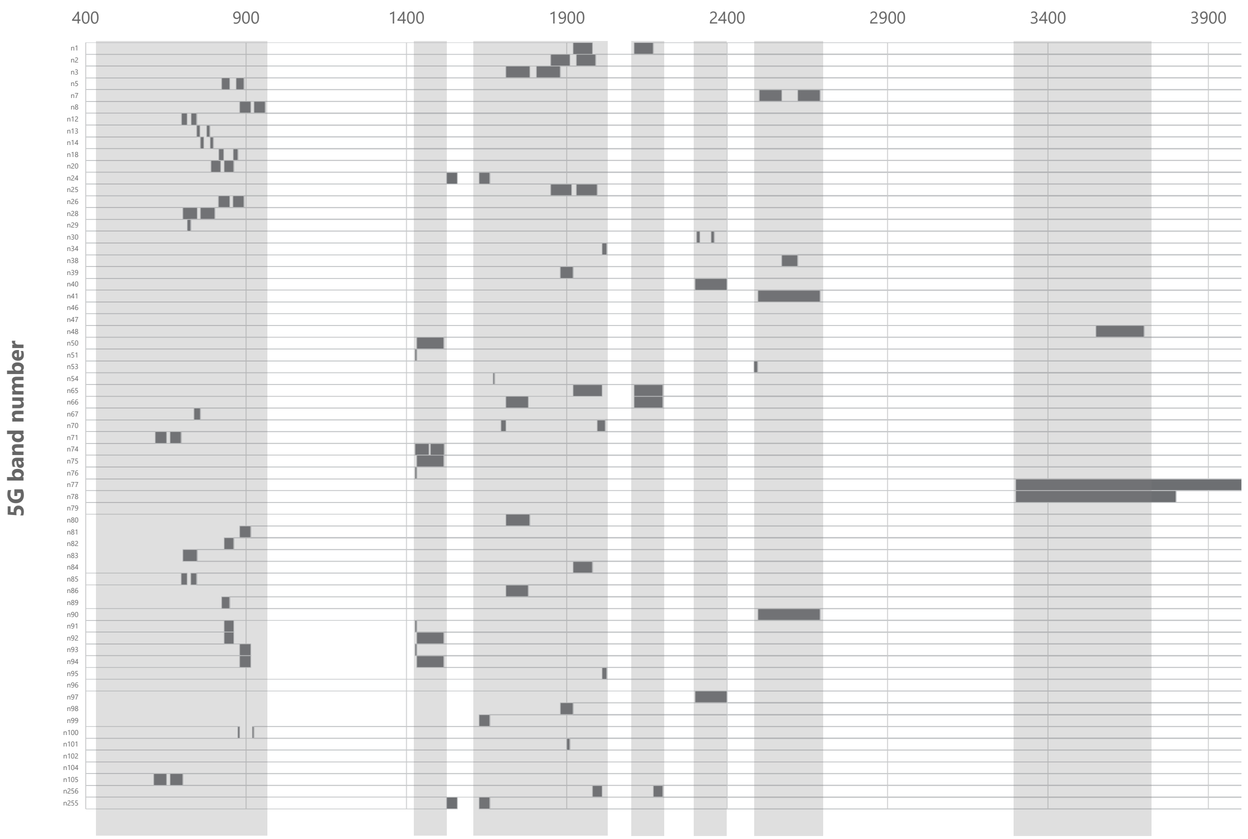
Figure A.2: Spectrum allocated to LTE bands globally)



A.1 5G NR revisions

With the advent of 5G new radio (NR), many of the existing LTE bands have been reidentified, with bands named as “n1”, “n2”, and so on. Other bands have been left as LTE-only identifications, while others have been introduced.

Figure A.3: Spectrum allocated to 5G band numbers



The AWS-1 and AWS-3 bands, for example, (LTE bands 4 and 10) are not assigned for 5G, but this is not to say that this spectrum is no longer allocated to the public mobile broadband service. Firstly, LTE networks are continuing to operate, and so this spectrum is still assigned in the previous generation; secondly, the new band n66 includes all the spectrum which was previously included in bands 4 and 10.

The overlap between bands illustrated here and the number of potential band plans that can be defined by regulators can cause inefficiencies in the assignment and award of spectrum; any interference caused by a lack of international harmonisation in band plans will further decrease efficiency.

A.2 Tables of LTE and 5G band numbers

This appendix includes tables showing the band numbering system used for LTE and 5G technologies, as illustrated above.

Figure A.4: LTE band numbers

Band number	Name	Type	Downlink start	Downlink end	Uplink start	Uplink end	Total bandwidth	Duplex spacing	Region
1	2100	FDD	2110	2170	1920	1980	120	190	Global
2	1900 PCS	FDD	1930	1990	1850	1910	120	80	North America
3	1800+	FDD	1805	1880	1710	1785	150	95	Global
4	AWS-1	FDD	2110	2155	1710	1755	90	400	North America
5	850	FDD	869	894	824	849	50	45	North America
7	2600	FDD	2620	2690	2500	2570	140	120	Region 1
8	900 GSM	FDD	925	960	880	915	70	45	Global
9	1800	FDD	1844.9	1879.9	1749.9	1784.9	70	95	Region 3
10	AWS-3	FDD	2110	2170	1710	1770	120	400	North America
11	1500 Lower	FDD	1475.9	1495.9	1427.9	1447.9	40	48	Japan
12	700 a	FDD	729	746	699	716	34	30	North America
13	700 c	FDD	746	756	777	787	20	31	North America
14	700 PS	FDD	758	768	788	798	20	30	North America
17	700 b	FDD	734	746	704	716	24	30	North America
18	800 Lower	FDD	860	875	815	830	30	45	Japan
19	800 Upper	FDD	875	890	830	845	30	45	Japan
20	800 DD	FDD	791	821	832	862	60	41	Region 1
21	1500 Upper	FDD	1495.9	1510.9	1447.9	1462.9	30	48	Japan
22	3500	FDD	3510	3590	3410	3490	160	100	EMEA
24	1600 L-band	FDD	1525	1559	1626.5	1660.5	68	101.5	North America
25	1900+	FDD	1930	1995	1850	1915	130	80	North America
26	850+	FDD	859	894	814	849	70	45	North America
27	800 SMR	FDD	852	869	807	824	34	45	North America
28	700 APT	FDD	758	803	703	748	90	55	APAC, EU
29	700 d	SDL	717	728			11		North America

Band number	Name	Type	Downlink start	Downlink end	Uplink start	Uplink end	Total bandwidth	Duplex spacing	Region
30	2300 WCS	FDD	2350	2360	2305	2315	20	45	North America
31	450	FDD	462.5	467.5	452.5	457.5	10	10	Global
32	1500 L-band	SDL	1452	1496			44		EMEA
33	TD 1900	TDD	1900	1920			20		EMEA
34	TD 2000	TDD	2010	2025			15		EMEA
35	PCS Lower	TDD	1850	1910			60		North America
36	PCS Upper	TDD	1930	1990			60		North America
37	PCS Center	TDD	1910	1930			20		North America
38	TD 2600	TDD	2570	2620			50		EMEA
39	TD 1900+	TDD	1880	1920			40		China
40	TD 2300	TDD	2300	2400			100		China
41	TD 2600+	TDD	2496	2690			194		Global
42	TD 3500	TDD	3400	3600			200		Global
43	TD 3700	TDD	3600	3800			200		Global
44	TD 700	TDD	703	803			100		APAC
45	TD 1500	TDD	1447	1467			20		China
46	TD Unlicense	TDD	5150	5925			775		Global
47	TD V2X	TDD	5855	5925			70		Global
48	TD 3600	TDD	3550	3700			150		Global
49	TD 3600r	TDD	3550	3700			150		Global
50	TD 1500+	TDD	1432	1517			85		EU
51	TD 1500-	TDD	1427	1432			5		EU
52	TD 3300	TDD	3300	3400			100		Global
53	TD 2500	TDD	2483.5	2495			11.5		Global
54	TD 1700	TDD	1670	1675			5		Global
65	2100+	FDD	2110	2200	1920	2010	180	190	Global
66	AWS	FDD	2110	2200	1710	1780	160	400	North America
67	700 EU	SDL	738	758			20		EMEA
68	700 ME	FDD	753	783	698	728	60	55	EMEA
69	DL b38	SDL	2570	2620			50		Global
70	AWS-4	FDD	1995	2020	1695	1710	40	300	North America
71	600	FDD	617	652	663	698	70	46	North America
72	450 PAMR	FDD	461	466	451	456	10	10	EMEA
73	450 APAC	FDD	460	465	450	455	10	10	APAC

Band number	Name	Type	Downlink start	Downlink end	Uplink start	Uplink end	Total bandwidth	Duplex spacing	Region
74	L-band	FDD	1475	1518	1427	1470	86	48	North America
75	DL b50	SDL	1432	1517			85		EU
76	DL b51	SDL	1427	1432			5		EU
85	700 a+	FDD	728	746	698	716	36	30	North America
87	410	FDD	420	425	410	415	10	10	EMEA
88	410+	FDD	422	427	412	417	10	10	EMEA
103	NB-IoT	FDD	757	758	787	788	2	30	Global

Figure A.5: 5G NR band numbers

Band number	Name	Type	Downlink start	Downlink end	Uplink start	Uplink end	Total bandwidth	Duplex spacing	Region
n1	2100	FDD	2110	2170	1920	1980	120	190	Global
n2	1900 PCS	FDD	1930	1990	1850	1910	120	80	North America
n3	1800	FDD	1805	1880	1710	1785	150	95	Global
n5	850	FDD	869	894	824	849	50	45	Global
n7	2600	FDD	2620	2690	2500	2570	140	120	EMEA
n8	900	FDD	925	960	880	915	70	45	Global
n12	700 a	FDD	729	746	699	716	34	30	North America
n13	700 c	FDD	746	756	777	787	20	-31	North America
n14	700 PS	FDD	758	768	788	798	20	-30	North America
n18	800 Lower	FDD	860	875	815	830	30	45	Japan
n20	800	FDD	791	821	832	862	60	-41	EMEA
n24	1600 L	FDD	1525	1559	1626.5	1660.5	68	-101.5	North America
n25	1900+	FDD	1930	1995	1850	1915	130	80	North America
n26	850+	FDD	859	894	814	849	70	45	North America
n28	700 APT	FDD	758	803	703	748	90	55	APAC,EU
n29	700 d	SDL	717	728			11		North America
n30	2300 WCS	FDD	2350	2360	2305	2315	20	45	North America
n34	TD 2000	TDD	2010	2025			15		EMEA
n38	TD 2600	TDD	2570	2620			50		EMEA
n39	TD 1900+	TDD	1880	1920			40		China
n40	TD 2300	TDD	2300	2400			100		APAC
n41	TD 2600+	TDD	2496	2690			194		Global
n46	TD Unlicense	TDD	5150	5925			775		Global

Band number	Name	Type	Downlink start	Downlink end	Uplink start	Uplink end	Total bandwidth	Duplex spacing	Region
n47	V2X	TDD	5855	5925			70		Global
n48	TD 3600	TDD	3550	3700			150		Global
n50	TD 1500+	TDD	1432	1517			85		EU
n51	TD 1500-	TDD	1427	1432			5		EU
n53	TD 2500	TDD	2483.5	2495			11.5		
n54	TD 1700	TDD	1670	1675			5		
n65	2100+	FDD	2110	2200	1920	2010	180	190	Global
n66	AWS	FDD	2110	2200	1710	1780	160	400	North America
n67	700 EU	SDL	738	758			20	0	EMEA
n70	AWS-4	FDD	1995	2020	1695	1710	40	300	North America
n71	600	FDD	617	652	663	698	70	-46	North America
n74	L-band	FDD	1475	1518	1427	1470	86	48	EMEA
n75	DL 1500+	SDL	1432	1517			85		EU
n76	DL 1500-	SDL	1427	1432			5		EU
n77	TD 3700	TDD	3300	4200			900		
n78	TD 3500	TDD	3300	3800			500		
n79	TD 4700	TDD	4400	5000			600		
n80	UL n3	SUL	0	0	1710	1785	75		Global
n81	UL n8	SUL	0	0	880	915	35		Global
n82	UL n20	SUL	0	0	832	862	30		EMEA
n83	UL n28	SUL	0	0	703	748	45		APAC, EU
n84	UL n1	SUL	0	0	1920	1980	60		Global
n85	700 a+	FDD	728	746	698	716	36	30	North America
n86	UL n66	SUL	0	0	1710	1780	70		North America
n89	UL n5	SUL	0	0	824	849	25		North America
n90	TD 2600+	TDD	2496	2690			194		Global
n91	FD 1500-	FDD	1427	1432	832	862	35	595	North America
n92	FD 1500+	FDD	1432	1517	832	862	115	600	North America
n93	FD 1500-	FDD	1427	1432	880	915	40	547	North America
n94	FD 1500+	FDD	1432	1517	880	915	120	552	North America
n95	UL n34	SUL	0	0	2010	2025	15		China
n96	6Ghz	TDD	5925	7125			1200		North America
n97	UL n40	SUL	0	0	2300	2400	100		APAC
n98	UL n39	SUL	0	0	1880	1920	40		China

Band number	Name	Type	Downlink start	Downlink end	Uplink start	Uplink end	Total bandwidth	Duplex spacing	Region
n99	UL n24	SUL	0	0	1626.5	1660.5	34		North America
n100	RMR 900	FDD	919.4	925	874.4	880	11.2	45	0
n101	RMR 1900	TDD	1900	1910			10		
n102	Lower 6GHz	TDD	5925	6425			500		
n104	7GHz	TDD	6425	7125			700		
n105	APT 600	FDD	612	652	663	703	80	51	
n256	NTN 2GHz	FDD	2170	2200	1980	2010	60	190	Non-terra
n255	NTN 1.6GHz	FDD	1525	1559	1626.5	1660.5	68	101.5	Non-terra

Appendix B Full results for analysis of spectrum assigned by country

This appendix contains more detailed charts illustrating the amount of spectrum assigned in each country analysed. Due to the number of countries the information is divided into four charts, split by geography.

Figure B.1: Spectrum assigned (MHz) in ITU Region 1 (Europe and Central Asia)

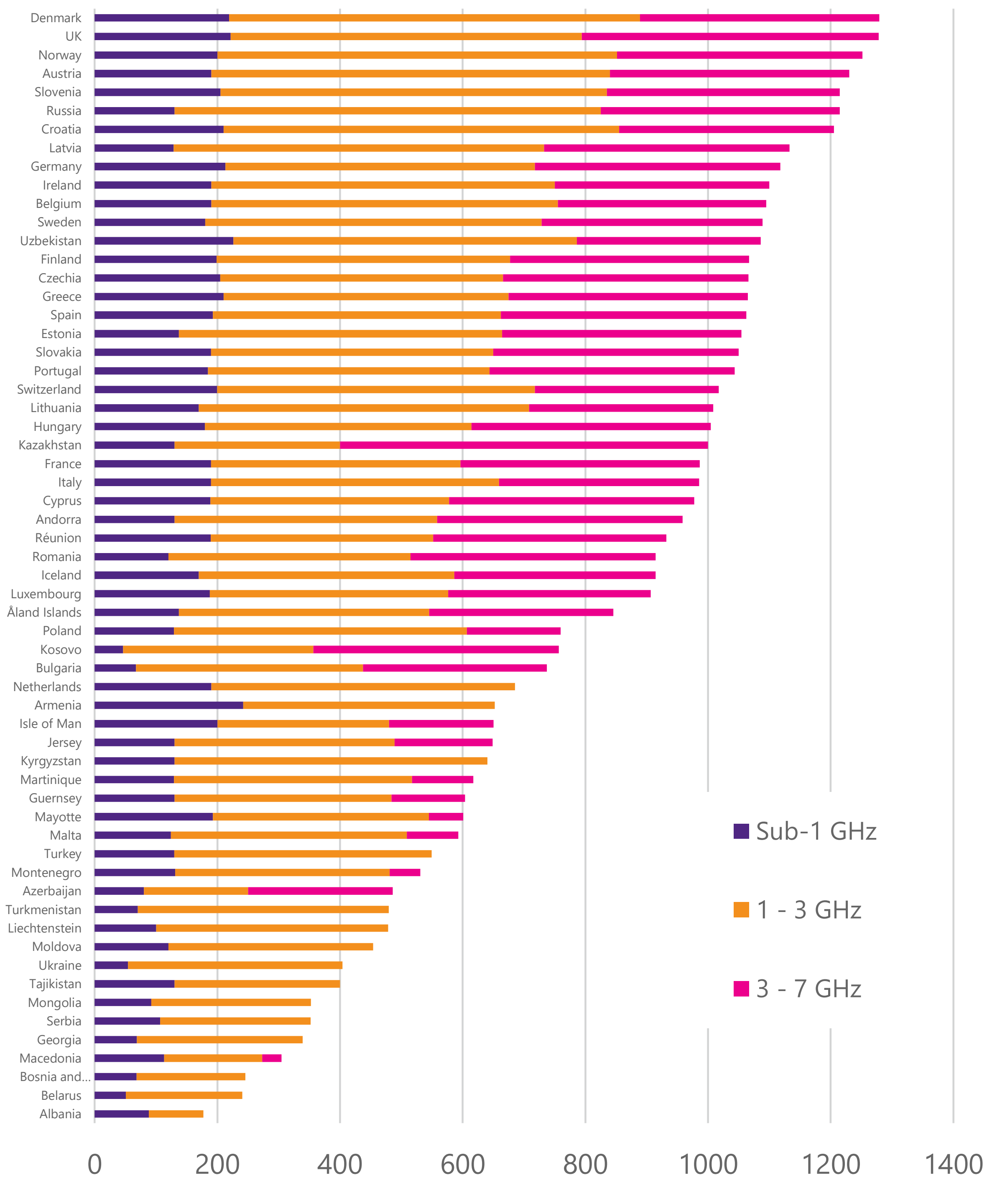


Figure B.2: Spectrum assigned (MHz) in ITU Region 1 (Africa and Middle East)

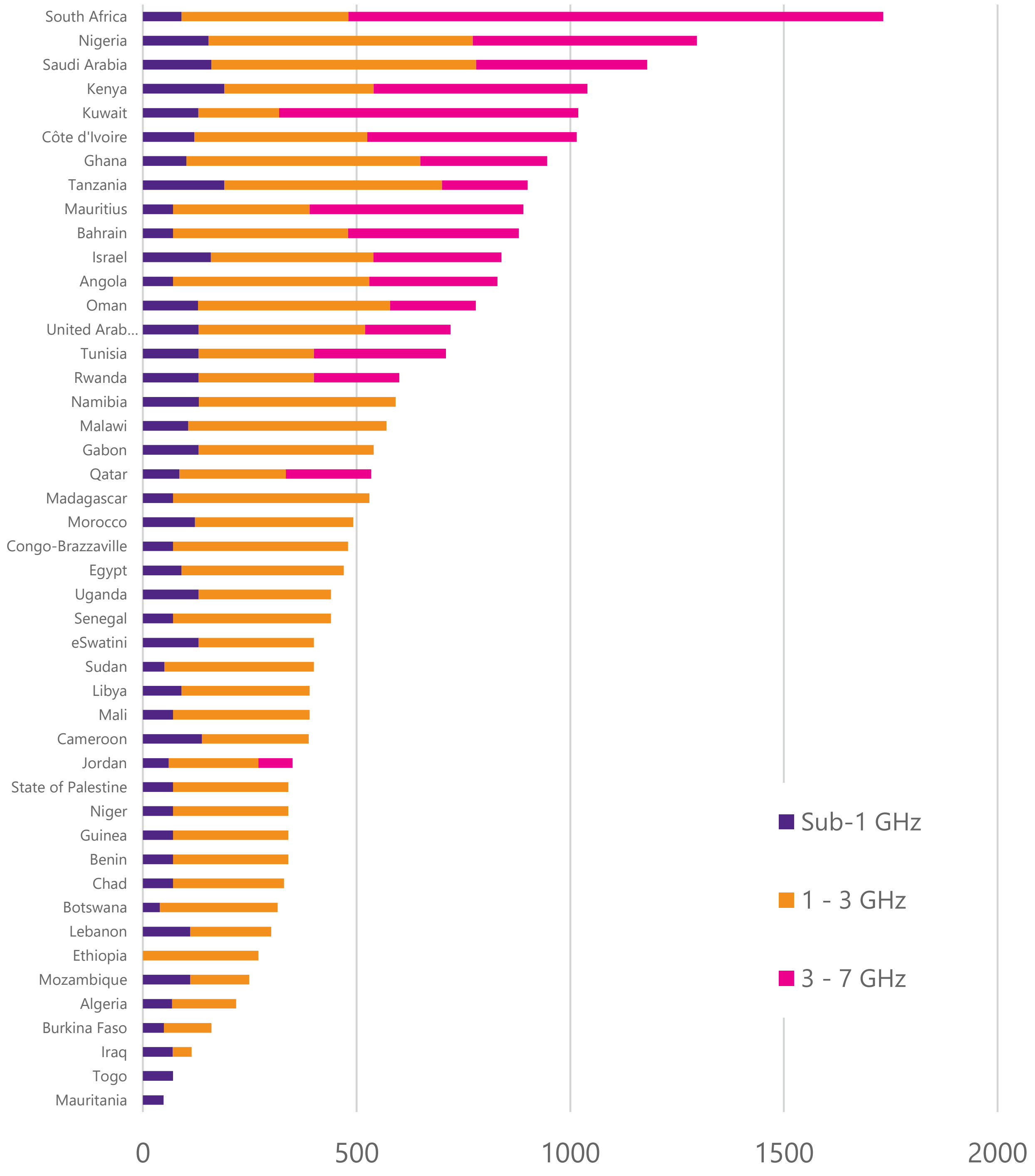


Figure B.3: Spectrum assigned (MHz) in ITU Region 2 (Americas)

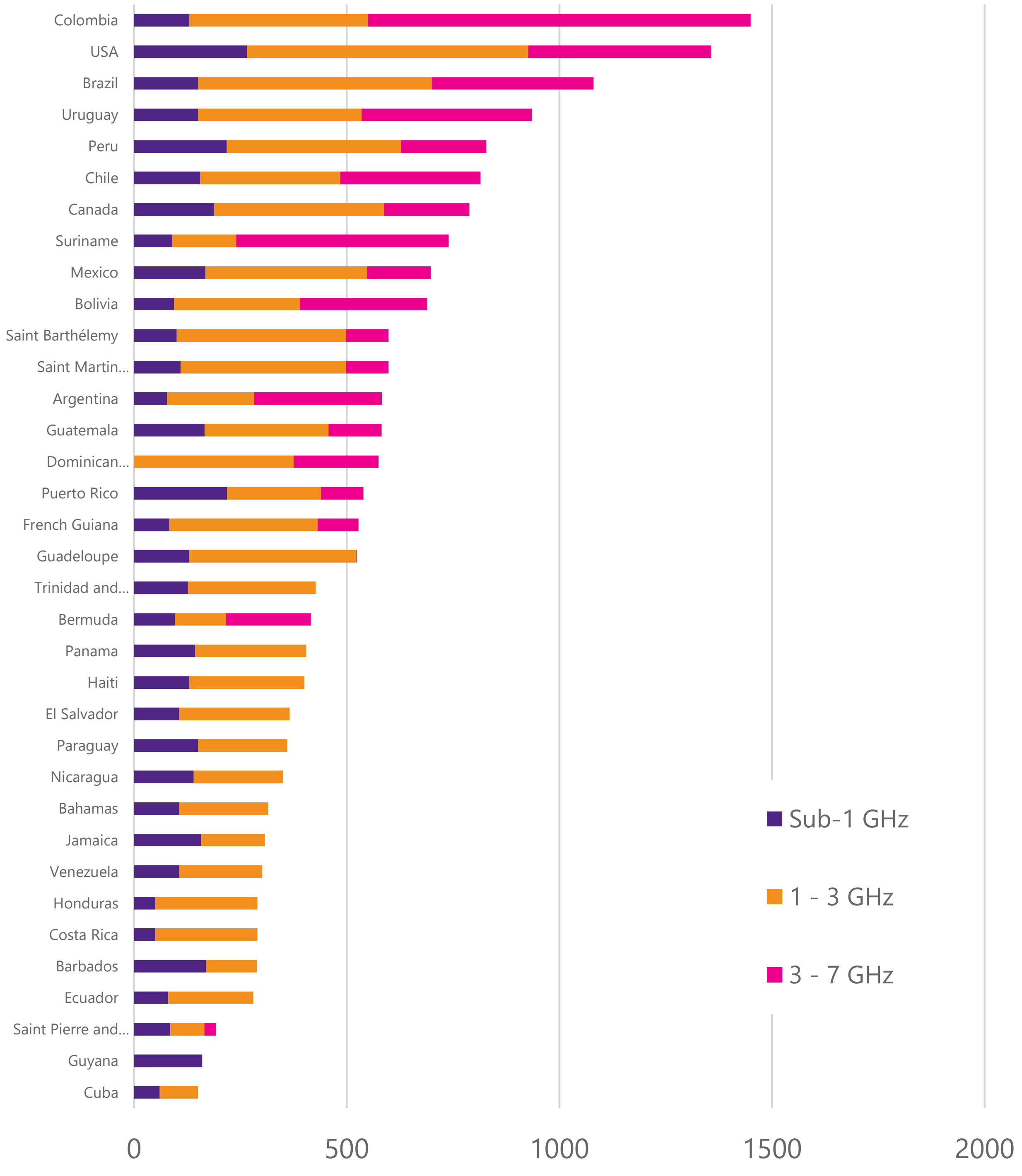


Figure B.4: Spectrum assigned (MHz) in ITU Region 3 (Asia Pacific)