Vision 2030: mmWave Spectrum Needs

Estimating High-Band Spectrum Needs in the 2025-2030 Time Frame

June 2022

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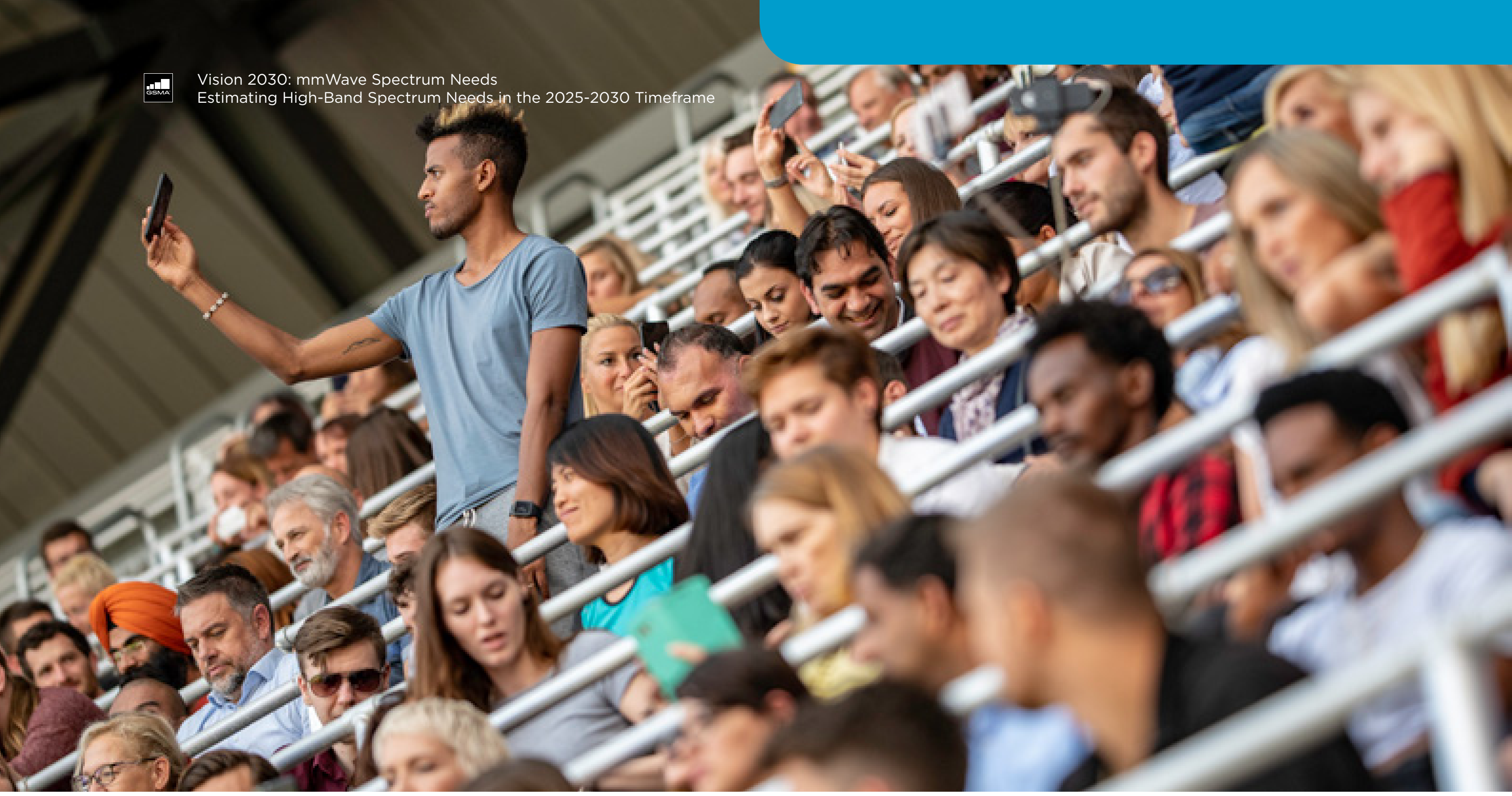


Executive summary

mmWave is essential to complement low- and mid-band spectrum and ensure a successful 5G deployment

Millimetre wave (mmWave) spectrum[1] is essential for the deployment of high-capacity, low-latency 5G networks. It complements low and mid-band spectrum implementations in dense urban areas and provides fibre-like connectivity to suburban areas, and households in rural towns through 5G fixed wireless access (FWA) technologies. It also helps ensure secure, reliable and low-latency networks in contexts such as manufacturing plants or high-density locations e.g. stadia and travel hubs.

mmWave spectrum presents challenges and opportunities unique to its physical characteristics. It offers unmatched bandwidth when compared to any other 5G band, providing capacity, speed and low latency; however, mmWaves have limited coverage capabilities, with reduced ability to penetrate glass, concrete and wood.

As mobile data traffic continues to grow rapidly, with demand for higher data rates to serve new applications, mmWave spectrum will play a key role in guaranteeing 5G network capacity, as it can accommodate more capacity and bandwidth than any other band. Because spectrum in these bands is abundant, mmWave rollouts are ideally placed to support low- and mid-band spectrum in providing capacity to 5G networks.

Successful and effective mmWave spectrum assignments are therefore important to ensure 5G achieves its true potential in terms of performance and socio-economic impact. Any spectrum capacity constraints should be addressed early by licensing adequate mmWave spectrum for IMT services.

A number of 5G use cases will depend on mmWave for successful deployment: enhanced mobile broadband (eMBB), especially in dense urban areas; FWA in urban and suburban areas and rural towns; and 5G enterprise networks for Industry 4.0 factories.

1 mmWave spectrum referred to in this document includes the following: 26 GHz, 28 GHz, 40 GHz and 66 GHz.

Figure i: How mmWave enables the success of 5G use cases

Source: GSMA Intelligence

eMBB

Dense urban area deployment to complement low bands and mid-bands

FWA

FWA deployment to complement low bands and mid-bands in urban, suburban and rural areas

Enterprise networks

mmWave-only enterprise network deployment on large Industry 4.0 factory floors to enable high-bandwidth, low-latency applications

5 GHz per market will be needed on average to satisfy expected demand for different use cases

By 2030, an average of 5 GHz of mmWave spectrum per market will be needed to satisfy demand for different 5G use cases, including eMBB, FWA and enterprise networks. The findings of this report underline how crucial mmWave spectrum is when considering the growth that consumer and household data will continue to experience over the period to 2030. Current 5G network capacity worldwide, based on low and mid-band spectrum, will not be sufficient to satisfy demand for 5G services by 2030:

- To provide eMBB services, an average of 4.5 GHz of mmWave spectrum will be needed to provide the necessary capacity on top of low and mid-band spectrum. This assumes that adequate mid-band spectrum will be assigned by 2030.[2]
- We expect 5G FWA to need between 350 MHz and 1.2 GHz of mmWave spectrum by 2030 to provide FWA services in urban and suburban areas and rural towns. mmWave will complement the capacity and coverage provided by sub-7 GHz spectrum, in order to sustain fibre-like speeds in households located in these areas.
- Enterprise networks used in manufacturing Industry 4.0 factories will require approximately 150 MHz of mmWave spectrum.

Mid-band spectrum assignments, 5G and FWA penetration and industrial 5G applications uptake are the main drivers affecting the identified range.

2 As recommended in Estimating the mid-band spectrum needs in the 2025–2030 time frame, a report by Coleago Consulting Ltd for GSMA, 2021

Figure ii: Expected amount of mmWave spectrum needed per market by 2030

Source: GSMA Intelligence

eMBB*	FWA**	Enterprise networks
4.5 GHz	350 MHz	150 MHz

Total: 5 GHz

* In early adopter countries
** In dense urban environments

Key policy priorities to maximise 5G socio-economic benefits

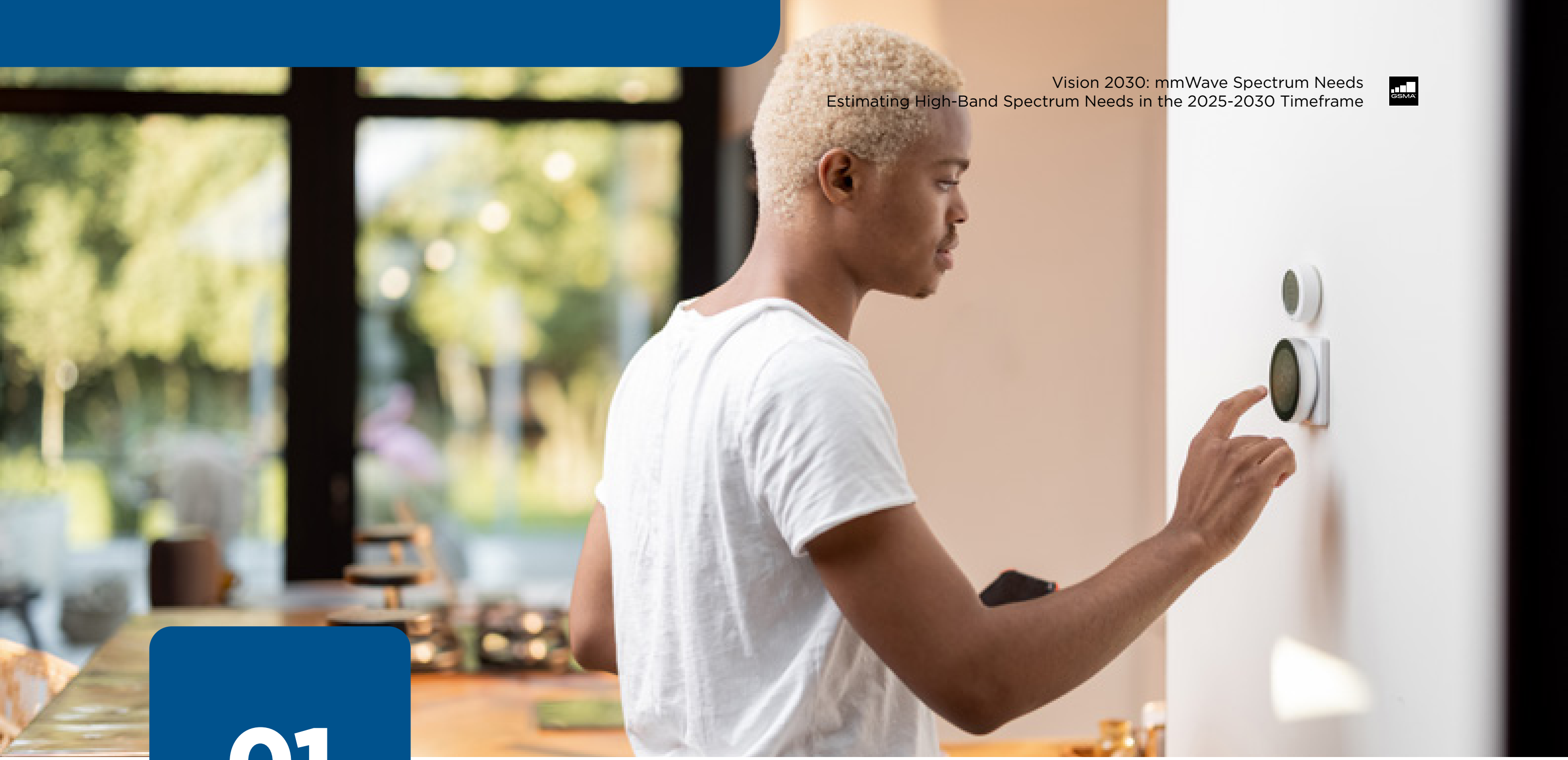
Current industry positions[3] are calling for at least 800 MHz to be awarded per operator in initial mmWave bands (e.g. 26/28 GHz). However, this is unlikely to be enough in the longer term.[4]

This study supports the following policy recommendations for ensuring adequate network capacity by 2030:

- **Making 5 GHz or more of mmWave spectrum available.**
- **Taking a holistic approach to the release of spectrum in all 5G bands and ensure operators have a clear roadmap to assignments.**
- **Consider spectrum needs for when 5G is reaching its peak, likely to be in the 2025-2030 timeframe in most countries.**

Such an approach will ensure both coverage and capacity bands are adequately available. mmWave spectrum should not be considered a replacement for mid-band and vice-versa.

3 5G Spectrum, GSMA Public Policy Position, GSMA, 2021
4 Assuming a range of three to four operators per market, the total mmWave spectrum currently advocated for would come short of 3.5 GHz in total.



01

Introduction

This report sets out the findings of a study prepared by GSMA Intelligence on the required amount of 5G mmWave spectrum worldwide by 2030 to satisfy the expected demand for 5G services.

Higher bandwidth mmWave deployments are expected to play a key role in the delivery of a range of 5G use cases:

- **Enhanced mobile broadband (eMBB):** The bandwidth available in mmWave bands can help to accommodate high-capacity eMBB applications for consumers on top of the already available capacity provided by low and mid-band spectrum. This will be particularly significant in densely populated urban environments and at specific locations where large volumes of data are produced (e.g. transport hubs and event venues).
- **Fixed wireless access (FWA):** 5G FWA deployments currently rely on both mid-bands and mmWave bands. 5G FWA networks are being rolled out in underserved areas with few fixed broadband alternatives. This includes rural towns, suburban and urban areas. Additionally, in markets where FTTH coverage is low, such as low and middle-income countries, FWA is being used as a reliable and faster time-to-market alternative to FTTH. In our modelling we focus on these scenarios, assuming mmWaves would be used as an additional capacity layer complementing mid-bands.
- **Enterprise networks for verticals and enterprise solutions**: mmWaves are expected to play a primary role in the deployment of networks in, for example, stadia and factory floors for a number of reasons. mmWave spectrum is a good fit for indoor environments due to the low risk of interference and the significant bandwidth available in these bands to enable traffic-intensive use cases. It is also well suited to applications where concurrent traffic is high and uplink requirements are particularly important, such as in the case of a high density of video cameras for computer vision, AR/VR applications and automated guided vehicles (AGVs).

In this study, we therefore calculate the amount of mmWave spectrum needed based on the forecasted demand for 5G services in three main scenarios. First, we assess the mmWave spectrum required to satisfy 5G eMBB use cases in the most densely populated areas of 10 cities globally. Second, we assess the mmWave spectrum required to provide FWA services in urban and suburban areas and rural towns, differentiating between highly developed and developing economies. Finally, we assess the mmWave spectrum required to implement enterprise networks on a representative manufacturing Industry 4.0 factory floor.

The modelling exercise follows and complements the previous GSMA (2021)[5] report. An annex is included, which contains supplementary material on the methodology and assumptions used in implementing the model.

The need for spectrum is driven by two main factors: the density of mobile networks in each area and the traffic in the area. Considering that there are limits to site densification (interference and permission planning), we assume a very dense mobile infrastructure (a network with an inter-site distance of 400 metres) and look at the spectrum needs according to different levels of traffic demand density measured in Gb/s per square kilometre.

In the development of the ITU's IMT-2020 requirements, the user-experienced data rate relates to people, but this will account for only part of the traffic. Connected cars, cameras and IoT devices will generate substantial amounts of traffic. Actually, one of the requirements of 5G is to support 10 million devices per square kilometer[6]. We expect this non-human generated traffic to be highly correlated with population density and thus also generated mostly in areas characterised by high population density.

5 Estimating the mid-band spectrum needs in the 2025–2030 time frame, a report by Coleago Consulting Ltd for GSMA, 2021
6 Recommendation: ITU REC-M2083

02

mmWave spectrum requirements for 5G eMBB by 2030

Depending on the urban characteristics of the city analysed and the expected 5G penetration, an average of 3 GHz and 4.5 GHz of mmWave spectrum will be needed to satisfy demand for IMT services in the assessed scenario. This assumes that adequate mid-band spectrum will be assigned by 2030, as recommended in GSMA (2021).[7]

Figure 1: Expected amount of mmWave spectrum needed for 5G eMBB based on 5G adoption and expected data consumption growth

Source: GSMA Intelligence

Early adopter countries[7]	Other countries
4.5 GHz	3 GHz

7 Ibid.
8 In this report, early adopter countries are those characterised by high levels of 5G penetration and smartphone penetration and higher-than-average expected data consumption growth

Demand for 5G services is expected to continue growing rapidly in upcoming years. Urban areas, especially the densest parts of them, risk experiencing near-saturation of their networks without the use of mmWave spectrum.

As demand for mmWave spectrum is driven by population density and expected 5G penetration rates, the densest parts of cities in most developed economies – which are generally associated with higher 5G penetration – are where mmWave will play the most significant role in adding network capacity on top of low and mid-band spectrum.

Spectrum demand model results in selected cities

We have calculated mmWave spectrum requirements for 10 cities worldwide. Details of the modelling exercise, including an extensive explanation of the assumptions, data and calculations used, are presented in the annex.

The results of the model are presented in Table 1. Cities are ordered from the smallest to highest amount of mmWave necessary to satisfy demand for 5G services in dense urban areas.

The results presented account for the two main determinants of demand and supply for 5G services: the activity factor, ranging in central scenarios from 10% to 15%; and the mid-band spectrum available by 2030, reflecting both a scenario where no further mid-band spectrum will be assigned to IMT by 2030 and a scenario where recommendations from GSMA (2021)[9] on mid-band spectrum needs are integrated.

The results of our modelling show a wide range of spectrum needs for each city and this requires some interpretation. As explained above, the key variables driving differences in the need for mmWave band spectrum are population density, the activity factor and amount of mid-band spectrum available.

Differences in population density and the size of the identified urban centre help explain the gaps between the results for cities located in countries that are similar in terms of economic development. For example, the density in the most populated quartile in Johannesburg (more than 50,000 people per square kilometre) is higher than in Mumbai (around 35,000 people per square kilometre). This drives up the need for additional spectrum, as further densification is made impossible.

The activity factor, defined as the percentage of connections active at any given time, is a second element that is responsible for differences in terms of spectrum needs for cities with similar population densities but different economic characteristics, a proxy that can indicate higher or lower expected 5G penetration.

Providing a lower and higher limit, we aimed to address the fact that the activity factor is likely to be different around the world. For example, we based this on countries' income levels as a proxy for 5G adoption and usage, as it can be expected that a country with a higher income classification will have a higher usage of smartphones – specifically, 5G smartphones – than one characterised by a lower income classification. Based on the income level classification of the assessed cities, we highlighted the activity factor for each city that we think will most realistically reflect the use of 5G services by 2030. The values selected are presented in Table 1.

9 In this report, early adopter countries are those characterised by high levels of 5G penetration and smartphone penetration and higher-than-average expected data consumption growth.

Table 1: Downlink spectrum needs in the 10 cities analysed, selected values

Source: GSMA Intelligence

City	Dense urban area (km²)	Population density (pop/km²)	mmWave needs if no additional mid-band available (MHz)		mmWave needs if additional mid-band available (MHz)	
			Activity factor, 10%	Activity factor, 15%	Activity factor, 10%	Activity factor, 15%
Mumbai	529	34,904	1750	**2800**	0	**600**
Madrid	236	12,304	1900	**3150**	850	**2050**
Moscow	582	17,110	**2850**	4500	**1050**	2700
São Paulo	889	12,667	**2900**	4600	**1200**	2950
Beijing	421	22,273	2850	**4650**	1650	**3400**
Paris	116	24,769	4350	**6800**	3000	**5450**
Istanbul	133	40,644	**5000**	7800	**3800**	6600
New York	206	18,241	5700	**8900**	4150	**7350**
Johannesburg	30	16,523	**6300**	9600	**5100**	8450
Ho Chi Minh City	69	52,902	**6550**	10150	**5050**	8650
Average for early adopter countries			6000		4500	
Average for other countries			4500		3000	

Note: Numbers in bold highlight the activity factor that we consider will most realistically reflect the use of 5G services for each city by 2030.

While each city will present a set of socio-economic and geographical differences that will affect demand and supply of 5G services, and the subsequent need for mmWave spectrum, we can average out the results of the 10 cities analysed based on income classification. This provides a global estimate of the spectrum needs for IMT services in the mmWave bands by 2030.

Our assessment indicates that for early adopter countries up to 4.5 GHz of mmWave spectrum will be needed to satisfy demand for IMT services in the assessed scenario, which assumes that adequate mid-band spectrum will be assigned by 2030, as recommended in GSMA (2021).[10]

For other countries, the expected amount of mmWave spectrum necessary to satisfy 5G services demand in dense urban areas is smaller compared with early adopter countries. We estimate that on average up to 3 GHz of mmWave spectrum will be required in cities located in countries with this income classification, assuming that adequate mid-band spectrum will be assigned by 2030, as recommended in GSMA (2021).[11]

10 In this report, early adopter countries are those characterised by high levels of 5G penetration and smartphone penetration and higher-than-average expected data consumption growth.
11 Ibid.

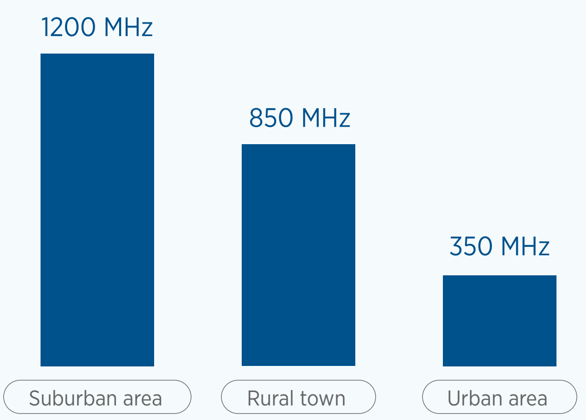
03

mmWave spectrum requirements for 5G FWA in urban, suburban and rural areas by 2030

We estimate that, on average, 350 MHz of mmWave spectrum will be required to provide fibre-like connectivity using 5G FWA in a dense urban environment. In areas characterised by a lower FTTH penetration, including suburban areas and rural towns, 700–1200 MHz (suburban area) and 50–850 MHz (rural town) of mmWave spectrum will be necessary to satisfy 5G FWA demand in households located in these areas.

Figure 2: Expected amount of mmWave spectrum needed for 5G FWA based on environment

Source: GSMA Intelligence



FWA is one of the main 5G use cases and a key solution for delivering fixed broadband connectivity objectives. mmWave spectrum provides greater bandwidth to support lower-latency and higher (gigabit) speeds.

While the majority of current 5G FWA deployments focus on mid-band spectrum in the 3.5–3.8 GHz bands, a number of 5G mmWave FWA networks have already been deployed worldwide. In the US, the use of mmWave spectrum in FWA networks was first adopted by Verizon in 2018. In addition to this, mmWave spectrum is being used as a capacity and performance booster to complement coverage provided by lower bands by several operators around the world, including TIM and Fastweb in Italy, US Cellular and Verizon in the US, and NBN and Telstra in Australia. 5G FWA services are currently being launched worldwide; as of March 2022, 72 operators offered 5G FWA services, while another 16 have announced plans to launch.[12]

The results of the study show how, with the right amount of mmWave spectrum being available, 5G FWA technology will allow fibre-like connectivity in areas where lower FTTH penetration, driven by high deployment costs, would otherwise limit access to fast, reliable connectivity.

In particular, 5G networks in suburban areas will require additional capacity to supply the significant increase in data consumption by households. mmWave is ideally placed to provide this layer of additional capacity while also allowing higher speeds and lower latency.

A recent series of GSMA studies[13] has shown the cost-effectiveness of this technology in providing fibre-like connectivity in regions not covered by FTTH. Some of these studies[14] have shown how under some conditions deployment of a mmWave FWA network can be cheaper than an FTTH alternative.

Depending on the FTTH coverage, 5G FWA can be both more economical and faster to deploy than fibre in bringing 100 Mb/s connectivity to households and businesses located in rural areas. The use of 5G FWA mmWave in small rural towns is expected to provide substantial cost savings compared with FTTH deployment. Furthermore, our assessment assumes that while 5G FWA networks in rural areas will be mostly deployed on mid-bands, as data consumption grows or as the number of subscribers increases, we expect operators to add capacity using mmWave.

Details of the modelling exercise, including an extensive explanation of the assumptions, data and calculations used, are presented in the annex.

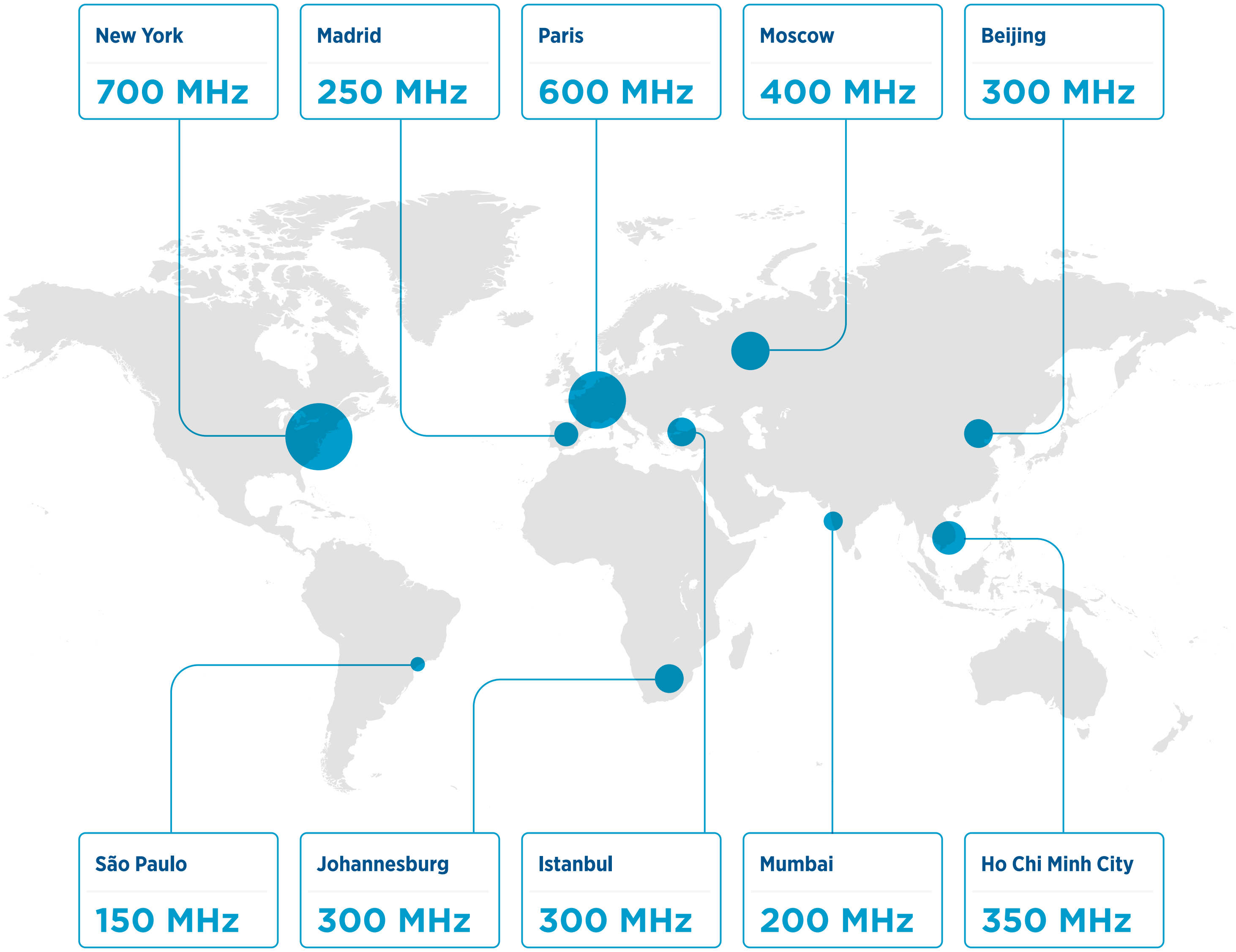
3.1 Spectrum demand model results: 5G FWA in urban areas

According to the demand and supply drivers presented above, we estimate that 150–700 MHz of mmWave spectrum will be necessary to satisfy 5G FWA demand in households located in dense urban areas, based on an FWA penetration of 30%. This creates an average of approximately 350 MHz across the 10 cities analysed. Even when accounting for a lower FWA penetration rate, reflecting higher FTTH penetration, such areas are characterised by a high number of households with an expected increase in data consumption in the period to 2030.

12 GSMA Intelligence
13 The 5G FWA opportunity: disrupting the broadband market, GSMA Intelligence, 2021
14 The 5G FWA opportunity: a TCO model for a 5G FWA network using mid-band plus mmWave, GSMA Intelligence, 2022

Figure 3: **5G FWA mmWave spectrum needs, dense urban areas by city**

Source: GSMA Intelligence



3.2 Spectrum demand model results: 5G FWA in suburban areas and rural towns

According to the demand and supply drivers presented above, we estimate that based on an FWA penetration of 60% in suburban areas and rural towns, 700–1200 MHz (suburban area) and 50–850 MHz (rural town) of mmWave spectrum will be necessary to satisfy 5G FWA demand in households located in these areas.

Table 2: 5G FWA mmWave spectrum needs, suburban areas

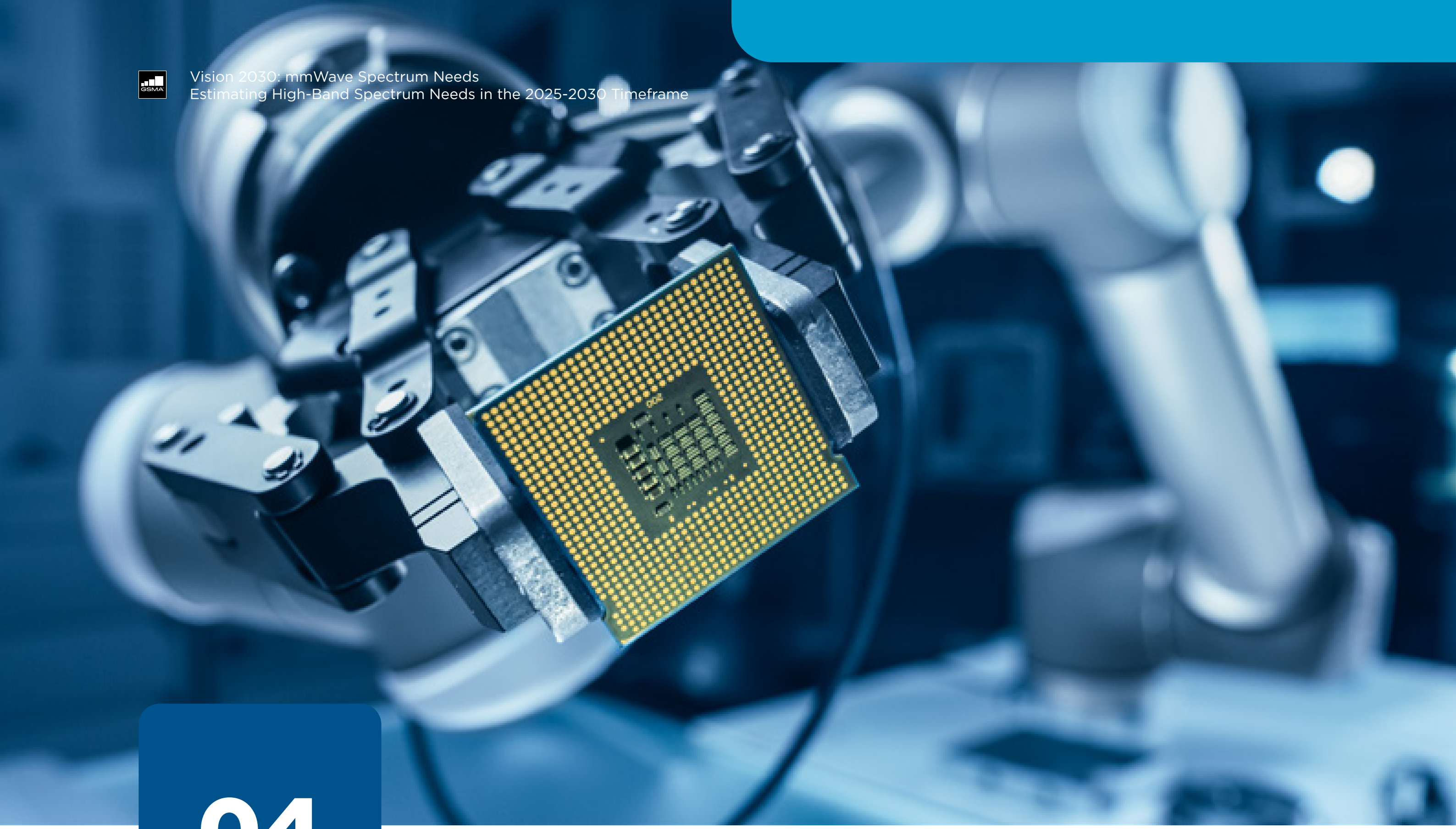
Source: GSMA Intelligence

Region (suburban)	Amount of mmWave spectrum (MHz) needed to satisfy FWA demand (downlink) in suburban areas
Europe	1200
North America	1050
Latin America	700

Table 3: 5G FWA mmWave spectrum needs, rural towns

Source: GSMA Intelligence

Region (rural town)	Amount of mmWave spectrum (MHz) needed to satisfy FWA demand (downlink) in rural towns
Europe	850
North America	600
Latin America	50



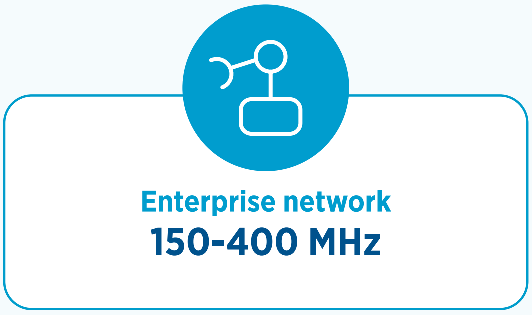
04

mmWave spectrum requirements for a 5G network on an Industry 4.0 factory floor

A network for an Industry 4.0 factory floor will require 150–400 MHz mmWave spectrum, depending on the technology adopted in the plant and the number of IoT devices connected.

Figure 4: Expected amount of mmWave spectrum needed for a network on an Industry 4.0 factory floor

Source: GSMA Intelligence



mmWave spectrum is expected to play a key role in the deployment of 5G enterprise networks, such as for factory floors, campuses and laboratories.

It is expected that the majority of dedicated enterprise network deployments will be supported by mobile network operators.[15] There are various reasons for this, including access to wider spectrum to support higher-bandwidth use cases or device densities, and the availability of the bespoke expertise necessary to design, implement or operate the dedicated network.

mmWave is expected is to be vital in the deployment of secure, reliable and ultra-fast enterprise networks. Thanks to the high capacity and extremely low latency provided by this band, and the ability to support large quantities of traffic in upload, 5G networks deployed using mmWave spectrum are expected to support a larger set of industrial use cases. These include robots, high-definition cameras, AGVs and AR/VR.

In this study, we look at a hypothetical factory floor deploying manufacturing Industry 4.0 equipment, including connected IoT devices, several AGVs, HD cameras for quality control and maintenance, and AR/VR headsets for workers involved in the maintenance of the factory equipment. We look at small, medium and large-sized enterprises, and we account for different degrees of technological readiness, based on assumptions developed through interviews with industry experts.

Our model foresees that 150–400 MHz of mmWave spectrum will be required to satisfy capacity demand for an enterprise network, such as in the case of a manufacturing plant.

Most of the demand will be driven on the upload, due to HD cameras and other devices requiring higher bandwidth in the upload compared to download. For this reason, mmWave spectrum, which is particularly suited for high upload bitrate, represents the ideal solution for networks in manufacturing.

Details of the modelling exercise, including an extensive explanation of the assumptions, data and calculations used, are presented in the annex.

15 5G IoT Private & Dedicated Networks for Industry 4.0, GSMA, 2020

Technical annex

Modelling mmWave spectrum needs for 5G eMBB in dense urban areas

The presented analysis is based on the need for additional mmWave spectrum in delivering user-experienced data rates of 100 Mb/s on downlink (DL) and 50 Mb/s on uplink (UL), as set out in the ITU Requirements for IMT-2020.[16]

The need for spectrum is driven by two main factors: the density of mobile networks in each area and the traffic in the area. Considering that there are limits to site densification (interference and permission planning), we assume a very dense mobile infrastructure (a network with an inter-site distance of 400 metres) and look at the spectrum needs according to different levels of traffic demand density, measured in Gb/s per square kilometre.

In the development of the ITU's IMT-2020 requirements, the user-experienced data rate relates to people, but this will account for only part of the traffic. Connected cars, cameras and IoT devices will generate substantial amounts of traffic. Hence, one of the requirements of 5G is to support 10 million devices per square kilometre. We expect this non-human generated traffic to be highly correlated with population density and thus also generated mostly in areas characterised by high population density.

The advantage of focusing on the 5G requirements is that the model is easy to validate, as it relies on a small number of key assumptions around typical cell sizes and average spectral efficiencies that are representative of future 5G deployments.

Overview of the spectrum demand model

In our model, we forecast traffic demand in these areas based on expected data and population growth in the selected cities, looking at two different mid-band spectrum assignments profiles (with and without the additional mid-band spectrum as recommended in GSMA (2021).[17]

We then compute mmWave spectrum needs based on the difference between traffic demand and traffic supply (i.e. the excess demand), assuming mmWave antennas would be placed on each and every base station in the area analysed.

Population density distribution

To assess the demand in the densest area by population of the analysed cities, we use granular population data and a clustering algorithm to identify the most densely populated areas in each city. An example is provided for the city of Paris in Figures A1, A2 and A3. For each city (in this case, Paris) we determine the limits of the urban areas based on publicly available national and international sources, as reflected in Figure A1.

Once we have determined the urban areas of the city, we cluster by area based on location and population density, as shown in Figure A2. Finally, we reflect uneven geographical distributions of users within each area by computing the percentage of potential users by area quartile, as illustrated in Figure A3. Based on the data traffic assumption presented above, we assumed that data demand follows population density.

16 Report ITU-R M.2441, Emerging usage of the terrestrial component of International Mobile Telecommunication (IMT) and Report ITU-R M.2410, Minimum requirements related to technical performance for IMT-2020 radio interface(s)
17 Estimating the mid-band spectrum needs in the 2025–2030 time frame, A report by Coleago Consulting Ltd for GSMA, 2021

Figure A1: Example of dense urban area identification and clustering, Paris

Source: © OpenStreetMap contributors

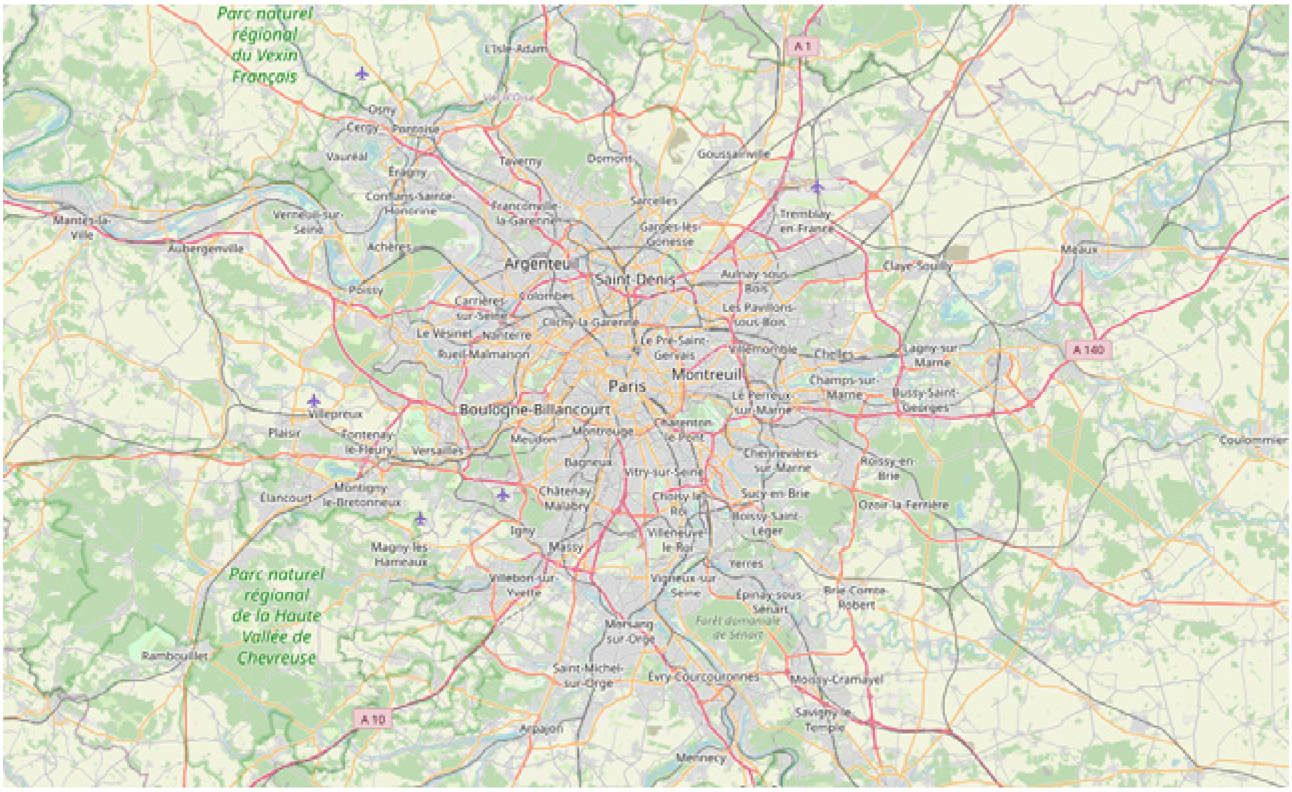


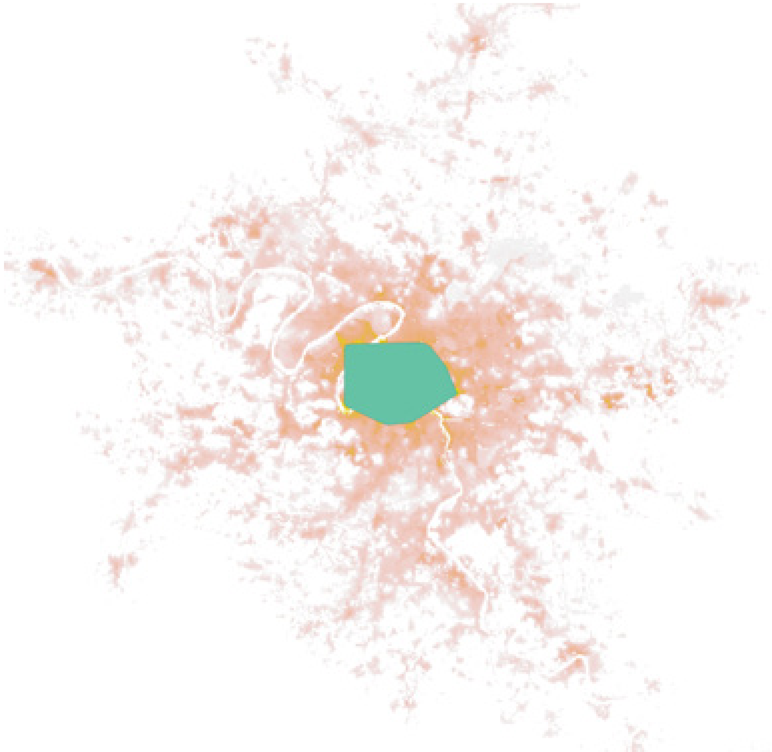
Figure A2: Example of city area clustering based on location and population density, Paris

Source: GSMA Intelligence

Note: Areas highlighted in green reflect the most densely populated areas, while areas highlighted in yellow reflect the least densely populated areas.

Figure A3: Example of computation of percentage of potential users by area quartile within each cluster, Paris

Source: GSMA Intelligence



Note: Highlighted area in green represents the densest urban area.

The area traffic density demand – key assumptions

To model the demand for capacity in a city with a particular population density, we consider the following drivers:

- **The 5G IMT-2020 requirement:** We consider the 5G IMT-2020 requirement for a downlink user-experienced data rate of 100 Mb/s and a 50 Mb/s uplink data rate.
- **Population density**: This varies by city and is the key driver explaining differences in spectrum needs between cities and, by implication, between countries. The population is distributed by quartile of population density within a city, with higher population density in the first quartile and lower in the fourth, to correctly reflect different population distributions in dense urban environments.
- **Activity factor**: The activity factor is defined as the percentage of connections active at any given time, reflected by an assumption of concurrent demand at busy times.
- **5G penetration:** 5G penetration data is provided by GSMA Intelligence's data forecasting database.

The area traffic capacity supply – key assumptions

The variables in the availability model for capacity supply per square kilometre are as follows:

- **Number of macro cell sites per square kilometre, driven by the inter-site distance**: We assume that each operator would deploy mmWave on top of every single sub-7 GHz macro site in the dense urban area identified.
- **The role of outdoor small cells:** We assume three outdoor small cells per macro site.
- **Base station design margin, site sectorisation and spectral efficiency**. More details presented in the tables below.
- **Amount of existing spectrum in low bands and mid-bands:** We conducted our analysis based on a baseline scenario (described in more detail below) and on an alternative scenario accounting for the conclusion of the GSMA (2021)[18] study on mid-band spectrum needs.

Baseline spectrum and additional spectrum

As a baseline, the model uses the same low and mid-band spectrum scenarios presented and used in the GSMA (2021)[19] analysis, to ensure comparability between results.

The baseline spectrum assumption includes a wide definition to ensure that the model does not overestimate demand for additional IMT spectrum. The baseline spectrum is the maximum low and mid-band spectrum that could be made available given the status of IMT band identification. This includes:

- spectrum currently assigned to operators;
- spectrum available but not assigned; and
- mmWave spectrum identified in WRC-19 for IMT and is expected to be made available for 5G before 2025.

The baseline spectrum varies by country. In line with previous literature on the topic, we assume that in the 2025–2030 time frame all 2025 baseline IMT low bands, lower mid-bands and upper mid-bands will be deployed for 5G NR on all macro sites. Regarding outdoor small cells, we assume that they will be used in all base stations (macro and small).

As mentioned above, we also assess a sensitivity scenario where in the baseline we account for the additional mid-band spectrum recommended in GSMA (2021).[20]

Example: Paris city centre modelling

We looked at the urban centre of Paris, characterised by a dense urban area of approximately 116 square kilometres and a population of 2.8 million, resulting in a population density of around 25,000 inhabitants per square kilometre. We distribute population based on density to understand the number of inhabitants living in different densities, clustering population by quartile. For example, in Paris we observe that almost 40% of the total urban population – an area of approximately 29 square kilometres – live in the first quartile. We can therefore assume that it is in this quartile that capacity demand will be at its highest and where mmWave spectrum will thus most likely be needed on top of already available low and mid-band spectrum.

18 Estimating the mid-band spectrum needs in the 2025–2030 time frame, A report by Coleago Consulting Ltd for GSMA, 2021
19 Ibid.
20 Ibid.

Table A1: Population distribution by quartile of population density, Paris

Source: GSMA Intelligence, WorldPop and Columbia university data

Quartile	Percentage of population	Population	Dense urban area (km^2)	Density of population using a 5G device (pop/km^2)
1st	38%	1,081,321	29	37,436
2nd	28%	813,081	29	28,149
3rd	21%	612,060	29	21,190
4th	12%	355,264	29	12,300

Demand side

Based on the most recent GSMA Intelligence forecast, 5G penetration in Paris is expected to reach 100% in 2030. We assume a range of connected and active users, with central values set at 10% and 15%. This reflects the percentage of connections active at any given time i.e. between 10% and 15% of all users will be using the network simultaneously. This range can be justified when considering that by 2030 5G should be deployed in major urban areas in developing economies and should reach full coverage in developed economies. Furthermore, recent estimates[21] suggest that consumers spent almost five hours a day on their smartphones in 2021 (approximately 20% of the day) and this time is expected to grow in upcoming years. Based on this estimate, our core range of 10% and 15% appears conservative, especially when considering peak times.

Based on the 5G ITU-R IMT-2020 requirement of 100 Mb/s download and 50 Mb/s upload, we can expect between 370 $Gb/s/km^2$ and 560 $Gb/s/km^2$ downlink traffic demand in the densest quartile of the Paris urban area, and approximately 250 $Gb/s/km^2$ to 370 $Gb/s/km^2$ when averaging across the four quartiles.

Table A2: Population distribution by quartile of population density and associated demand in the Paris area

Source: GSMA Intelligence, WorldPop and Columbia university data

Quartile	Percentage of population	Population	Dense urban area (km^2)	Density of population using a 5G device (pop/km^2)	DL traffic demand ($Gb/s/km^2$) Based on activity factor, 10%	DL traffic demand ($Gb/s/km^2$) Based on activity factor, 15%
1st	38%	1,081,321	29	37,436	374	562
2nd	28%	813,081	29	28,149	281	422
3rd	21%	612,060	29	21,190	212	318
4th	12%	355,264	29	12,300	123	184

21 State of Mobile in 2022, data.ai, 2022

Supply side

Based on the low and mid-band spectrum available, we compute the expected area capacity supply based on the technical parameters. We consider a first scenario where we assume that in the 2025–2030 time frame all 2025 baseline IMT low bands, lower mid-bands and upper mid-bands will be deployed for 5G NR on all macro sites. In addition to this, we consider a sensitivity scenario where we account for the additional mid-band spectrum allocation by city/country; as concluded in GSMA (2021),[22] mid-band spectrum will need more capacity than is currently being planned/assigned by regulators in most cases.

For Paris, by 2030 5G networks will have capacity (download and upload) ranging from 80 Gb/s/km^2 to 250 Gb/s/km^2, depending on the amount of mid-band spectrum available. The higher value is the result of calculations that assume the recommendation of 2 GHz of mid-band spectrum for IMT services included in GSMA (2021)[23] will be implemented.

Having calculated the area traffic demand density, we can compare this with the area traffic capacity using the assumptions stated above and assess the need for mmWave spectrum to fully satisfy the demand for IMT services in the dense urban areas of Paris by 2030.

Depending on the activity factor assumed and on the amount of mid-band spectrum available, our modelling suggests that between 3 GHz and 7 GHz of mmWave spectrum will be required to fully satisfy the demand for 5G services in the first quartile (i.e. the densest) of the urban areas of Paris in 2030.

Table A3: Downlink spectrum needed in densest urban area (i.e. first quartile) of Paris

Source: GSMA Intelligence

mmWave needs if no additional mid-band available		mmWave needs if additional mid-band available	
Activity factor, 10%	Activity factor, 15%	Activity factor, 10%	Activity factor, 15%
4350 MHz	6800 MHz	3000 MHz	5450 MHz

Averaging the activity factors, we conclude that to provide capacity for the expected demand of 5G services in the densest urban areas of Paris, a total of 5.5 GHz of mmWave spectrum will be required, in a scenario where no further mid-band spectrum is allocated to IMT. If additional mid-band spectrum will be assigned in line with GSMA (2021),[24] we estimate that approximately 4.5 GHz of mmWave spectrum would suffice to satisfy demand.

22 Estimating the mid-band spectrum needs in the 2025–2030 time frame, a report by Coleago Consulting Ltd for GSMA, 2021
23 Ibid.
24 Ibid.

Modelling mmWave spectrum needs for 5G FWA in urban, suburban and rural areas

To model the demand for capacity for 5G FWA services, we proceeded in a slightly different way depending on the population size, density and geographical location of the city, differentiating between urban, suburban and rural area scenarios. For the urban scenario, we analyse the same 10 cities analysed in the eMBB segment presented above. For the suburban and rural areas, we look at three hypothetical cities in suburban and rural areas located in Europe, North America and Latin America, which are the regions currently expected to deploy 5G FWA networks in the near future.

For each city/scenario, we consider the following drivers of demand:

- **Expected data consumption**: We consider expected data consumption by household, for fixed connectivity, based on forecasted data.
- **An assumption on FWA penetration**: This assumption is informed by industry experts and market intelligence. We assume FWA penetration to be higher in areas where FTTH will not be available i.e. in suburban and rural areas.
- **Household density**: This varies by city and is the key driver explaining differences in spectrum needs between cities and, by implication, between countries.

Similar to the approach taken in modelling the demand side for capacity for 5G FWA services, we use slightly different approaches to model the supply side, differentiating between urban, suburban and rural area scenarios.

Furthermore, as we specifically focus on 5G FWA with a fibre-like target download speed – only achievable with the use of mmWave spectrum – we assume no low or mid-band spectrum will be used to provide this service.

For the urban scenario, we consider the following drivers of supply of 5G FWA capacity supply:

- **Number of macro cell sites per square kilometre, driven by the inter-site distance**: We assume that each operator would deploy mmWave on top of every single sub-7 GHz macro site in the dense urban area identified.
- **The role of mid-band outdoor small cells:** We assume three outdoor small cells per macro site.
- **Base station design margin, site sectorisation and spectral efficiency**: We assume this to be the same as the eMBB supply capacity model.

For the suburban and rural area scenarios, we consider the following drivers of supply of 5G FWA capacity supply:

- **Number of macro cell sites per square kilometre, driven by the inter-site distance**: We calculate the number of macro cells assuming an inter-site distance of 700 metres for the suburban model and 1,500 metres for the rural model. We assume no small cells will be used in the deployment of 5G FWA networks in suburban and rural areas.
- **Base station design margin, site sectorisation and spectral efficiency**: We assume this to be the same as the eMBB supply capacity model.

Modelling mmWave spectrum needs for a 5G enterprise network – manufacturing

To understand the potential capacity demand for 5G services in a factory-floor environment, we researched and assessed current and planned pilot projects around the globe currently deploying connectivity solutions in the manufacturing sector.

The variables driving the demand capacity are as follows:

- **Use case requirements**: We look at use case requirements in terms of download and upload speeds, as reflected in Table A4.
- **Concurrent use assumptions:** We assume a percentage of concurrent use for each use case, in a similar function to the activity factor parameter used in the eMBB segment presented above.
- **Number of employees and size of firm**: We look at three different types of firms – small, medium, and large – and attribute an average number of employees for each category of firm.

Several assumptions in terms of number of devices and technical parameters have been made, based on industry experts' feedback and our research.

Table A4: Use case requirements in terms of download and upload speeds for an enterprise network for a manufacturing plant

Source: GSMA Intelligence

Use case	Definition	DL (Mb/s)	UL (Mb/s)
AR/VR headset	Remote augmented reality for equipment troubleshooting maintenance and repair	25	25
AGV	Automatic inspection of product lines via automated guided vehicles (AGVs)	20	120
Security camera	Security cameras	2	25
Other IoT	Other IoT devices	5	10

To supply 5G capacity in an enterprise network manufacturing plant, we assume that a mmWave indoor cell will be placed at an inter-site distance of 30 metres. In line with the previous eMBB and FWA segment of the model, we assume that mmWave networks will perform similarly in terms of technical aspects to a 3.5 GHz network, including similar spectral efficiency in both download and upload.

Additional data used in the model

Table A5: Baseline and sensitivity analysis scenario spectrum allocation, by city and by band, total

Source: GSMA Intelligence

	Baseline scenario		Sensitivity scenario
	Total low band	Total mid-band	Total mid-band
Paris	190	935	2280
Madrid	190	935	2000
Beijing	150	1115	2330
Ho Chi Minh City	180	955	2510
Mumbai	137	588	2780
Moscow	190	755	2570
New York	180	950	2510
São Paulo	140	970	2640
Istanbul	190	1035	2240
Johannesburg	196	674	1850

Table A6: Population density by city

Source: UN

City	Dense urban area (km^2)	Population	Population density (pop/km^2)
Paris	116	2,861,726	24,769
Madrid	236	2,908,232	12,304
Beijing	421	9,381,999	22,273
Ho Chi Minh City	69	3,647,073	52,902
Mumbai	529	18,462,965	34,904
Moscow	582	9,959,337	17,110
New York	206	3,758,953	18,241
São Paulo	889	11,255,707	12,667
Istanbul	133	5,386,886	40,644
Johannesburg	30	500,739	16,523

Table A7: 5G penetration in 2030 by city

Source: GSMA Intelligence

City	5G penetration
Paris	100%
Madrid	100%
Beijing	100%
Ho Chi Minh City	77%
Mumbai	31%
Moscow	82%
New York	100%
São Paulo	89%
Istanbul	67%
Johannesburg	92%

Table A8: Dense urban deployment parameters

Source: GSMA Intelligence

Band category	Deployment	Sectors	Average ISD (m)	Cell range (m)	Average spectral efficiency (bit/s/Hz) DL	Average spectral efficiency (bit/s/Hz) UL	Loading factor	Small cells per macro (outdoor)
Low band	Macro	3	400	267	1.8	1.8	85%	N/A
Lower mid-band	Macro	3	400	267	2.2	2.5	85%	N/A
Upper mid-band	Macro	3	400	267	6	4.1	85%	N/A
Upper mid-band	Outdoor small cell	1	Not used	100	3.7	2.6	85%	1.8
High band (mmWave)	Macro	3	400	267	6	4.1	85%	N/A
High band (mmWave)	Outdoor small cell	1	Not used	100	3.7	2.6	85%	1.8

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