Estimating the mid-band spectrum needs in the 2025-2030 time frame

Global Outlook

A report by Coleago Consulting Ltd

July 2021

The GSMA represents the interests of mobile operators worldwide, uniting more than 750 operators and nearly 400 companies in the broader mobile ecosystem, including handset and device makers, software companies, equipment providers and internet companies, as well as organisations in adjacent industry sectors. The GSMA also produces the industry-leading MWC events held annually in Barcelona, Los Angeles and Shanghai, as well as the Mobile 360 Series of regional conferences.

For more information, please visit the GSMA corporate website at www.gsma.com

Follow the GSMA on Twitter: @GSMA

About Coleago Consulting Ltd

Founded in 2001, Coleago is a specialist telecoms management consulting firm. Our expertise has been developed exclusively within the telecoms sector and delivers a rare combination of telecoms-related commercial, technical, and regulatory skills and experience. Since 2001 we have worked on over 110 spectrum related projects in developed and emerging markets. Since 2017 our spectrum projects included the transition to 5G, including valuing spectrum most relevant for 5G such as 600 MHz, 700 MHz, 3.5 GHz, and mmWave. We advise regulators on spectrum policy, spectrum roadmap, spectrum pricing, spectrum auctions and capacity building on the topic best practice in spectrum auctions. For mobile operators Coleago delivers regulatory advocacy and responses to consultation, spectrum valuation, bid strategy development and live auction support. Coleago also authored complete bid books for spectrum licence awards by means of a beauty contest.

For further information, please visit www.coleago.com

Content

coleagoconsulting

Exhibits

Contact

Stefan Zehle, MBA
CEO,
Coleago Consulting Ltd

Tel: +44 7974 356 258
stefan.zehle@coleago.com

David Tanner, MA (Hons), MSc, MIET, CEng
Managing Consultant,
Coleago Consulting Ltd

Tel: +44 7976 415250
david.tanner@coleago.com

coleagoconsulting

1 Executive summary

Global analysis of spectrum needs

One of the pillars in the vision for 5G is to provide ubiquitous high-speed wireless mobile connectivity to support several use-cases: "*IMT-2020 is expected to provide a user experience matching, as far as possible, that of fixed networks*"[1]. The need for IMT spectrum is driven by the requirements for 5G as set out in the ITU-R requirements for IMT-2020[2].

5G must deliver a user experienced mobile data rate of 100 Mbit/s in the downlink and 50 Mbit/s in the uplink and accommodate 1 million connections per km^2. This poses a huge challenge in cities with a high traffic density. We have modelled the 5G mobile area traffic demand and supply in 36 cities around the world. We focus on cities with population densities of more than 8,000 per km^2. In these cities, substantial amounts of mid-band spectrum are found to be required to deliver the 5G vision in an economically feasible manner, taking different national income levels into consideration.

Exhibit 1: Total mid-band spectrum needs 2025-2030 time frame

	Minimum estimate	Maximum estimate
High income cities	1,260 MHz	3,690 MHz
Upper middle income cities	1,020 MHz	2,870 MHz
Lower middle income cities	1,320 MHz	3,260 MHz

Source: Coleago

The range of estimates per national income category reflects the different population densities of the cities analysed, and our view with regards to the extent of 5G take-up and offload to high-bands in the examined countries.

The total[3] mid-band spectrum needs when averaged over all 36 examined cities is estimated to be 2,020 MHz in the 2025-2030 time frame.

Policymakers will, therefore, need to consider making more mid-band[4] available and prepare national spectrum roadmaps that carefully consider future 5G demand. There is a concern in the mobile industry that regulators may not be fully aware of the scale of the 5G traffic density challenge in urban areas. Specifically, there is a concern that regulators may not be planning to clear and award enough licensed mid-band spectrum for 5G between now and 2030. There is also a risk that decisions surrounding additional unlicensed spectrum, or 5G spectrum set-asides for local use or for vertical industries, may leave mobile operators with a lack of additional 5G spectrum thus jeopardising their ability to deliver 5G services and a speed consistent with the ITU-R IMT-2020 vision.

The results of the study presented in this report will help regulators to make informed decisions by quantifying the need for additional mid-band spectrum with specific reference to 5G NR (for simplicity also referred to as "5G", "IMT" or "IMT-2020") that relies on the assignment of individual spectrum licenses to operators, which are required to ensure the quality of service to the end users, be they people or objects.

1 Report ITU-R M.2441-0 (11/2018), "Emerging usage of the terrestrial component of International Mobile Telecommunication (IMT)"
2 Report ITU-R M.2441-0 (11/2018), "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)"
3 The total mid-band (i.e., 1500-7125 MHz) spectrum needs includes the "baseline mid-band spectrum" for each city (spectrum already in use by mobile operators and expected future assignments in the period of 2021 to 2025), as well as the spectrum that is estimated to be needed on top up to 2030.
4 Based on current availability and ongoing discussions, policymakers should focus on the 3300-7125 MHz range to fulfil the upper mid-band spectrum needs

5G NR (New Radio) is the radio access technology developed by 3GPP for IMT-2020 networks and relies on the assignment of individual spectrum licenses (i.e., to operators), which are required to ensure the quality of service to the end users, including for enhanced mobile broadband (eMBB) and fixed wireless access (FWA), but also verticals use cases such as Industry 4.0 and automotive communications.

Modelling spectrum need in cities

Our model focuses on the user experienced mobile data rate of 100 Mbit/s on the downlink and 50 Mbit/s on the uplink in a city, i.e., ensuring citywide speed coverage. The relevant metrics are: (i) area traffic density demand, and (ii) area traffic capacity supply in terms of Gbit/s/km^2. We examine the area traffic capacity requirement against the background of increased concurrent bandwidth demand from human users and other use cases.

On the demand side, we look at mobile area traffic demand density in cities in the 2025-2030 time frame using the following method:

- We use the population density in cities as a proxy for mobile area traffic demand density that is triggered by both human and non-human users. This is appropriate because traffic generated by, for example, connected vehicles, cameras or video-based sensors occurs where people are located, and is in addition to the traffic generated by human users. Hence, tying traffic demand per capita to the 100 Mbit/s downlink and 50 Mbit/s uplink requirements generates a realistic estimate for future area traffic demand which takes account of all use cases.

- We examine the mobile area traffic capacity requirement against the background of increased concurrent bandwidth demand from both human users and other use cases. This is presented in the form of an activity factor ranging from 10% to 25%. In terms of the calculations, the value represents the proportion of the population which demand 100 Mbit/s in the downlink and the proportion of the population which demand 50 Mbit/s in the uplink during the busy period. Therefore, the larger values of the activity factor are representative of greater take-up of 5G use cases in the 2030 time frame. The activity factor is therefore a proxy for the demand by both human users and machine-to-machine communications.

- The mobile area traffic density demand is the net demand after deducting offloading traffic to high-band sites and indoor small cells. Depending on the city, and factors such as the amount of mid-band indoor small cells and the percentage of traffic offloaded to high-bands, the area traffic demand varies between 300 to 500 Gbit/s/km^2. This is only 3% to 5% of the ITU-R traffic capacity requirement of 10 Mbit/s/m^2 that 5G networks should be capable of delivering at specific hotspots, which is reasonable as it is based on usage across the city.

On the supply side, we begin by considering the network evolution in the 2025-2030 time frame. Aiming for a realistic estimate of spectrum needs from 2025 to 2030, we make the following conservative assumptions with respect to area traffic capacity supply:

- The “baseline spectrum” for each city includes spectrum already in use by mobile operators as well as expected future assignments in the period of 2021 to 2025. In regards to future spectrum assignments, we included not only spectrum that is on the current roadmap in different countries, but also spectrum that could be added to the roadmap by 2025. Depending on the specific city among the 36 cities addressed, the baseline spectrum amount varies from 725 MHz up to 1,420 MHz.

- We assume that, depending on the country, within the 2025 to 2030 time frame, mobile operators will have made the investment to use all “baseline spectrum” for 5G.

- We also assume that each operator will deploy three outdoor small cells per each of its macro sites, invest in MIMO upgrades, install indoor small cells, and deploy high-band (mmWave) spectrum on outdoor and indoor sites.

Despite these investments to supply mobile area traffic capacity, the report concludes that there will be a significant shortfall of upper mid-band spectrum. Policymakers will, therefore, need to consider making more spectrum in mid-bands available to allow operators to meet the IMT-2020 targets.

Additional mid-band spectrum before 2030 would enable mobile operators to deliver the ITU-R IMT-2020 requirements, notably the user experienced data rates of 100 Mbit/s and upload date rates of 50 Mbit/s in UL in cities and to deliver smart cities in an economically feasible manner.

- Our analysis concludes that in addition to the investment in densification, the **total mid-band spectrum needs when averaged over all 36 examined cities is estimated to be 2,020 MHz in the 2025-2030 time frame.** This is required to deliver the 5G vision of user experienced mobile data rates of 100 Mbit/s on the downlink (download speeds) and 50 Mbit/s on the uplink (upload speeds) across the city, i.e., citywide speed coverage, for a range of human and non-human communications and to deliver smart cities in an economically feasible manner.
- We examined whether small-cell densification could be an alternative to more upper mid-band spectrum. For example, in a city with a population density of 18,000 per km^2 and 7.2 macro sites per km^2, 177 additional outdoor small cells per km^2 are required to deliver the same capacity as an additional 1,250 MHz of mid-band spectrum. Considering an urban area of 100 km^2, 17,700 additional small cells would be required (compared to 720 macro sites) in the absence of the additional 1,250 MHz. These are significant numbers of outdoor small cells with relatively small inter-site distances, particularly when it is noted that this average spacing must be maintained across the entirety of the large city areas involved. This approach would clearly have a negative impact on the city environment from an aesthetics point of view and also be very costly. Such small inter-site distances, over such large areas, may also not be practically possible from an interference point of view. With such site densities, operators would also push against the technical limits of network densification.
- A reasonable question is whether densification could be considered through the use of high-band (mmWave) macro/small cells rather than with mid-band small cells. Given the different options for mmWave densification (e.g., densifying using only mmWave small cells or adding mmWaves to the existing macro mid-bands grid in conjunction with mmWave small cells), and considering the different sizes of cities and their propagation environments (influenced by street design, building characteristics, etc.), estimating the exact number of needed mmWave sites requires a case-by-case analysis. However, all options for such a densification would require new mmWave macro sites and/or new mmWave small cells over large areas (i.e., not only locally). Given the relatively smaller inter-site distances that are required by the mmWaves and the average spacing that must be maintained across the entirety of the large city areas involved, this densification approach would not represent a viable option, being very costly and undesirable from an environmental perspective.

Mid-band spectrum for FWA

The benefits of making available additional upper mid-band spectrum extends beyond cities. Additional upper mid-band spectrum provides a sustainable path to bridge the urban-rural digital divide.

Using additional mid-band spectrum for 5G FWA would reduce the cost of delivering future-proof fibre-like fixed wireless access services to households and enterprises.

- In countries that have good urban and suburban broadband infrastructure, there is often a lack of broadband in many rural small towns and villages. FWA relying on additional mid-band spectrum would make it possible to overcome the urban-rural digital divide in a time frame consistent with national broadband development plans. Importantly, additional spectrum would provide sufficient bandwidth to ensure that FWA will also be able to address the needs for fixed connectivity as a long-term solution for rural areas.

In countries where affordability is an issue, the economic implications associated with additional mid-bands are even more apparent. FWA is the fastest growing method of bringing fixed broadband to the unconnected due to the limited availability of copper and fibre broadband

- In lower-income countries where affordability is key, the economic benefits associated with additional mid-bands are even more apparent. There are 1.1 to 1.2 billion households worldwide without broadband access and FWA is the fastest growing method of bringing fixed broadband to the unconnected due to the limited availability of copper and fibre broadband.
- Upper mid-band spectrum has a key role to play in providing fibre-like access via 5G at an affordable cost. The ITU and UNESCO Broadband Commission for Sustainable Development 2025 Targets make this explicit: "By 2025, entry-level broadband services should be made affordable in developing countries, at less than 2% of monthly gross national income per capita."[5] Using additional mid-band spectrum for 5G would make a key contribution towards attaining the United Nations Sustainable Development Goals and the Broadband Commission 2025 targets. Alternative solutions based on satellite or fibre typically have higher costs and, therefore, outside the affordability of many.

Exhibit 2 summarises the benefits of using additional upper mid-band spectrum for IMT 5G NR for a) countries with good fixed wired broadband and b) countries with limited fixed wired broadband, bringing capabilities such as the economic delivery of a consistent 100 Mbit/s DL and 50 Mbit/s UL user experienced mobile data rate on transport routes (highways and railways).

Exhibit 2: Benefits of additional mid-bands for 5G

Benefit of using additional upper mid-band spectrum for IMT	Countries with extensive wired broadband	Countries with limited wired broadband
Economic delivery of a consistent 100 Mbit/s DL and 50 Mbit/s UL user experienced mobile data rate, citywide, urban and suburban	✓	✓
Ensures that FWA broadband is a long-term solution	✓	✓
Lower cost for urban FWA overcomes lack of fibre or xDSL broadband access		✓
Improves rural FWA broadband economics to bridge the digital divide	✓	✓
Helps to deliver United Nations Sustainable Development Goals		✓
Economic delivery of a consistent 100 Mbit/s DL and 50 Mbit/s UL user experienced mobile data rate on transport routes (highways and railways)	✓	✓
Contributes to reaching the ITU and UNESCO Broadband Commission 2025 targets		✓

Source: Coleago Consulting

[5] Broadband Commission for Sustainable Development 2025 Targets: "Connecting the Other Half"

Key findings

The analysis of future needs clearly shows the importance of additional mid-band spectrum for 5G and its evolution. The findings of our study point towards the following conclusions:

- Without additional upper mid-band spectrum, it will be impossible to economically deliver the ITU-R IMT 2020 (5G-NR) requirement of a 100 Mbit/s downlink and 50 Mbit/s uplink near guaranteed user experienced mobile data rate across entire urban areas, and to address smart city needs – key to mitigate climate change.
- In addition to deploying additional mid-band spectrum, mobile operators need to make substantial investments in higher order MIMO base station upgrades, small cells, and high bands to deliver these user experienced mobile data rates.
- The cities in our sample range from 8,000 to 31,000 people per km^2. The UN organisation UN Habitat defines the optimum population density for a sustainable city as 15,000 per km^2. Globally, there are 626 cities with such high-density population clusters of at least 40 km^2.[6] These cities can be found in all six ITU Regional groups (APT, ASMG, ATU, CEPT, CITEL, RCC). Together these cities contain an estimated 1.64 billion people. This scale illustrates why allocating additional upper mid-band spectrum to IMT is of such a significance for a large proportion of the world's population.
- Depending on the city from our sample of 36 countries, in areas with a population density greater than 8,000 per km^2, the mid-band spectrum needs have been estimated in order to deliver the ITU-R IMT 2020 requirements for human and non-human communications and for the development of smart cities.
- The total mid-band spectrum needs when averaged over all 36 examined cities is estimated to be 2,020 MHz in the 2025-2030 time frame.
- In areas with a population density below 8,000 per km^2, using the additional spectrum would also deliver benefits. The benefits would either be a lower site density or faster broadband speeds including for FWA. A lower site density translates into a lower cost per bit which in turn will translate into lower retail prices as well as less overall power consumption.
- In countries that overwhelmingly rely on wireless for connectivity, with limited fixed broadband infrastructure, the availability of additional mid-band spectrum would enable operators to deliver fibre-like 5G FWA to rural towns and villages, thus helping to achieve rural broadband connectivity targets.
- In countries that have good urban and suburban broadband infrastructure, the availability of additional mid-band spectrum would enable 5G FWA solutions reducing the average cost of bringing 100 Mbit/s connectivity to the remaining unconnected rural towns/villages. For example, in Europe, a 79% cost-reduction compared to fibre to the home. It would also ensure that fibre-like speed FWA is a long-term solution capable of supporting Very-High-Capacity Networks (VHCN) at speeds above 100 Mbit/s.
- Outside populated areas, substantial capacity is required on major transport routes (highways and railways) to serve the connected vehicles and smart road use cases.

[6] Based on data provided in Demographia World Urban Areas, (Built Up Urban Areas or World Agglomerations), 16th annual edition, June 2020,

2 The requirements for 5G drive the need for IMT spectrum

2.1 Spectrum to deliver the 5G vision

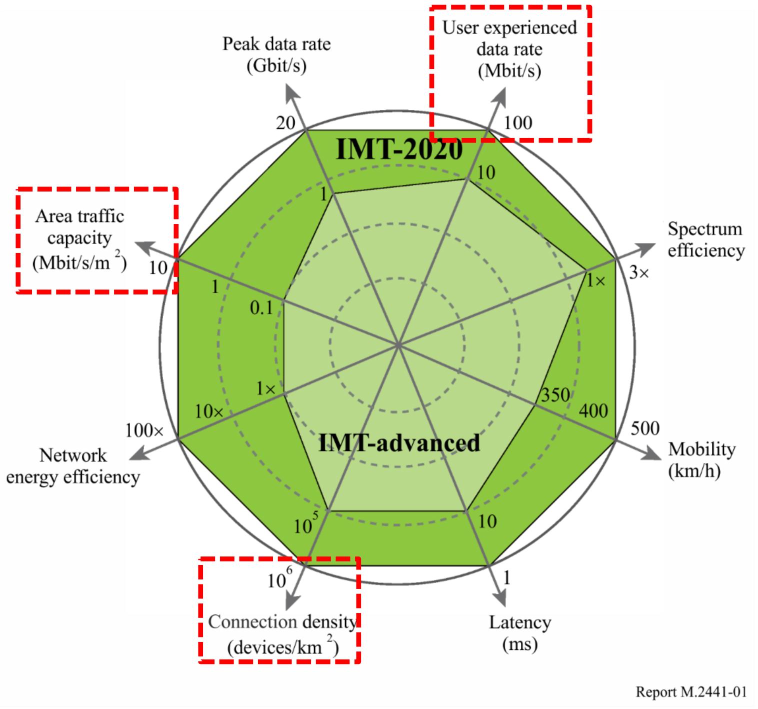
One of the pillars in the vision for 5G is to provide ubiquitous high-speed wireless connectivity to mobile and fixed users: "*IMT-2020 is expected to provide a user experience matching, as far as possible, that of fixed networks*"[7]. The need for IMT spectrum is driven by the requirements for 5G as set out in the ITU-R requirements for IMT-2020[8].

5G requirements focus on area traffic capacity, near guaranteed data rates, low latency and reliability, and this drives the need for spectrum.

Exhibit 3 shows the IMT-2020 (5G) requirements compared to LTE-Advanced (LTE-A). The requirements are not just an incremental percentage improvement, but a multiple improvement, i.e., a revolution rather than an evolution. In assessing the need for additional IMT spectrum we are focusing on two of these new 5G requirements:

- The user experienced data rate jumps from 10 Mbit/s to 100 Mbit/s - a factor of 10 increase (see Appendix D: for a more detailed description); and
- Area traffic capacity moves from 0.1 Mbit/s/m^2 to 10 Mbit/s/m^2 – a 100-fold increase (see Appendix E: for a more detailed description).
- The connection density increases 10-fold to 10 million devices per km^2.

Exhibit 3: IMT 2020 requirements



Source: Report ITU-R M.2441-0 (11/2018)

Radio frequencies are the key ingredient to deliver these requirements. Therefore, there is also a step change in the need for IMT spectrum. Clearly, improved spectral

[7] Report ITU-R M.2441-0 (11/2018), "Emerging usage of the terrestrial component of International Mobile Telecommunication (IMT)"

[8] Report ITU-R M.2441-0 (11/2018), "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)"

efficiency associated with higher orders of MIMO, the 5G radio interface, and densification will enable mobile operators to squeeze more capacity out of existing spectrum resources. However, it isn't remotely sufficient to deliver the capacity requirements of 5G.

2.2 Low, mid, and high frequency bands

Spectrum in the range of 450 MHz to 50 GHz is used today for IMT and band plans exist in many frequency ranges. Depending on the frequency range and the amount of spectrum in the range, different frequency bands serve different purposes and cannot, therefore, be used as substitutes for each other. Therefore, we need to assess the demand for additional IMT spectrum depending on the frequency range. The large number of frequency bands can be categorised into four groups: low-bands, lower mid-bands, upper mid-bands, and high bands.

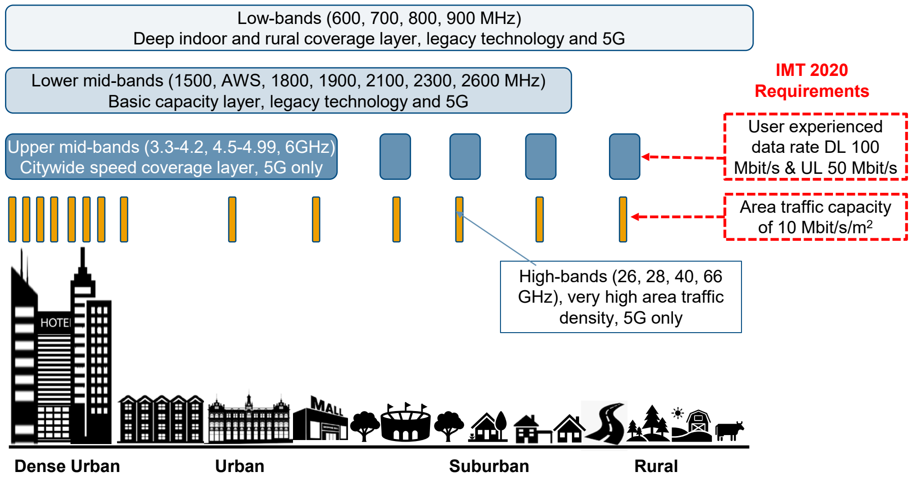
- Low-bands (e.g., 600, 700, 800, 900 MHz) are effective at addressing very wide area coverage and deep indoor coverage given their good propagation characteristics. However, there is little spectrum available and hence the channel bandwidth does not provide much capacity.
- Lower mid-bands (e.g., 1500, AWS, 1800, 1900, 2100, 2300, 2600 MHz) are already used for IMT for 2G, 3G, 4G and 5G. The lower mid-bands have been the capacity layer for 4G data traffic and in most countries the spectrum is used in FDD mode. China and the US are notable exceptions to this, with extensive 5G deployments in the 2600 MHz band with a TDD band plan. The use of this band for 5G will certainly grow over time.

Upper mid-bands (e.g., 3.3-4.2 GHz, 4.5-5 GHz, 5.925-7.125 GHz) are newer to 5G and offer a much wider bandwidth. This is a key 5G capacity resource. The upper mid-bands offer a good combination of propagation and capacity for cities.

- Upper mid-bands (e.g., 3.3-4.2, 4.5-5, 5.925-7.125 GHz) are newer to 5G and offer much wider bandwidths. This is a key 5G capacity resource. As of mid-2020, upper mid-band spectrum used in most countries is in the range of 3300 to 3800 MHz. Upper mid-bands offer a good combination of propagation and capacity for cities. 3GPP standards currently support a 100 MHz wide channel and for a maximum bandwidth of 400 MHz in carrier aggregation mode.
- High-bands (e.g., 26, 28, 40, 50, 66 GHz, also referred to as mmWaves) are effective at addressing areas with very high traffic density and extreme peak data rates.

The exhibit below shows the capabilities of each spectrum range and relates to their mix of coverage and capacity. The wider the rectangle, the higher the coverage. The shorter the rectangle, the higher the capacity. The closer the rectangles, the more the range is foreseen for such area, in order to guarantee the IMT-2020 requirements.

Exhibit 4: Mix of spectrum for 5G



Source: Coleago Consulting

3 Spectrum for city-wide speed coverage

3.1 Estimating spectrum requirements in the context of 5G

The ITU-R methodology for calculating spectrum requirements is set out in "Recommendation ITU-R M.1768-1(04/2013), Methodology for calculation of spectrum requirements for the terrestrial component of International Mobile Telecommunications". Input parameter values to be used in this methodology have been updated from those employed in Report ITU-R M.2078 (2006) in order to reflect the developments in mobile telecommunication markets. Report ITU-R M.2290-0 (12/2013) Future spectrum requirements - estimate for terrestrial IMT" applies this methodology to arrive at a forecast for 2020. This methodology proved to be useful to forecast spectrum requirements in the medium term in the context of WRC-15.

The ITU methodology was driven by traffic volume which was a reasonable approach because LTE is essentially used for best effort smartphone connectivity. In contrast the 5G vision is for a ubiquitous high speed user experience and connectivity for a wide range of new uses coupled with new features. Therefore, a key factor in driving the demand for capacity is the vision that 5G should provide the 100 Mbit/s user experienced data rate in the downlink and 50 Mbit/s in the uplink (for simplicity, we will refer to these throughput requirements as 100/50 Mbit/s requirement in the rest of the report) anytime, anywhere and while "on the move". While fundamentally a particular speed cannot be guaranteed in a mobile network, there is a quasi-guarantee which translates into a high probability of experiencing this data rate. This means networks will be designed to deliver a data rate (Mbit/s) rather than data volume (Gbytes/month). As a result, as we transition to 5G, the need for capacity will grow faster than traffic volume.

5G is not simply a continuation as we know it. The 5G vision is for a ubiquitous fibre-like speed user experience and connectivity for a wide range of new uses coupled with new features.

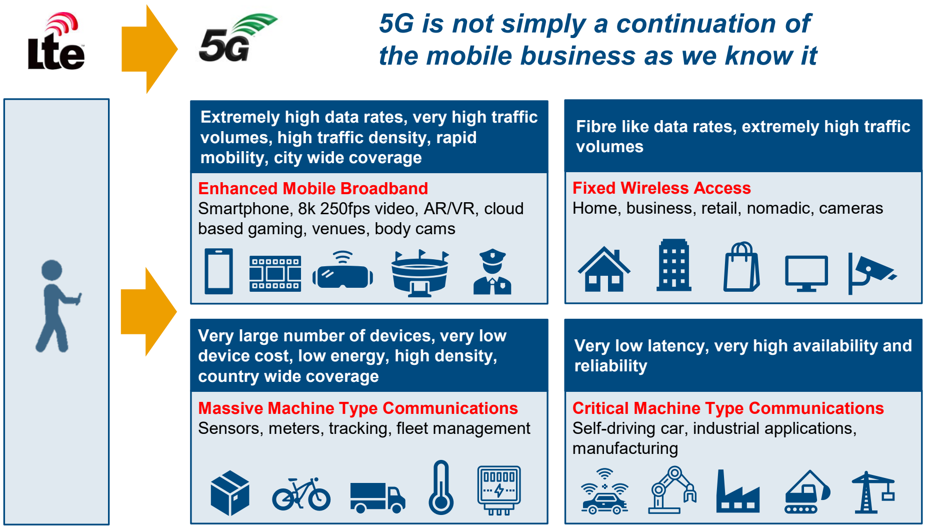
5G also enables the Internet of Things (IoT) with Massive Machine Type Communications (mMTC) and Ultra Reliable and Low Latency Communications (uRLLC). 5G end to end features such as making available a slice of the network for specific use cases bring a new dimension to how wireless communications can be used.

Exhibit 5 illustrates the 5G set of applications and use cases, all enabled by the enhanced capabilities of 5G compared to 4G. With these capabilities 5G is an enabling platform for what has been described as the “4th industrial revolution”[9]. While appearing futuristic today, connected vehicles, smart deliveries with drones and robots and smart cities will generate traffic volumes far higher than todays’ smartphone driven data usage rates.

5G envisions many use cases towards the city of the future or smart cities. These are crucial for our environment. In these cities, industries will be able to control energy consumption, through traffic management and transport will be able to pick the most optimized paths

Driven by these requirements, we have based our analysis of the need for additional upper mid-band spectrum in delivering near guaranteed user experienced data rates of 100 Mbit/s on the DL and 50 Mbit/s on the UL, anytime, anywhere in cities while “on the move”.

Exhibit 5: New use cases and applications drive 5G spectrum needs



Source: Coleago Consulting

3.2 ITU-R IMT-2020 user experienced data rate requirement

We have developed a concise and easily verifiable model to examine the need for mid-band spectrum in an urban environment to deliver the 100 Mbit/s user experienced data rate in downlink and 50 Mbit/s in the uplink ITU-R requirement for IMT-2020.

We have developed a concise and easily verifiable model to examine the need for upper mid-band spectrum to deliver the 100 Mbit/s user experienced data rate in the downlink and 50 Mbit/s in the uplink ITU-R requirements for IMT-2020 (5G) city wide. The need for spectrum is driven by traffic density measured in Gbit/s per km^2. Therefore, to examine future spectrum needs for IMT, we need to analyse traffic demand in areas with high population densities, i.e., cities. What matters in assessing spectrum needs is area traffic density demand vs. area traffic capacity supply.

Looking at 5G tariff plans, unlimited data volumes are becoming common and instead of selling data volume, 5G mobile operators sell speed (Mbit/s), i.e. the user experienced data rate

Our model is aligned with a change in how mobile broadband is being sold. In a 4G world, mobile operators sell data volumes (usually in gigabytes). Looking at 5G tariff plans, unlimited data volumes are becoming common and instead of selling data volume, 5G mobile operators are increasingly selling speed (Mbit/s), i.e., the user experienced data rate. While this is new for mobile connectivity, selling speed rather than data volume is of course the norm for fibre, cable, or xDSL fixed broadband. As explained above, the vision for 5G is to deliver fibre-like connectivity anytime,

[9] Klaus Schwab, The Fourth Industrial Revolution, Magazine of Foreign Affairs, 12 Dec 2015

anywhere. Hence, we need to base traffic forecasts on the user experienced data rate and not monthly data volumes.

In the development of the ITU's IMT-2020 requirements, the user experienced data rate relates to human users 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 km^2. The uncertainty over how much simultaneous capacity will be required for all of these use cases in a given area is very large and bottom-up models of future traffic are speculative. Our approach is to use population density in cities as a proxy for traffic density to estimate the minimum or floor capacity requirement. This is conservative, since traffic generated by connected vehicles and video-based sensors could be a multiple of traffic generated by human users. Hence tying traffic demand per capita based on the ITU-R IMT-2020 requirements generates a conservative estimate for future spectrum needs.

The advantage of focusing on the 5G requirements for a minimum data rate is that the model is easy to validate because it relies on a small number of key assumptions.

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.

For each city, we took account of the spectrum needs identified for both downlink and uplink and calculated the additional upper mid-band spectrum needs. Since the identified additional upper mid-band spectrum is expected to have a TDD band plan, it will be shared in the time domain between the DL and the UL, in this case assuming a DL:UL ratio of 3:1.

There is some uncertainty over how the DL:UL ratio may change over time. For example, some applications such as cameras will increase the need for UL capacity. In the longer term the total DL and UL area traffic demand must be served using additional upper mid-band spectrum and by adjusting the DL:UL split in synchronised TDD bands proportionate to relative demand. To examine the relevance of the DL:UL assumed demand, we tested the sensitivity of the DL:UL ratio of 3:1. Within the spectrum scenarios considered, the 3:1 ratio gives the lower demand for additional upper mid-band spectrum. Our modelling shows that in the longer term the uplink may become the driver for additional spectrum needs.

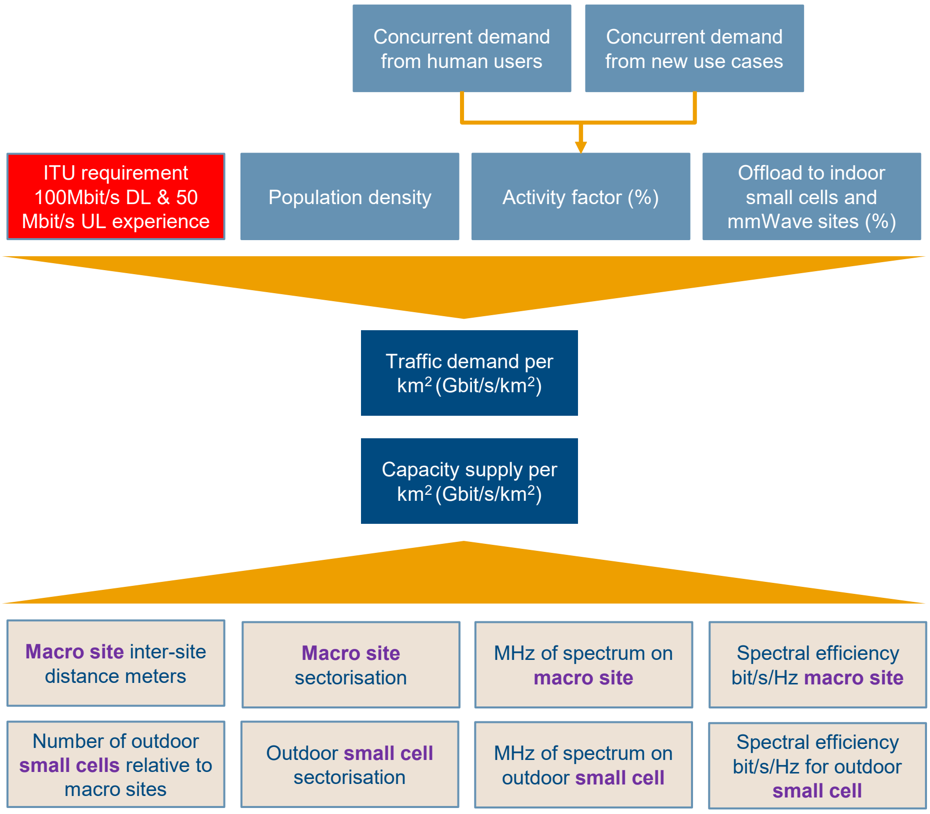
The 100 Mbit/s DL and 50 Mbit/s UL data rate requirements are not the same as a guaranteed data rate. The economics of mobile networks are driven by the fact that radio access network resources are *shared* amongst users. This is the key reason why per gigabyte retail prices for mobile data services have declined substantially and, with the introduction of 5G, continue to decline at a fast rate. In a simultaneously multi-user network, the user experienced data rate is dependent on the probability of simultaneous demand from multiple users in a given cell. Providing a guaranteed data rate for all users would not be feasible from an economic perspective. The area traffic capacity supply is derived from an average spectral efficiency which cannot guarantee that the user experienced data rate is delivered consistently at all times. Therefore, it would be inappropriate to turn the ITU-R IMT 2020 user experienced data rate requirements into a regulatory obligation.

3.3 Modelling upper mid-band spectrum needs

3.3.1 Overview of the spectrum demand model

We have developed a methodology which allows us to compare area traffic density demand with area traffic capacity supply in cities. The metric used is Gbit/s per square kilometre (Gbit/s/km^2). To model future area traffic density demand we used several drivers which are explained in detail in section 3.3.2 below and we forecast relevant variables in the 2025-2030 time frame which are examined in section 3.3.3 below. The excess demand over supply drives the forecast of the need for additional upper mid-band spectrum. Exhibit 6 summarises the variables in the model.

Exhibit 6: Area traffic demand and capacity supply model



Source: Coleago Consulting

3.3.2 The area traffic density demand side – key assumptions

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

- The IMT-2020 requirement for a downlink user experienced data rate of 100 Mbit/s and a 50 Mbit/s uplink data rate;
- The population density, which varies by city and is the key driver explaining differences in spectrum needs between cities and by implication between countries;
- An assumption of concurrent demand at busy times from human users and new use cases (the activity factor);
- An assumption of how much of the traffic demand would be satisfied by high bands (24 GHz and above) sites; and
- An estimate of the percentage of traffic offloaded to indoor upper mid-band small cells.

The objective is to compare the traffic density demanded in a city with the capacity delivered, depending on the amount of spectrum deployed. We describe these drivers in more detail below.

100 Mbit/s DL and 50 Mbit/s UL user experienced data rate

The ITU-R requirement is that 5G must deliver a DL user experienced data rate of 100 Mbit/s and 50 Mbit/s in UL. This is the starting point for the demand analysis.

In order to deliver 100 Mbit/s DL and 50 Mbit/s UL user experienced data rate citywide, i.e., anytime anywhere in the city, mobile operators must cater for speed coverage across the entire city area. This implies that the traffic per square kilometre over an entire city area is a function of the population density in that city. This results in an average traffic demand per square kilometre (Mbit/s/km^2).

Citing an average implicitly assumes that traffic demand is evenly distributed across the city area. In reality that is not the case but, for our approach to demand modelling, the simplified assumption that traffic which would be carried by low-bands and lower / upper mid-bands would be relatively evenly distributed is reasonable, considering the following:

- As explained below, data usage and the duration of usage is increasing and hence high bandwidth demand extends over longer periods of time.
- Today's traffic distribution relates largely to traffic demand from smartphones. In a mid-term future, traffic demand by new use cases and new applications will occur in locations within a city where previously there may not have been a need for much capacity, for example on urban transport routes. This tends towards a more even demand for capacity across a city area.
- There are always areas with a very high 5G area traffic density demand. Our model takes account of this by assuming that high-bands will provide 5G capacity in those areas. This will effectively take care of localised peaks in area traffic demand thus leaving the demand in the remaining area more evenly distributed (i.e., offload to high-bands as called in this model).

Population density

Our approach is to use population density in cities as a proxy for traffic density to estimate the minimum or floor capacity requirement.

Our approach is to use population density in cities as a *proxy* for traffic density to estimate the minimum or floor capacity requirement. Traffic generated by connected vehicles and video based sensors could be a multiple of traffic generated by human users and therefore tying traffic demand per capita to the user experience data rate generates a conservative estimate for future spectrum needs.

The population density is the average in a dense area of a city. We focused on cities that have a sizeable area with a population density of at least 8,000 per km^2. In many cases, the high-density area is not the same as the administrative area of a city or the build-up area of a city, like in in Istanbul, where we base our analysis on what is still a large high-density area of 698 km^2 with an average population density 17,316 per km^2, while its entire administrative area is of 1,375 km^2. A detailed explanation on urban extents and population density is shown in Appendix C.

In principle, *other things being equal*, the higher the density, the greater the demand per km^2 and consequently the higher the population density the greater the need for additional mid-band spectrum.

Concurrent demand for capacity – the activity factor

As regards the requirement to serve users demanding 100 Mbit/s in the downlink and 50 Mbit/s in the uplink, not all users in a particular cell would require this at the same time. We need an assumption with regards to the concurrent or simultaneous demand for capacity during the busy period of a cell, including human and non-human usage.

In our model, demand from human and non-human use cases is captured in the form of an "*activity factor"* to represent concurrent demand for bandwidth in the busy period of a cell, considering 100 Mbit/s DL / 50 Mbit/s UL equivalent demand per capita, then, applying this activity to the population density. The higher the activity factor the greater the need for additional mid-band spectrum.

In addition to human users, 5G is designed to support massive machine type communications and critical machine type communications such as connected cars, sensors, and cameras. The 5G vision anticipates 10 million connections per km^2. When this becomes a reality, in dense cities with population densities of 10,000 to 30,000 people per km^2, human users will only account for less than 1% of connections. Therefore, there will be considerable bandwidth demand from diverse non-human use cases.

To illustrate the relative scale of device density, we looked at vehicles and cameras:

- In European cities there is around one vehicle per two people. Vehicles include cars, commercial vehicles, and public transport vehicles.
- The number of connected cameras is growing, adding to UL demand. For example, in London there are an estimated one CCTV camera per 13 people. Cameras are being added at a fast rate including, bicycle riders, body cams, LIDAR cameras for traffic monitoring. Where previously simple sensors may have been used, camera-based analysis using AI will become commonplace. Today most cameras do not use cellular connectivity, but new installations are increasingly connected via cellular. Furthermore, cameras for mobile use, such as body cams, rely on cellular connectivity. While not all camera may require 50 Mbit/s, some stream 24/7, i.e., the notional activity factor for cameras which stream 24/7 is 100%, i.e., there is a continuous traffic demand which contributes to total concurrent area traffic demand.

These non-human use cases include those that require a high bit rate at a specific time such as cameras and assisted driving cars and those that require a lower bit rate such as meters and simple sensors. In aggregate these devices will create significant concurrent area traffic demand which adds to demand from human users.

The activity factor which represents concurrent 100/50 Mbit/s equivalent area traffic demand per capita will increase over time driven by the following factors:

- Increased adoption of 5G smartphones and associated data usage;
- Increase in sustained video streaming downlink and uplink;
- Higher bit rates demand by better device capabilities;
- Application driven high bandwidth and low latency requirements; and
- Increasing density of non-human connected devices.

Looking at the increase in data usage from humans, already today mobile network usage is dominated by smartphones and is increasing rapidly. In Finland average usage is already nearly five times higher than this: "*Mobile data usage grew to 34 gigabytes per Finn per month during the first half of 2019, which is 21 per cent more than the year before*"[10]. Looking specifically at 5G users in South Korea, monthly data usage is three times[11] higher compared to 4G users. This is driven by the fact that users opt for 5G plans which offer unlimited data usage and do not throttle speed above a certain limit.

The key driver in the growth of mobile usage is video, including streaming content, video calling, video gaming, and streaming from cameras. These all demand a constant speed over longer time periods that can run into the hours rather than minutes. The longer the period during which people and other devices stream video, the more concurrent use there will be. This is evident from FTTH, xDSL, and cable broadband which have a busy period lasting several hours rather than the peaky traffic pattern associated with today's mobile use. Long streaming times leads to a situation where more people use their devices concurrently in the same cell. This translates into a higher activity factor for human users.

[10] Source: Traficom, Finish Transport and Communications Agency, 2.11.2019
[11] Source: MITC, December 2019 traffic

Not only is the duration of video sessions increasing, but also the bit rate. For example, the capabilities of smartphones are advancing offering ever higher video quality and 4K video is now available on mobile orientated streaming platforms such as YouTube. Exhibit 7 shows the video quality settings available on an iPhone 12 (5G) and the amount of data is created for a one-minute video. Exhibit 8 shows the relationship between video quality and required bandwidth. Even today's 5G smartphones have applications that require a data rate of 59 Mbit/s. In the future we will see duplex video calls at this data rate simultaneously in the uplink and the downlink and over the next 10 years we will see applications that require a data rate of 100 Mbit/s and above. For example, 6 Degrees of Freedom or Free Viewpoint AR/VR video requires a data rate of 200 Mbit/s[12] and higher. Appendix G contains examples data rates required for new applications, including AR and VR.

Exhibit 7: Video quality options and impact on bandwidth demand

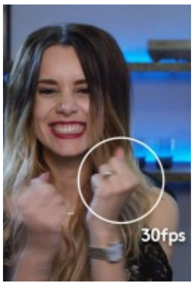
10:21

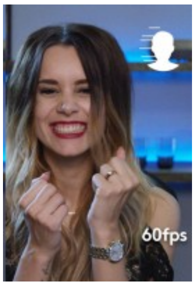
Camera — Record Video

Record Video	**Impact on data usage:**
720p HD at 30 fps	(Lowest quality on iPhone12)
1080p HD at 30 fps	1.4x the lowest quality
1080p HD at 60 fps	2.2x the lowest quality
4K at 24 fps	3.3x the lowest quality
4K at 30 fps	4.2x the lowest quality
4K at 60 fps ✓	**9.8x the lowest quality**

QuickTake video will always record with 1080p HD at 30 fps.

A minute of video will be approximately:
- 45 MB with 720p HD at 30 fps (space saver)
- 65 MB with 1080p HD at 30 fps (default)
- 100 MB with 1080p HD at 60 fps (smoother)
- 150 MB with 4K at 24 fps (film style)
- 190 MB with 4K at 30 fps (higher resolution)
- 440 MB with 4K at 60 fps (higher resolution, smoother)

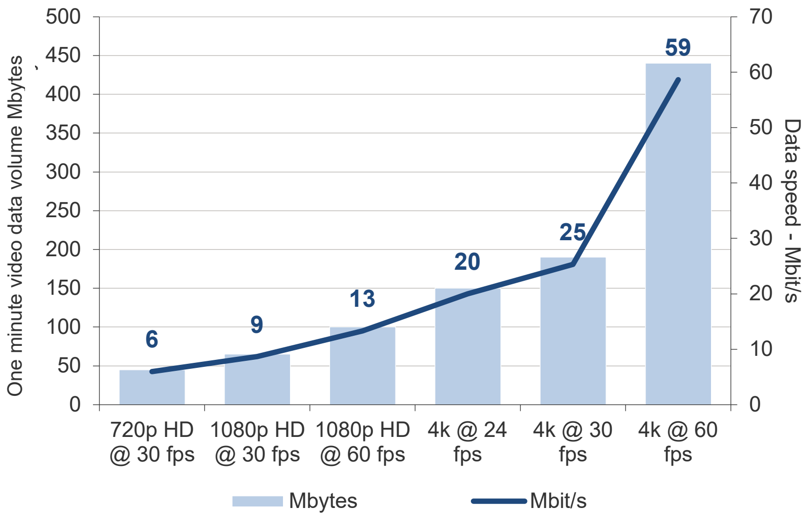




Source: iPhone 12 screenshot

[12] "VR and AR Pushing Connectivity Limits", Qualcomm, October 2018

Exhibit 8: Video data volume and data rate depending on video quality



Source: Coleago

There is considerable uncertainty over how much of the demand for the new use cases in a given area will be simultaneous. Traffic generated by connected vehicles, cameras, and video-based sensors could be a multiple of traffic generated by human users as illustrated by the following examples:

- Conventional and LIDAR cameras stream data continuously, i.e., they demand bandwidth over hours, and even 24/7. Body worn cameras worn by first responders and other field operatives may stream continuously during several hours.
- Connected cars today generate hardly any traffic. However, over a 10-year time frame a connected car may generate about as much data as 3,000 people as explained in Chapter 6 of this report[13]. We note that only part of the data will be streamed live.

Since today's data usage is still dominated by 4G, one cannot use today's usage to extrapolate what concurrent bandwidth demand will be once 5G has been widely adopted in the 2025-2030 time frame. While demand for area traffic capacity will clearly increase by orders of magnitude, there is uncertainty over the speed and quantum. It is with this in mind that we analyse the need for additional mid-band spectrum for a range of activity factors.

In highly industrialised countries, we expect that the activity factor for mobile 5G in cities will reach 25% within the 2030 time frame considered by this report. In countries with lower access to wired broadband, 5G FWA may also drive concurrent demand for the user experience data rate in cities, thus pushing up the activity factor to 20-25% levels.

High-bands offloading factor

As of April 2021, high=bands (mmWaves) have started to be deployed. It is clear that mmWave will be deployed by 2025-2030 more largely and thus we consider traffic offload to this range. The higher the percentage of traffic offloaded to high-band spectrum, the lower the demand for additional upper mid-band spectrum.

[13] Brian Krzanich, CEO, Intel, 2019

In our model we use a range of high-band offload factors from 10% to 45%. This is a wide range which reflects uncertainty over the timing and deployment density due to differences in population density, speed of network evolution and other factors between cities:

- Over time, more and more high-band sites will be deployed in dense areas and, hence, the proportion of 5G traffic served by high-band sites will increase. In other words, the further we move into the future, the higher the percentage of offload to high-bands will be.
- However, high-bands will not provide continuous coverage in a city, but will be deployed to serve indoor and outdoor locations with a very high traffic density. Several factors will drive the deployment of high-band sites, among other factors, the speed of network evolution, population density and traffic density.
- Whether or not high-bands are deployed outdoors or indoors does not matter; what matters is that they will absorb part of the area traffic demand that would otherwise need to be carried by upper mid-band small cells. In our model this is referred to as offloading to high-bands. In any case the notion of outdoor vs indoor is not clear cut, in the sense that, for example, a busy railway station or a stadium may be partly indoor and partly outdoor.

Offloading to indoor mid-band small cells

The area traffic density demand analysis focuses on 5G mobile traffic and capacity supplied by outdoor 5G macro sites and outdoor upper mid-band small cells. Base stations serve both outdoor and indoor mobile traffic. However, given the requirements to provide 100/50 Mbit/s anywhere, in some locations upper mid-band small cells are expected to be installed indoors to provide speed coverage. These indoor sites reduce demand for capacity on cell sites located outdoors, i.e., traffic is offloaded from outdoor sites to indoor small cells. Therefore, while in principle we are considering outdoor cell density we need to take account of the fact that indoor upper mid-band small cells effectively offload outdoor sites.

There are already 4G in-building solutions. However, given the requirement to provide a user experienced data rate also indoors, for example a shopping mall, we expect operators will deploy more upper mid-band small cells which will increase the percentage of traffic carried by indoor upper mid-band small cells. We assume that on top of offload to high bands sites, an additional 10% traffic will be offloaded to upper mid-band indoor cells.

Exhibit 9: Offload to 5G high bands & indoor upper mid-band small cells

Offload to high bands
In cities, 10% to 45% of 5G mobile traffic is expected to be offloaded to high bands (mmWave).

Offload to indoor upper mid-band small cells
In cities, 10% of 5G mobile traffic is assumed to be offloaded to upper mid-band small cells located indoors.

Source: Coleago

Offload and onload to and from Wi-Fi

Wi-Fi carries substantial amounts of traffic generated by mobile devices in countries that have a good fixed broadband infrastructure, but no 5G and 4G unlimited plans.

However, our model focuses on delivering the requirements for 5G mobile and not on other wireless or wired access technologies. We do not make a forecast for all data traffic in a city. Nevertheless, the effect of Wi-Fi offload is implicitly included in the model through the activity factor, as, for example, in countries with high availability wired broadband, the activity factor would be significantly higher without Wi-Fi offload.

5G networks must deliver the predictable and "on the move" user experienced speed of 100/50 Mbit/s. For instance, it is immaterial how many TV screens there will be, that are connected to an FTTH connection plugged in or via Wi-Fi, we simply do not count this traffic as requiring IMT spectrum.

Similarly, we do not explicitly add traffic arising from the trend to *Wi-Fi onload*, i.e., for example people using 5G enabled laptops, the use of 5G FWA routers, or simply the using the Personal Hotspot function of a 5G smartphone to provide Wi-Fi connectivity to multiple nearby devices.

3.3.3 The area traffic capacity supply side – key assumptions

The variables in the city capacity supply per km^2 availability model are:

- The number of macro cell sites per km^2, driven by the inter-site distance;
- The role of mid-band outdoor small cells;
- Base station design margin;
- The site sectorisation;
- The spectral efficiency; and
- The amount of existing spectrum and additional spectrum that should be made available in the future.

Number of macro cell sites

A key assumption is the number of macro base station sites per km^2 across a city at which the spectrum is used. For this we have not made operator specific assumptions, but for the sake of simplicity we model this as if all operators in a city share the same sites.

A key assumption is the number of macro base station sites per km^2 across a city in which the spectrum is used. In a typical city, sub-1 GHz and lower mid-bands are deployed mostly on macro sites while upper mid-bands are deployed on macro sites and small cells. There is no standard definition of what a macro site is and what a small cell is. We define a macro site as a larger structure carrying all available spectrum bands, operating at higher output power and typically with three sectors, noting that in reality a single macro may only be equipped with a subset of an operators' assets.

As regards the number of macro sites in a city, we have not made operator specific assumptions, but for the sake of simplicity we model this as if all operators share the same sites. Since not all physical sites are multi-tenant, the real number of physical sites would be higher but not all spectrum would be used at each site. The capacity calculation does not depend on this issue because total supplied capacity is the number of sites multiplied by the amount of spectrum on each site. Our simplified approach is, therefore, representative.

The number of macro sites in a city is calculated using the inter-site distance and the area of that city. We assume that the average inter-site distance for macro sites in cites with a high population density is or will be 400 meters[14]. This is the average over a reasonably sized area, typically in excess of 100 km^2. In some cities inter-site distances are already below 400 meters, but some of these sites cannot make use of all available spectrum, for example low-bands because of interference issues.

[14] 400m intersite distance corresponds to 133m cell radius (266m cell range)

In cities, the macro cells inter-site distance is driven by the need to provide capacity rather than range. However, when inter-site distances get shorter, co-channel and adjacent channel interference management starts to become problematic. This effectively sets a macro-site densification limit where the capacity gain of increased densification is offset by capacity loss due to measures taken to manage interference between macro sites.

We explain below that in our model we assume that all available spectrum is deployed on all sites which may over-estimate the supplied area traffic capacity and compensates for situations where the actual macro inter-site distance is less than 400 metres. Hence our assumption is broadly representative of what an urban macro deployment might look like at the point where the maximum macro-site densification is reached.

We validated the macro inter-site distance assumption by comparing the number of macro sites predicted by the model with the number of actual sites for the cities in our sample.

The role of mid-band outdoor small cells

We need to take account of future site build with 2025-2030 in mind. 5G will rely on outdoor small cell deployment to ensure speed coverage and hence the number of cell sites is expected to increase substantially.

Outdoor small cells would not provide continuous coverage but would be deployed to fill in speed coverage holes. These speed coverage holes are at locations where, for example, due to blockage by buildings, upper mid-bands used at macro sites do not provide the speed coverage. In other words, outdoor small cells provide consistency of area traffic capacity by in-filling any speed coverage holes at the macro layer.

The precise number of outdoor small cells required to fill in speed coverage holes depends on the topology of a particular city. Based on our work with operators[15], in a typical urban area in a 15 years' time frame the number of outdoor small cells for upper mid-band deployment would be two to three times the number of macro sites. In our model, we conservatively assume that the number of upper mid-band outdoor small cells in cities would grow to be three times the number of macro sites per operator.

In our model we assume that each outdoor small cell uses all available upper mid-bands spectrum. We assume colocation for macro sites, but small cells will not accommodate the entire spectrum of all operators. In practice in a three operator scenario, there would be nine small cells per macro site.

In theory mobile operators could build many more small cells. However, there are two constraints: economic and environmental. It is significantly more cost effective to add spectrum to an existing site because this reduces capital expenditure and operational expenditure. In a competitive market this translates into lower retail prices, i.e., a consumer surplus. Secondly, local authorities are keen to limit mobile sites to the number necessary to provide a good 5G service because a very large number of sites is not desirable from an environmental perspective, both visual and with regards to power consumption. The benefit of using additional upper mid-bands spectrum to reduce the number of small cells is discussed in more detail. Densification is further analysed in chapter 4.

Design margins

In practice, site capacity at a base station in the busy period cannot be fully utilised. In order to manage interference, a design margin of at least 15% is required and, therefore, 15% of the nominal capacity cannot be used. The assessment of the spectrum needs in this report is based on the busy period when base stations are heavily loaded. This approach ensures that the need for additional spectrum is not overestimated which could occur if a higher design margin equivalent to less loaded base stations is considered.

[15] Source: Coleago Consulting work with several operators in Europe and North America.

Site sectorisation

A typical urban macro-cell deployment uses three sector sites. In some cities where macro sites are very densely spaced, these sites may only have one or two sectors. In our model we use the simplified assumption that all urban macro sites have three sectors. This maximises the capacity (and consequently minimises demand for additional spectrum) and also compensates for the fact that in some cities the inter-site distance may be less than the 400 metres assumed in our model.

Small cells have predominantly only one sector. Our model is consistent with this assumption.

Spectral efficiency

We have used appropriate assumptions with regards to the downlink and uplink spectral efficiency for the different types of spectrum in an urban environment. While currently 2G, 3G and 4G are deployed in low-bands and lower mid-bands, in time these will all be refarmed to 5G-NR. Therefore, we used the higher spectral efficiency for 5G with an appropriate MIMO configuration.

The spectral efficiency values used are based on those typically used by many mobile operators for whom we have carried out long-term network dimensioning work. In some cases, the values are lower than those published by the ITU-R[16].

The ITU-R spectral efficiency values are achievable under ideal conditions in a dense urban environment, but here we are modelling a real-world deployment and consider average spectral efficiency not only over a cell area but over an entire city. The high population density areas include both dense urban and urban environments. For example, the ITU-R target for dense urban eMBB is 7.8 bit/s/Hz which could be achieved by using 64-element MIMO at the base stations. However, across a city in upper mid-bands a mix of MIMO configurations will be used and hence we used a blended average spectral efficiency.

Baseline spectrum and additional spectrum

We assume that all available low-bands, lower mid-bands, and upper mid-bands will be deployed on all macro sites. As regards small cells, we assume that upper mid-band spectrum will be used on all small cells.

To calculate how much additional spectrum is required to address the needs in the 2025 to 2030 time frame, we first need to identify the spectrum that is and can be expected to be available to mobile operators in the low- and mid-bands before 2025. We call this the baseline spectrum. The additional upper mid-band spectrum demand is the spectrum that is needed on top of the baseline spectrum.

Our baseline spectrum assumption includes a wide definition so as to ensure that we do not over-estimate demand for additional IMT spectrum. The baseline spectrum is the maximum low- and mid-band spectrum that could be made available given the current status of IMT band identification. This includes:

- Spectrum currently assigned to operators;
- Spectrum available but not assigned; and
- Spectrum which has a mobile allocation and is expected to be made available for 5G before 2025.

The baseline spectrum varies by country and we have taken account of this to model demand for additional upper mid-band spectrum in each city. Exhibit 11 summarises this.

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. As regards to outdoor small cells, we assume that upper mid-band spectrum will be used on all outdoor small cells.

[16] Spectrum efficiencies used in the context of ITU-R were derived from simulations that do not account for the “implementation losses” (non-calibrated antenna, hardware impairments, aging). Such simulations use the “full buffer” assumption that allows to exploit the perfect scheduler performance, real traffic is different. Furthermore, those simulations rely on the uniform distribution of end users but this is not the reality.

The last column in Exhibit 10 below shows the baseline spectrum typically available in a city. The baseline spectrum varies by city, as shown in Exhibit 11. In the spectrum demand model, the baseline spectrum resources deliver the baseline area traffic capacity. When area traffic demand exceeds this baseline capacity, additional spectrum is required.

Exhibit 10: Key 5G modelling assumptions for future urban environment

Band	Category	Average inter-site distance (m)	Number of sectors	Average DL/UL spectral efficiency (bit/s/Hz)	Typical baseline spectrum available**
600-900 MHz	Macro site; Low-bands	400	3	1.8 / 1.8	190 MHz
1.500-2.600 GHz	Macro site; Lower mid-bands	400	3	2.2 / 2.5	460 MHz
3.3- 7.125 GHz	Macro site; Upper mid-bands	400	3	6.0 / 4.1	400 MHz
3.3-7.125 GHz	Macro site; Additional upper mid-bands	400	3	6.0 / 4.1	Spectrum demand model output
3.3-7.125 GHz	Outdoor small cell; Upper mid-bands	n/a*	1	3.7 / 2.6	400 MHz
3.3-7.125 GHz	Outdoor small cell; Additional upper mid-bands	n/a*	1	3.7 / 2.6	Spectrum demand model output

* For outdoor small cells this does not assume contiguous coverage because outdoor small cells are deployed to fill in speed coverage holes rather than providing contiguous coverage. Hence the inter-site distance is irrelevant.

** The baseline spectrum varies by city.

Source: Coleago Consulting

Exhibit 11: Baseline spectrum for selected cities

City	Low Band FDD	Low Band SDL	Lower Mid Band FDD	Lower Mid Band SDL	Lower Mid Band TDD	Upper Mid Band TDD	Low Band Total	Lower Mid Total	Upper Mid Total	Total Total
Paris	190	0	410	85	40	400	190	535	400	1125
Lyon	190	0	410	85	40	400	190	535	400	1125
Marseille	190	0	410	85	40	400	190	535	400	1125
Berlin	190	0	410	85	40	300	190	535	300	1025
Hamburg	190	0	410	85	40	300	190	535	300	1025
Munich	190	0	410	85	40	300	190	535	300	1025
Rome	190	0	410	85	40	400	190	535	400	1125
Milan	190	0	410	85	40	400	190	535	400	1125
Madrid	190	0	410	85	40	400	190	535	400	1125
Barcelona	190	0	410	85	40	400	190	535	400	1125
Amsterdam	190	0	410	85	40	400	190	535	400	1125
Moscow	190	0	410	0	155	190	190	565	190	945
Sao Paulo	140	0	410	60	100	400	140	570	400	1110
Lagos	170	0	410	0	130	100	170	540	100	810
Tokyo	150	0	270	10	190	800	150	470	800	1420
Bogotá	210	0	340	90	120	400	210	550	400	1160
Mexico City	210	0	400	90	150	300	210	640	300	1150
New York	170	10	320	0	190	440	180	510	440	1130
Nairobi	190	0	270	0	190	200	190	460	200	850
Johannesburg	196	0	264	0	220	190	196	484	190	870
Mumbai	137	0	188	0	100	300	137	288	300	725
Jakarta	160	0	270	0	280	300	160	550	300	1010
Hong Kong	245	0	360	0	90	380	245	450	380	1075
Ho Chi Minh City	180	0	410	0	145	400	180	555	400	1135
Beijing	150	0	270	0	345	500	150	615	500	1265
Yangon	160	0	270	0	365	200	160	635	200	995
Cairo	130	0	270	0	190	200	130	460	200	790
Istanbul	190	0	410	85	140	400	190	635	400	1225
Tehran	130	0	290	0	130	200	130	420	200	750
Baku	190	0	410	0	155	200	190	565	200	955
Minsk	190	0	410	0	155	200	190	565	200	955
Tashkent	190	0	410	0	155	200	190	565	200	955
Makkah	240	0	270	0	375	500	240	645	500	1385
Riyadh	240	0	270	0	375	500	240	645	500	1385
Amman	190	0	270	0	375	400	190	645	400	1235
Bangkok	170	0	350	0	250	300	170	600	300	1070

Source: NRAs, GSMA, Coleago

3.4 Spectrum demand model results

3.4.1 Introduction

Using the methodology and parameters in chapter 3.3 above in combination with the population densities shown in Exhibit 14 we modelled the needs for additional upper mid-band spectrum to meet the downlink and uplink area traffic demand in a sample of larger cities in different regions in the 2025-2030 time frame.

The key variables that explain the demand for spectrum are:

- Population density;
- The activity factor; and
- The percentage of traffic offloaded to high bands.

3.4.2 Example: Paris area

We have calculated the area traffic demand for the downlink and the uplink depending on the activity factor and the percentage of traffic that is offloaded to high bands. The result is shown in Exhibit 12 below. France is a high-income country and hence it could be expected that by 2030 100% of smartphone users are 5G and that there will be a high-density of other 5G use cases. This would mean a 25% activity factor is relevant for Paris. Given the high activity factor, it is reasonable to assume that 45% of traffic will be offloaded to high-band spectrum. With those assumptions the area traffic demand density forecast to be 311 Gbit/s/km^2.

To put the average area traffic demand density across the more densely populated area of Paris of 311 Gbit/s/km^2 into perspective we can compare it to the ITU-R IMT-2020 area traffic requirement of 10 Mbit/s/m^2. 10 Mbit/s/m^2 equates to 10,000 Gbit/s/km^2. Our 310 Gbit/s/km^2 on average across the whole city is only 3.1% of the hotspot peak. This illustrates that our numbers are modest by comparisons to localised traffic density peaks.

Exhibit 12: Area traffic demand in the Paris area

Offload to High-Band	Dowlink Traffic Demand (Gbit/s/km^2) Activity Factor 5%	10%	15%	20%	25%	Uplink Traffic Demand (Gbit/s/km^2) Activity Factor 5%	10%	15%	20%	25%	DL + UL Traffic Demand (Gbit/s/km^2) Activity Factor 5%	10%	15%	20%	25%
10%	74	147	221	294	368	37	74	110	147	184	110	221	331	442	552
15%	69	138	207	276	345	35	69	104	138	173	104	207	311	414	518
20%	64	129	193	258	322	32	64	97	129	161	97	193	290	386	483
25%	60	120	179	239	299	30	60	90	120	150	90	179	269	359	449
30%	55	110	166	221	276	28	55	83	110	138	83	166	248	331	414
35%	51	101	152	202	253	25	51	76	101	127	76	152	228	304	380
40%	46	92	138	184	230	23	46	69	92	115	69	138	207	276	345
45%	41	83	124	166	207	21	41	62	83	104	62	124	186	248	311

Source: Coleago

Having calculated the area traffic demand density, we can compare this with the area traffic capacity using the assumptions stated above and different availability levels of upper mid-band spectrum in addition to the baseline spectrum. Exhibit 13 shows the downlink spectrum need for the Paris urban area which is larger than the Paris city administrative area but has a lower average population density compared to the Paris city area. The population density is plotted on the horizontal axis. The urban area extends beyond the city limits and includes 243[17] km^2 with a population of 4,468,000 and an average population of 18,400 per km^2. This population density for the Paris urban area is indicated by the vertical purple line.

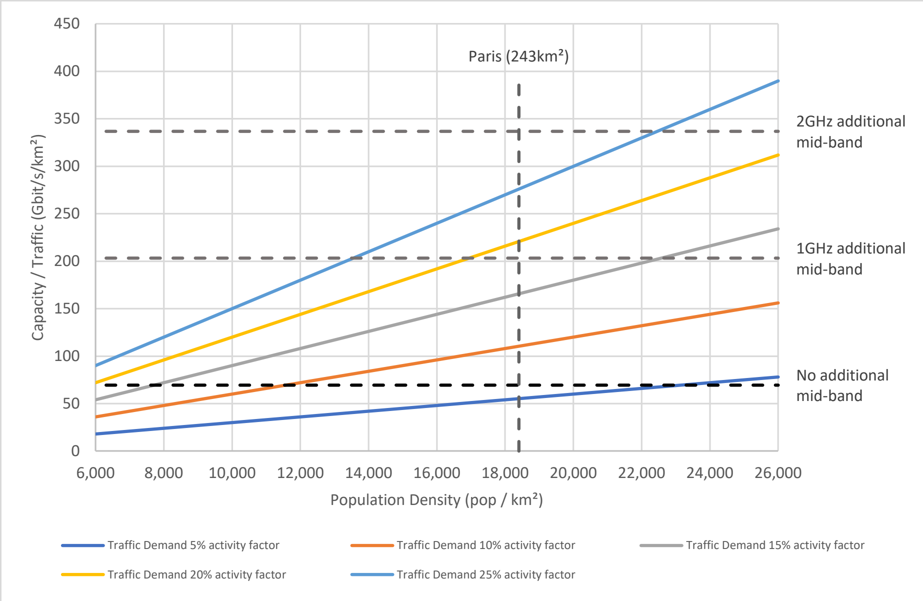
The upward sloping-coloured lines are the area traffic demand at various activity factors. The lines are upward sloping because area traffic demand increases in proportion to population density. The area traffic demand and capacity in Gbit/s/km^2 is shown on the left-hand vertical axis. In this chart we only show the downlink traffic.

The dashed horizontal lines indicate the area traffic capacity depending on the amount of spectrum available. The lowest line shows the area traffic capacity if no additional upper mid-band spectrum is available. The four other lines show the area traffic capacity at increments of 500 MHz of additional upper mid-band spectrum.

[17] In Coleago's previous European spectrum demand report (https://www.gsma.com/gsmaeurope/resources/imt-spectrum-demand/) we based our analysis on the area of Paris inside the Boulevard Périphérique which is essentially the Paris administrative city area only. However, the urban area continues beyond the city limit and therefore in this report we extended the area to included highly urbanised parts beyond the Boulevard Périphérique. This reduces the average population density in the area.

The point at which the upward sloping demand lines crosses the Paris area population density line shows the required area traffic capacity. For example, the yellow line which represents the 20% traffic demand activity factor crosses the Paris population density line at just above the 1 GHz of additional spectrum line, where the area traffic capacity / demand shown on the vertical axis is 202 Gbit/s/m^2. This figure can also be seen in Exhibit 12 in the first table, which shows the downlink demand in the cell 20% activity factor and 35% offload to high bands.

Exhibit 13: Downlink spectrum need in Paris urban area



Note: This chart is based assuming 35% offload to high bands.

Source: Coleago Consulting

3.4.3 Spectrum demand in sample cities

We have calculated the spectrum demand for a selection of cities around the world and Exhibit 14 shows the total mid bands spectrum needs, including the baseline mid-band spectrum and considering a range of activity factors and high bands offload factors.

In cities with a population density greater than 8,000 per km^2, additional mid-band spectrum is required to deliver the 5G NR experienced a DL data rate of 100 Mbit/s and an UL data rate of 50 Mbit/s

- The cities have been ordered by population density in ascending order. The amount of spectrum required increases with population density. Population density in urban areas is the key driver for additional upper mid-band spectrum needs.
- Looking at the table horizontally, the data shows a) with higher activity factors the need for upper mid-band spectrum increases and b) the lower the offload to high-bands, the higher the need for upper mid-band spectrum.
- We modelled the spectrum need depending on the percentage of traffic offload to high-bands with a range from 10% to 45%. The higher the activity factor the higher the traffic density. With high traffic densities operators will increasingly resort to upper mid-band small cells to provide area traffic capacity. Therefore, the higher the percentage of traffic that is likely to be offloaded to high-bands.
- The demand for additional spectrum also depends on the amount of baseline spectrum and this is material at lower activity factors. However, with a high activity factor, the amount of baseline spectrum matters relatively less.

Our analysis leads to the conclusion that the use of additional mid-band spectrum would enable the 5G NR experienced 100/50 Mbit/s data rate to be delivered in an economically feasible manner in the cities we examined, anytime, anywhere, citywide thus delivering not only the 5G experience for smartphone users but also enabling the smart city.

In areas with a population density below 8,000 per km², additional mid-band spectrum would reduce site density, which in turn would deliver environmental benefits.

In areas with a population density below 8,000 per km², additional mid-band spectrum would still deliver benefits. The benefit would either be a lower site density or a higher experienced data rate. A lower site density translates into a lower cost per bit which will in turn translate into lower retail prices. The improved power consumption is also important. The trade-off between additional spectrum and site densification is discussed in chapter 4.

Exhibit 14: Total (incl. base line) mid-band spectrum needs (MHz)

DL and UL total (including baseline) mid-bands spectrum need [MHz]														
City	Popn density per km²	Dense Area km²	Activity factor 10%			Activity factor 15%			Activity factor 20%			Activity factor 25%		
			High bands offload			High bands offload			High bands offload			High bands offload		
			30%	20%	10%	35%	25%	15%	40%	30%	20%	45%	35%	25%
Tehran	8,000	1,704	730	810	890	910	1020	1140	1040	1200	1350	1140	1330	1530
Amsterdam	8,386	117	940	970	1010	1010	1130	1260	1150	1320	1480	1260	1460	1660
Munich	8,836	92	870	940	1030	1050	1180	1300	1200	1370	1540	1300	1520	1730
Marseille	9,035	43	950	990	1040	1060	1200	1330	1220	1390	1570	1330	1540	1760
Hamburg	9,289	69	890	970	1060	1080	1220	1350	1240	1420	1600	1350	1580	1800
Minsk	9,541	192	920	1010	1100	1120	1260	1400	1290	1470	1650	1400	1630	1860
Baku	9,636	115	920	1010	1110	1130	1270	1410	1290	1480	1670	1410	1640	1880
Makkah	10,070	434	1150	1190	1230	1240	1360	1510	1390	1580	1780	1510	1750	2000
Milan	10,162	141	980	1030	1130	1150	1300	1450	1330	1520	1720	1450	1690	1940
Lyon	10,595	73	990	1060	1160	1190	1340	1500	1370	1570	1780	1500	1750	2010
Rome	10,955	171	1000	1090	1190	1220	1380	1540	1400	1610	1830	1540	1800	2060
Berlin	11,859	163	1030	1150	1260	1290	1460	1630	1490	1720	1950	1630	1920	2210
Amman	11,930	109	1130	1230	1350	1380	1550	1720	1580	1810	2040	1720	2010	2300
Tashkent	14,088	164	1180	1320	1450	1490	1690	1900	1720	2000	2270	1900	2240	2580
Johannesburg	14,681	222	1160	1300	1440	1480	1690	1900	1730	2010	2300	1900	2260	2610
Bangkok	14,696	513	1240	1380	1530	1560	1780	1990	1810	2100	2380	1990	2340	2700
Riyadh	15,000	145	1290	1430	1580	1610	1830	2050	1870	2160	2450	2050	2410	2770
Barcelona	15,576	179	1250	1400	1550	1590	1810	2040	1850	2150	2450	2040	2410	2790
Madrid	15,773	303	1260	1410	1560	1600	1830	2060	1870	2170	2480	2060	2440	2820
Bogotá	16,240	584	1290	1450	1600	1640	1880	2110	1920	2230	2550	2110	2510	2900
Mexico City	16,640	864	1380	1540	1700	1740	1980	2220	2020	2340	2660	2220	2620	3030
Istanbul	17,316	698	1420	1590	1760	1800	2050	2300	2090	2430	2760	2300	2720	3140
Jakarta	17,439	515	1370	1540	1710	1750	2000	2260	2040	2380	2720	2260	2680	3100
Beijing	18,185	953	1470	1640	1820	1860	2130	2390	2170	2520	2880	2390	2830	3270
Paris	18,400	243	1410	1590	1770	1810	2080	2350	2120	2480	2830	2350	2790	3230
Nairobi	18,758	241	1370	1560	1740	1780	2050	2330	2100	2460	2820	2330	2780	3230
Cairo	18,934	961	1400	1580	1760	1810	2080	2360	2130	2500	2860	2360	2820	3270
Tokyo	19,440	176	1450	1620	1810	1850	2130	2420	2180	2560	2930	2420	2890	3360
Ho Chi Minh City	20,087	484	1520	1720	1910	1960	2250	2540	2300	2690	3080	2540	3030	3510
New York	20,770	348	1530	1730	1930	1980	2280	2580	2330	2730	3130	2580	3080	3590
Moscow	20,975	204	1580	1780	1990	2040	2340	2640	2390	2800	3200	2640	3150	3660
Sao Paulo	21,542	266	1620	1830	2040	2090	2410	2720	2460	2870	3290	2720	3240	3760
Mumbai	24,773	944	1610	1850	2090	2150	2510	2870	2570	3050	3530	2870	3470	4070
Hong Kong	25,327	291	1730	1980	2220	2280	2650	3020	2710	3200	3690	3020	3630	4240
Yangon	25,327	291	1900	2140	2390	2450	2810	3180	2870	3360	3850	3180	3790	4410
Lagos	30,968	215	2140	2440	2740	2810	3260	3710	3340	3940	4540	3710	4460	5210

Spectrum need	< 10 MHz	10 to 500 MHz	500 - 1000 MHz	1000-2000 MHz	> 2000 MHz

Source: Coleago

Note: Figures are rounded down to the nearest 10 MHz. The figures exclude low-band spectrum.

3.5 Interpreting the findings

The results of our modelling show a wide range of spectrum needs for each of the cities and this requires some interpretation. As explained above, the key variables driving differences in the need for additional upper mid-band spectrum is population density, the activity factor and the high bands offload.

- The population density is a property of a particular city but the activity factor is an assumption. The activity factor will increase over time. A 15% activity factor may be a realistic assumption for 2025 in a high-income country whereas higher activity factors will be representative of the situation in 2030, the key reason being that over the next 10 years 5G adoption will increase. Mobile operators in Europe and North America expect that by 2029, 100% of their smartphone customer base is likely to be 5G enabled.
- The activity factor is likely to be different around the world, sometimes based on countries' income levels. For example, it is expected that Spain will have a fast adoption of 5G smartphones and other use cases if compared to Kenya. Therefore, when looking at the table which shows the spectrum demand, a 20-25% activity factor for Barcelona is likely to be relevant in the 2030 time frame whereas 10-15% may be a better estimate for Nairobi.
- Cities in countries with a relatively low per capita GDP have a less developed fixed network, notably FTTH. This means 5G FWA is also a demand driver in these cities whereas this not likely to be a significant factor in cities located in higher per capita GDP countries.
- Offloading to high-band spectrum is expected to increase with increased activity factor. Hence, for lower activity factors, lower ranges of high-band offload factor are relevant in the 2030 time frame, whereas for countries with higher activity factors, 30-45% of traffic may be offloaded to high bands.

The table in Exhibit 17 below highlights the cells corresponding to the activity factors that are likely to be reached in the 2025-2030 time frame in the specific sample cities, which in turn leads to the total spectrum needs in these cities (including the baseline spectrum) and includes a column showing the average value associated with the likely values for each city.

Depending on the city, in areas with a population density greater than 8,000 per km^2, the below total spectrum needs data from our 36 sampled countries has been highlighted from, taking different income levels into consideration.

Exhibit 15: Total mid-band spectrum needs 2025-2030 time frame

	Minimum estimate	Maximum estimate
High income cities	1,260 MHz	3,690 MHz
Upper middle income cities	1,020 MHz	2,870 MHz
Lower middle income cities	1,320 MHz	3,260 MHz

Source: Coleago

The range of estimates per national income category reflects the different population densities of the cities analysed, and our view with regards to the extents of 5G take-up and offload to high-bands in the examined countries.

The total[18] mid-band spectrum needs when averaged over all 36 examined cities is estimated to be 2,020 MHz in the 2025-2030 time frame.

The table below summarises the future spectrum requirements estimate for IMT in 2020 from Report ITU-R M.2290-0[19] issued in 2013. The spectrum needs from this ITU-R report include both low- and mid-band spectrum.

[18] The "baseline spectrum" for each city includes spectrum already in use by mobile operators as well as expected future assignments in the period of 2021 to 2025
[19] www.itu.int/pub/R-REP-M.2290

Exhibit 16: Total spectrum requirements for RATG 1 and RATG 2 in 2020

	Total spectrum requirements for RATG 1	Total spectrum requirements for RATG 2	Total spectrum requirements for RATGs 1 and 2
Lower density settings	440 MHz	90 MHz	1,340 MHz
Higher density settings	540 MHz	1,420 MHz	1,960 MHz

Source: Report ITU-R M.2290-0, 2013

Exhibit 17: Likely range for the total (incl. base line) mid-band spectrum needs (MHz) in 2025-2030

DL and UL total (including baseline) mid-bands spectrum need [MHz]														
	World Bank Income	Activity factor 10%			Activity factor 15%			Activity factor 20%			Activity factor 25%			City Aver.
		High bands offload			High bands offload			High bands offload			High bands offload			
City	Group	30%	20%	10%	35%	25%	15%	40%	30%	20%	45%	35%	25%	need
Tehran	Upper Middle	730	810	890	910	1020	1140	1040	1200	1350	1140	1330	1530	1110
Amsterdam	High	940	970	1010	1010	1130	1260	1150	1320	1480	1260	1460	1660	1230
Munich	High	870	940	1030	1050	1180	1300	1200	1370	1540	1300	1520	1730	1280
Marseille	High	950	990	1040	1060	1200	1330	1220	1390	1570	1330	1540	1760	1300
Hamburg	High	890	970	1060	1080	1220	1350	1240	1420	1600	1350	1580	1800	1320
Minsk	Upper Middle	920	1010	1100	1120	1260	1400	1290	1470	1650	1400	1630	1860	1370
Baku	Upper Middle	920	1010	1110	1130	1270	1410	1290	1480	1670	1410	1640	1880	1380
Makkah	High	1150	1190	1230	1240	1360	1510	1390	1580	1780	1510	1750	2000	1470
Milan	High	980	1030	1130	1150	1300	1450	1330	1520	1720	1450	1690	1940	1410
Lyon	High	990	1060	1160	1190	1340	1500	1370	1570	1780	1500	1750	2010	1460
Rome	High	1000	1090	1190	1220	1380	1540	1400	1610	1830	1540	1800	2060	1500
Berlin	High	1030	1150	1260	1290	1460	1630	1490	1720	1950	1630	1920	2210	1590
Amman	Upper Middle	1130	1230	1350	1380	1550	1720	1580	1810	2040	1720	2010	2300	1680
Tashkent	Lower middle	1180	1320	1450	1490	1690	1900	1720	2000	2270	1900	2240	2580	1850
Johannesburg	Upper Middle	1160	1300	1440	1480	1690	1900	1730	2010	2300	1900	2260	2610	1850
Bangkok	Upper Middle	1240	1380	1530	1560	1780	1990	1810	2100	2380	1990	2340	2700	1940
Riyadh	High	1290	1430	1580	1610	1830	2050	1870	2160	2450	2050	2410	2770	2000
Barcelona	High	1250	1400	1550	1590	1810	2040	1850	2150	2450	2040	2410	2790	1980
Madrid	High	1260	1410	1560	1600	1830	2060	1870	2170	2480	2060	2440	2820	2000
Bogotá	Upper Middle	1290	1450	1600	1640	1880	2110	1920	2230	2550	2110	2510	2900	2060
Mexico City	Upper Middle	1380	1540	1700	1740	1980	2220	2020	2340	2660	2220	2620	3030	2160
Istanbul	Upper Middle	1420	1590	1760	1800	2050	2300	2090	2430	2760	2300	2720	3140	2240
Jakarta	Upper Middle	1370	1540	1710	1750	2000	2260	2040	2380	2720	2260	2680	3100	2190
Beijing	Upper Middle	1470	1640	1820	1860	2130	2390	2170	2520	2880	2390	2830	3270	2330
Paris	High	1410	1590	1770	1810	2080	2350	2120	2480	2830	2350	2790	3230	2280
Nairobi	Lower middle	1370	1560	1740	1780	2050	2330	2100	2460	2820	2330	2780	3230	2260
Cairo	Lower middle	1400	1580	1760	1810	2080	2360	2130	2500	2860	2360	2820	3270	2290
Tokyo	High	1450	1620	1810	1850	2130	2420	2180	2560	2930	2420	2890	3360	2350
Ho Chi Minh City	Lower middle	1520	1720	1910	1960	2250	2540	2300	2690	3080	2540	3030	3510	2470
New York	High	1530	1730	1930	1980	2280	2580	2330	2730	3130	2580	3080	3590	2510
Moscow	Upper Middle	1580	1780	1990	2040	2340	2640	2390	2800	3200	2640	3150	3660	2570
Sao Paulo	Upper Middle	1620	1830	2040	2090	2410	2720	2460	2870	3290	2720	3240	3760	2640
Mumbai	Lower middle	1610	1850	2090	2150	2510	2870	2570	3050	3530	2870	3470	4070	2780
Hong Kong	High	1730	1980	2220	2280	2650	3020	2710	3200	3690	3020	3630	4240	2930
Yangon	Lower middle	1900	2140	2390	2450	2810	3180	2870	3360	3850	3180	3790	4410	3090
Lagos	Lower middle	2140	2440	2740	2810	3260	3710	3340	3940	4540	3710	4460	5210	3600

Source: Coleago

In assessing the reasonableness of the assumed demand and the findings, the assumption as to the level of concurrent area traffic demand in Gbit/s/km^2 is the key determinant in driving spectrum need. In most cities in our sample, with a 20% activity factor, these results show in an area traffic density is of less than 300 Gbit/s/km^2. Let's compare this to the ITU-R IMT-2020 area traffic requirement of 10 Mbit/s/m^2. 10 Mbit/s/m^2 equates to 10,000 Gbit/s/km^2. Our 300 Gbit/s/km^2 on average across the whole city is 3% of the hotspot peak, showing a reasonable averaged traffic across the city.

To illustrate the requirement for high traffic density in a mobile environment, we examined a public transport scenario using London Route Master bus. The bus has an area of 25 m^2 (2.5x10 meters) and a capacity for 80 passengers. If only 10% of the passengers use 4k video requiring 20 Mbit/s DL speed, this results in an area traffic demand of 6.4 Mbit/s/m^2. This is close to the 10 Mbit/s/m^2 requirement and well above the average area traffic capacity calculated for the sample cities.

3.6 Spectrum demand in other high-density cities

The cities in our sample range from 8,000 to 31,000 people per km^2. The UN organisation UN Habitat defines the optimum population density for a sustainable city as 15,000 per km^2.

Our analysis covers only a small sample of cities with high-density clusters of at least 40 km^2. Based on data provided in Demographia World Urban Areas, (Built Up Urban Areas or World Agglomerations), 16th annual edition, June 2020, we estimate that 626 urban areas have clusters of at least 40 km^2 with a population density of 8,000 or more. These cities can be found in all six ITU Regional groups (APT, ASMG, ATU, CEPT, CITEL, RCC). Together these cities contain an estimated 1.64 billion people. This scale provides a good illustration for why allocating additional upper mid-band spectrum to IMT is of significance for a large proportion of the world's population.

The size of population in the areas that would benefit from additional upper mid-band spectrum shows that additional upper mid-band spectrum would deliver large socio-economic benefits globally, but population is only a first level indicator of the scale of the benefit. The importance to the economy of additional spectrum to deliver the required user experienced data rates cities is far greater because economic activity and value generated is proportionally greater in urban areas compared to rural areas.

Exhibit 18: Population in cities with a density greater than 8,000 per km^2

Region	Population million
APT	885
CEPT	115
CITEL	322
ASMG	109
ATU	173
RCC	41
Total	1,644

Source: Coleago estimates based of Demographia World Urban Areas

Note: Where countries are members of more than one organisation, we have chosen the primary one based on geography.

4 Trade-off between additional spectrum and network densification

4.1 Small cell network densification

As stated above, in modelling the area traffic capacity in cities, we assume a substantial network densification, notably by building many upper mid-band outdoor small cells. We also account for the densification of indoor small cells and high-band sites through the two associated offloading factors, as explained in 3.3.3 above.

In other words, underlying our spectrum demand modelling is the assumption that the mobile operators will make substantial investments in small cells and also migrate their entire spectrum holdings to 5G when 100% of users are 5G-enabled, i.e., in the 2025-2030 time frame.

The investment in network densification and the deployment of 5G radios to cope with increases in traffic whilst revenues from consumers are flat or, at best, experiencing only limited increases, poses an economic problem. How can operators deliver 5G at a price that is affordable? Additional upper mid-band spectrum, available at reasonable cost is an essential element in solving this problem and maintaining a sustainable cost per bit.

However, there is clearly a trade-off between site numbers and spectrum in delivering the required capacity. If site numbers increase, then the spectrum required will reduce and vice-versa. Hence, should the additional mid-band spectrum requirement not be met (either in part or fully) then site numbers could increase beyond that assumed.

4.2 Site numbers increase with spectrum limitations

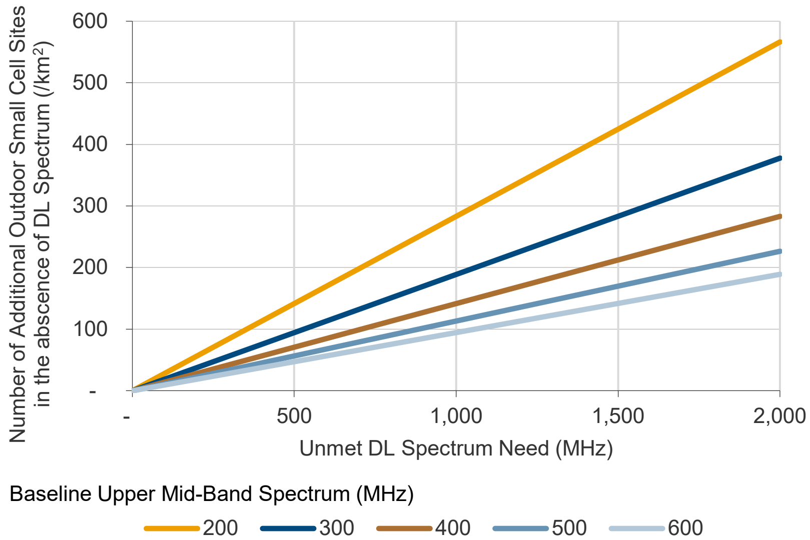
We have analysed the number of additional outdoor small cell sites needed to deliver the citywide capacity required for 5G should additional upper mid-band spectrum not be available. This analysis is illustrative to show the potential magnitude of the issue. As such, several caveats apply:

- The analysis is based on the thesis that the macro cell density (i.e., given by the assumed 400 meter inter-site distance) is already at (or approaching) the densest it can be, limited by needing to manage interference and by the difficulty in finding new sites in many cities. Hence any additional sites are assumed to be outdoor small cells.
- Potential interference issues between macro cells and outdoor small cells, and between small cells themselves, are discounted as we are simply seeking to understand the potential magnitude of the issue.
- Only the downlink requirement / spectrum need has been examined. If the additional spectrum needed to address uplink requirements is also considered then the number of additional small cells may be higher.

The results will vary by city due to the differing baseline spectrum allocations between cities. To provide a generic view, Exhibit 19 below therefore shows several curves relating to baseline upper mid-band spectrum allocation – using the same set of site-related parameters as used elsewhere in this study.

Exhibit 19 shows the number of additional outdoor small cells needed, per square kilometre, to deliver 100 Mbit/s citywide downlink speed coverage if our calculated additional mid-band spectrum need cannot be provided. It is important to note that the small cell figures are per square kilometre, with this number of small cells being needed across the same area that we considered in the city analysis above.

Exhibit 19: Additional outdoor small cells vs. unmet DL spectrum needs

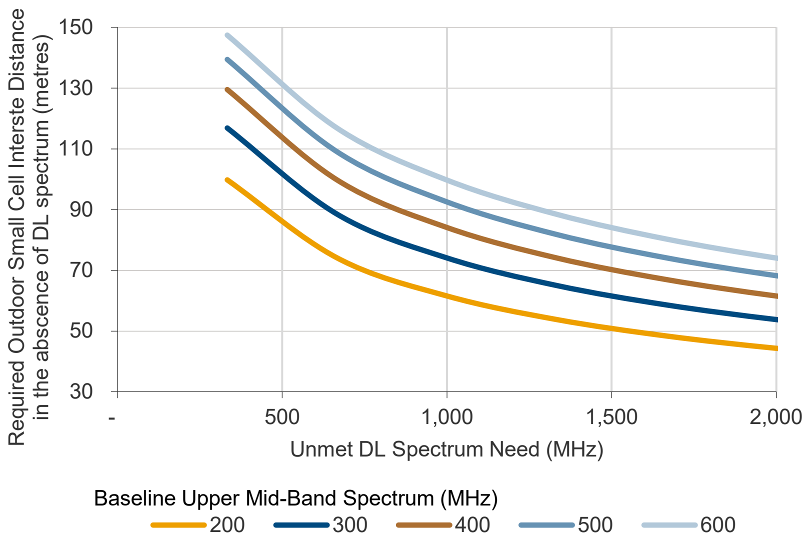


Source: Coleago

These are potentially significant numbers of additional outdoor small cells both to deploy and to operate / manage in terms of time and cost. The cost impact is examined below.

While such a densification may not even be feasible for several reasons (e.g., interference scenario, sites availability, cost, etc), such large numbers of cells will also increase the overall power consumption (investigated in section 4.3 below) as well as create an adverse aesthetical impact. The latter of these points can be further illustrated by translating the results above into an average spacing (inter-site distance) between the small cells. This is shown in Exhibit 20 below. Note that the inter-site distance here also includes the baseline of 3 small cells per macro – to provide a holistic comparison. Appendix H contains further detail on the calculations made.

Exhibit 20: Small cell inter-site distance vs. unmet DL spectrum needs



Source: Coleago

The generic results can be illustrated through example as shown in Exhibit 21 below:

- For Paris, the output of our spectrum need analysis shows between 1,130 and 1,370 MHz of additional DL mid-band spectrum being required in the 2030 time – depending on activity and high-band offload factors. Taking a need towards the middle of this range, 1,250 MHz for example, and with the baseline of 400 MHz upper mid-band spectrum, 177 additional outdoor small cells per square kilometre are required to deliver the same capacity as the additional 800 MHz. Note that these will be needed across the entire city area of 243[20] km^2, hence additional 42,978 outdoor small cells would be required across Paris in the absence of an additional 800 MHz of mid-band spectrum.
- The additional 42,978 outdoor small cells required across the city, in conjunction with our assumed baseline of 3 outdoor small cells per macro site (5,257 small cells related 1,752 macro cells across the 243 km^2), would have an average inter-site distance of 76 metres.
- Similar example calculations, for Hamburg, Mexico City and Mumbai, are presented in Exhibit 21 below.

Exhibit 21: Additional outdoor small cells and inter-site distance

	Paris	Hamburg	Mexico City	Mumbai
Additional DL mid-band spectrum need (MHz)	1,130 – 1,370	410 - 540	770 – 1,050	930 – 1,440
Selected example unmet DL spectrum requirement (MHz)	1,2500	500	900	1,200
Baseline spectrum available (MHz)	400	300	200	300
Number of additional outdoor small cells to deliver capacity equivalent to unmet spectrum requirement (/km^2)	177	94	255	227
Number of additional outdoor small cells required across the city	42,978	2,228	220,258	213,883
Number of baseline outdoor small cells (3 small cells per macro)	5,256	510	18,708	20.436
Resulting inter-site distance of outdoor small cells (m)	76	100	65	68

Source: Coleago

These are significant numbers of outdoor small cells with relatively small inter-site distances, particularly when it is noted that this average spacing must be maintained across the entirety of the large city areas involved. This will clearly have a negative impact on the city environment from an aesthetics point of view and would be very costly. Such small inter-site distances, over such large areas, may also not be practically possible from an interference point of view.

A reasonable question is whether densification could be considered through the use of high-bands (mmWave spectrum) macro/small cells rather than with mid-band small cells.

Given the different options for mmWave densification (e.g., densifying using only mmWave small cells or adding mmWaves to the existing macro mid-bands grid in conjunction with mmWave small cells) and considering the different sizes of cities and their propagation environments (influenced by street design, building characteristics,

[20] Refer to Annex D, exhibit 44 for additional details

etc.), estimating the exact number of needed mmWave sites requires a case-by-case analysis.

However, all options for such a densification would require new mmWave macro sites and/or new mmWave small cells over large areas (i.e., not only locally). Given the relatively smaller inter-site distances that are required by mmWave 5G and the average spacing that must be maintained across the entirety of the large city areas involved, this densification approach would not represent a viable option, being very costly and undesirable from an environmental perspective.

This finding is corroborated by Google who performed a preliminary study for the Defence Innovation Board to ascertain the approximate capital expenditure (capex) and base station counts needed for high bands deployments: "*Most operators are looking at deploying mmWave 5G sites on utility poles, given the poles' ease of accessibility and abundance. Using a database of utility poles in the United States, the study indicated that it would require approximately 13 million pole-mounted 28 GHz base stations and $400B dollars in capex to deliver 100 Mbit/s edge rate at 28 GHz to 72% of the U.S. population, and up to 1 Gbit/s to approximately 55% of the U.S. population.*" The magnitude of the investment demonstrates that this is not a feasible option.

4.3 Power increases with spectrum limitations

The potential scale of densification required to deliver the same capacity as unmet DL spectrum requirements could have an impact – in terms of the energy consumed by the network.

To examine this, we have made some simplifying assumptions on the power consumption of a 5G dense urban macro site and an outdoor small cell; 6kW and 0.5kW (or <10% of the macro site) respectively. We have also estimated that power saving features could deliver up to a 20% saving in consumption across all sites – and since we are deriving a simple comparative result, this estimate should be sufficient for the calculation here. Finally, we have assumed that loading 5G sites with new mid band spectrum, in addition to existing bands, requires a 20% uplift in power over macro sites not having this new spectrum.

Exhibit 22 below shows that comparative result – in terms of the relative increase in power consumption for the examples of the cities above, both with the additional DL mid-band spectrum and without.

Exhibit 22: Power consumption dependant on mid-band spectrum

	Paris	Hamburg	Mexico City	Mumbai
Reference macro site power consumption	6kW	6kW	6kW	6kW
Reference small cell power consumption	0.5kW	0.5kW	0.5kW	0.5kW
With additional mid-band spectrum				
Number of macro sites	1,752	170	6,236	6,812
Number of outdoor small cells (including the baseline)	5,256	510	18,708	20,436
Consumption reduction due to saving features	20%	20%	20%	20%
Uplift in power assumed due to additional spectrum	20%	20%	20%	20%
Reference power consumption (MW)	12.6	1.2	44.9	49.1
Without additional mid-band spectrum				
Number of macro sites	1,752	170	6,236	6,812
Number of outdoor small cells (including the baseline)	48,234	2,739	238,967	234,321
Consumption reduction due to saving features	20%	20%	20%	20%
Reference power consumption (MW)	27.7	1.9	125.5	126.4
Relative increase:	**2.2x**	**1.6x**	**2.8x**	**2.6x**

Source: Coleago

This calculation, despite its simplicity, shows a significant relative increase in energy consumption. We also note that this relates only to a single city within each country. Aggregating the increase at sites in other cities in each country could further increase overall energy consumption. These increases can impact on the environment.

4.4 Cost increases with spectrum limitations

The impact of the densification required to deliver the 5G requirements, in the absence of additional mid-band spectrum, can also be examined through required network expenditure. Here we present a simple model to project comparative 'total cost' of capital expenditure and operational expenditure over 10 years. Whilst there will be differences in cost between countries and regions, using comparative cost will lessen any impact as it is the ratio of costs that is important.

Based on our experience in working with mobile operators world-wide, we have made a small number of basic assumptions in calculating the comparative costs – which are used in both cases. We assume a macro site capex of USD 50,000, a small cell capex of USD 10,000 and an annual site opex of 25% of capex. No inflation has been applied to opex costs over the 10-year period, and a WACC of 7.5% is used to discount opex. These assumptions are typical values which vary slightly depending on the country and operator, but these variations will not change the order of magnitude cost implication. Cost for site acquisition is not included in the calculation for simplicity.

Exhibit 23 shows the resulting comparison – in terms of the relative increase in total cost for each of the example cities above, both with the additional DL mid band spectrum and without.

Exhibit 23: Radio network cost depending on mid-band spectrum

	Paris	Hamburg	Mexico City	Mumbai
With additional mid band spectrum				
Additional mid-band spectrum assumed (MHz)	1,250	500	900	1,200
Number of macro sites	1,752	170	6,236	6,812
Number of outdoor small cells (including the baseline)	5,256	510	18,708	20,436
Reference radio network capex cost over 10 years (USD m)	140	14	499	545
Reference radio network opex cost over 10 years (USD m)	259	25	920	1,005
Reference total radio network cost over 10 years (USD m)	399	39	1,419	1,550
Without additional mid-band spectrum				
Number of macro sites	1,752	170	6,236	6,812
Number of outdoor small cells (including the baseline)	48,234	2,739	238,967	234,321
Reference radio network capex cost over 10 years (USD m)	570	36	2,702	2,684
Reference radio network opex cost over 10 years (USD m)	1,051	66	4,983	4,951
Reference total radio network cost over 10 years (USD m)	1,621	102	7,685	7,635
Relative increase:	**4.1x**	**2.6x**	**5.4**	**4.9x**

Source: Coleago

As with our power consumption calculation, this simple calculation shows a significant relative increase in the cost of the radio network. With this relative cost increase being repeated at other cities across each country, the total increase in cost is a significant figure. Such increases will be extremely challenging for operators to bear without major revenue uplifts which are unlikely, as noted above.

5 Mid-band spectrum for 5G fibre-like speed FWA

5.1 Wireless is the fastest growing fixed broadband access technology

Fixed Wireless Access (FWA) is one of the 5G use cases. As a result of the performance improvement of LTE-A and now 5G NR, FWA is experiencing rapid growth world-wide. The Global Mobile Suppliers Association (GSA) identified 401 operators in 164 countries selling FWA services based on LTE. In addition, of the 75 operators that have announced 5G launches worldwide, GSA counted 38 operators that have announced the launch of either home or business 5G broadband using routers. Of these 38, GSA identified 31 operators selling 5G-based FWA services.[21]

FWA is the fastest growing form of fixed broadband connectivity

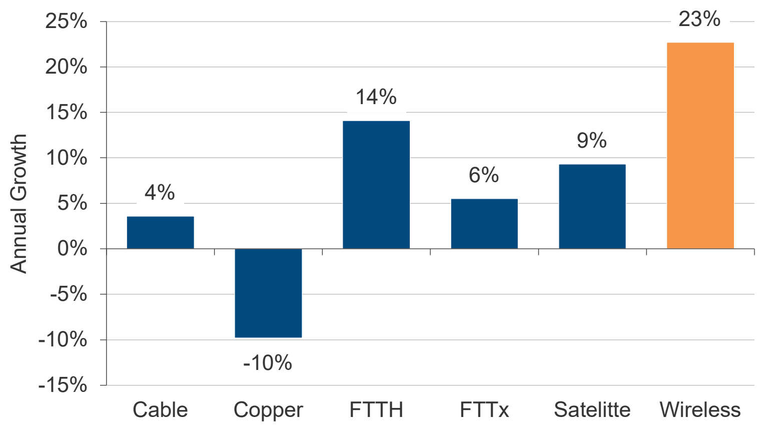
The figures from the GSA are corroborated by research from Point Topic. "*Wireless (mostly FWA) and FTTH connections were the fastest growing categories, having increased by 22.7 per cent and 14.1 per cent respectively between Q4 2018 and Q4 2019.*"[22], see Exhibit 24.

While some countries such as South Korea and UAE have near universal fibre access, most countries do not. In many countries, notably in Africa, emerging Asia, Eastern Europe and Latin America copper or fibre network access is limited. 5G FWA is also relevant in rural areas where there is no fibre and the cost of building fibre in terms of cost per home passed is relatively high.

With 5G FWA fixed wireless growth is likely to accelerate further to become the dominant form of fixed broadband connectivity

With 5G FWA, fixed wireless growth is likely to accelerate further (see Exhibit 25): "*we estimate there will be more than 60 million FWA connections by the end of 2020. This number is forecast to grow more than threefold through 2026, reaching over 180 million. Out of these, 5G FWA connections are expected to grow to more than 70 million by 2026, representing around 40 percent of total FWA connections.*"[23]

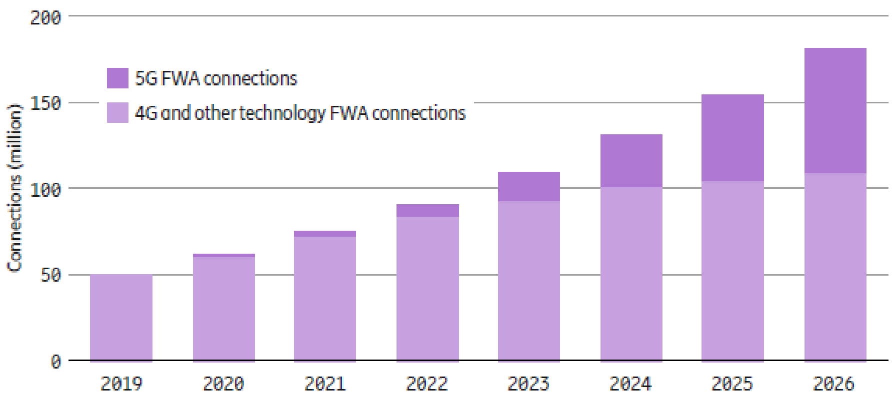
Exhibit 24: Growth of fixed broadband subscribers by technology in 2019



Source: World Fixed Broadband Statistics Q4 2019, Point Topic

[21] Fixed Wireless Access, General Report, Global mobile Suppliers Association, 19 May 2020
[22] Point Topic, World Fixed Broadband Statistics – Q4 2019
[23] Ericsson Mobility Report, November 2020

Exhibit 25: FWA connections



Source: Ericsson Mobility Report, November 2020

5.2 Spectrum demand drivers for 5G FWA vs. 5G mobile

Fixed Wireless Access (FWA) is one of the 5G use cases and is a key solution to deliver fixed broadband connectivity objectives. The role of 5G FWA is different in countries that have or will have extensive FTTH coverage and countries with a limited fixed broadband network infrastructure.

- In countries with an extensive FTTH coverage, 5G FWA is a lower cost and faster to implement solution compared to fibre to bring 100 Mbit/s connectivity to households and businesses located in villages. The use of additional upper mid-band spectrum for 5G FWA in rural small towns and villages will generate substantial cost savings compared with FTTH.
- In countries that do not have good FTTH coverage in cities, 5G FWA is a broadband access solution in cities as well as in rural small towns and villages. In rural small towns and villages in rural areas 5G FWA is likely to be the only economically feasible solution to fulfil broadband development goals both in terms of broadband speed and affordability.

Exhibit 26: Demand drivers for upper mid-band spectrum

	Urban areas with high population density	**Villages and rural small towns**
Country with extensive FTTH	**City-wide speed coverage**	**FWA**
Country with sparce fixed infrastructure	**City-wide speed coverage** **FWA**	**FWA**

Source: Coleago

5.3 Leveraging existing mobile infrastructure for rural FWA

In rural areas, mobile networks can supply to a greater proportion of villages and small towns compared to FTTH coverage. The cost of bringing 100 Mbit/s broadband connectivity to these rural population clusters can be significantly reduced if the existing cell towers are also used for 5G FWA. It is of course also much quicker to leverage the existing mobile infrastructure rather than laying fibre in every street.

A sustainable 5G FWA business case in rural small towns and villages requires a significant amount of spectrum with reasonable propagation characteristics and this can be found in upper mid-bands. Compared to low-band spectrum, mid-band spectrum is not useful to cover large areas where rural populations are widely spread out. While the range of upper mid-band spectrum is much smaller compared to low-bands spectrum, the radio range of 5G in 3.5 to 7 GHz is not a limiting factor when assessing the number of rural households which could be covered with a 100 Mbit/s service. Even with a cell radius of only 2 km, the area covered by a site could be of up to 12.6 km^2. If we assume a household density of only 50 per km^2, the area covered by a single site could include 628 households (assuming that enough spectrum is available). In other words, upper mid-band spectrum is an ideal FWA capacity band for populated rural towns and villages.

Exhibit 27 below provides an illustration for Rosenthal, a village in Germany with around 500 households and three existing cell towers located around the edge of the village. Exhibit 28 shows the village of Fô-Bourè in Benin which has a population of around 6,000 to 7,000 people of which around 4,000 are mobile users. The existing cell tower is located in the centre of the village.

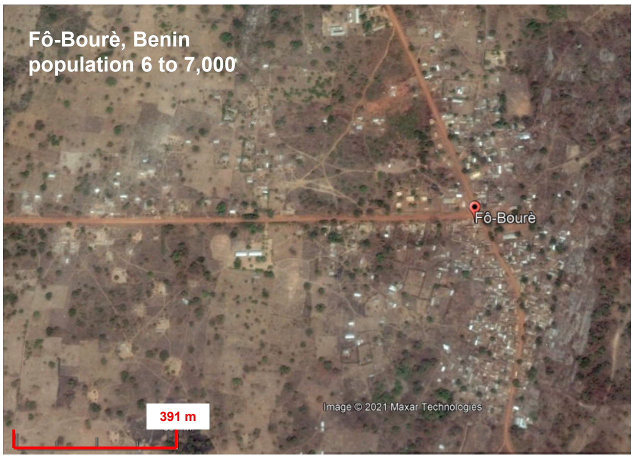
Exhibit 27: 5G FWA potential in village from existing cell towers, Germany

Source: Coleago

Exhibit 28: Potential 5G FWA in village from existing cell tower, Benin

Using upper mid-band spectrum for FWA, a single mast can cover an entire village.

There is an existing cell tower close to the red marker.



Source: Coleago

5.4 Improving the FWA economics with additional mid-band spectrum

The lack of rural broadband access is in large part due to the poor economics of connecting homes and business premises in areas with a low population density. For example, in Europe, the cost per rural home covered with fibre and connected is three to four times higher compared to the cost of bringing fibre connectivity to sub-urban and urban areas. Similarly, the cost of connecting rural small towns is much higher compared to urban areas and hence there is a wide gap in rural broadband connectivity.

Closing the rural connectivity using 5G FWA requires far less investment compared to FTTH. However, the FWA business case is highly dependent on the number of connections that can be supported per cell tower. In turn, this is a function of the amount of spectrum that can be deployed on a cell tower to deliver fibre like broadband FWA using 5G NR technology.

We have modelled how the availability of additional upper mid-band spectrum impacts on the number of homes that can be supported from a cell tower to deliver fibre-like speeds. The following assumptions differ from those used for 5G mobile.

- Outdoor customer premises equipment (CPE) may be used which results in an uplift to spectral efficiency. In addition, radios fitting for purpose in a flat rural area may be added, further enhancing cell radius for rural FWA. However, in a rural environment with a low building height 16-element MIMO would be deployed for FWA compared to 64-element MIMO for eMBB in a dense urban environment. Hence, we assume a lower downlink spectral efficiency of 5 bit/s/Hz.
- We assume a higher activity factor of 50% compared to 10-25% for mobile because fixed broadband monthly data usage in terms of the duration of streaming media is assumed to remain higher than mobile broadband usage as illustrated by the following examples:
  - in Q3 2019, average monthly broadband usage per household was 264.4 Gbytes / month[24]. For subscribers with a 100 Mbit/s+ connection usage was 333 Gbytes/month in Europe and 398 Gbytes in the US.
  - A further reference point is the service definition in the Connect America Fund Phase II Auction (Auction 903) rural broadband funding programme. The 100 Mbit/s broadband service must include a 2 Terabyte monthly usage allowance.

[24] Broadband Industry Report (OVBI) 3Q 2019, OpenVault

– Fixed broadband is used over longer continuous periods thus pushing up concurrent use (i.e., the longer the usage, the higher the activity factor).
– Streaming media, such as watching IP TV by household tends to occur at the same hours of the day, i.e., it tends to be concurrent.

To examine the impact of additional mid-band spectrum on the economics of rural FWA for towns and small villages, we need to identify the baseline spectrum available to deliver FWA. In rural small towns and villages there will also be substantial demand for 5G NR mobile. However, due to the lower population density compared to cities, in the short term this demand can be served with low-band and lower mid-band IMT spectrum. In this case, 300 to 500 MHz of upper mid-band spectrum may be sufficient to serve 100 Mbit/s to a small number of premises from a single mast.

In the long term, the total amount of mobile spectrum needed for the cities of 2,020 MHz on average provides a key opportunity for a sustainable 5G FWA business case in the upper mid-bands delivering a household experienced DL data rate of 100 Mbit/s, based on a utilisation factor of 50%. Exhibit 29 shows the number of households that can be served with:

A sustainable 5G FWA business case with fibre-like speeds in the upper mid-bands requires additional upper mid-band spectrum

- Baseline, only 400 MHz of upper mid-band spectrum is available to serve FWA bandwidth needs, the remainder of spectrum being used to serve mobile demand density in a village;
- An additional 1 GHz of upper mid-band spectrum is available; and
- An additional 2 GHz of upper mid-band spectrum is available.

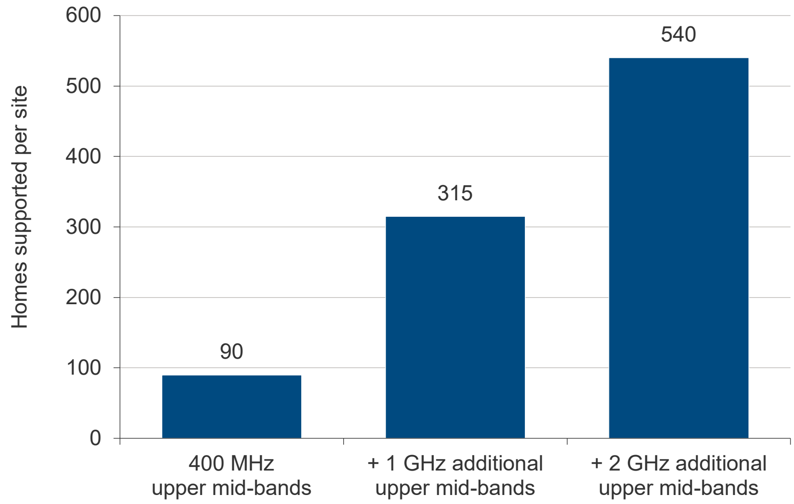
The more households that can be served per site, the lower the cost per home served with a 100 Mbit/s speed on the downlink.

Exhibit 29: FWA homes per site depending on amount of spectrum detaile

	Baseline	+1000 MHz	+ 2000 MHz
Mid-band spectrum - MHz	400	1400	2400
TDD DL:UL ratio	3	3	3
Spectral efficiency - bit/s/Hz	5	5	5
Sectors per site	3	3	3
Capacity per site - Mbit/s	4,500	11,250	22,500
Number of households supported	90	315	540

Source: Coleago

Exhibit 30: FWA homes per site depending on amount of spectrum



Source: Coleago Consulting

5.5 5G FWA in countries with an extensive FTTH coverage

In countries with an extensive FTTH coverage, delivering the connectivity objectives in rural areas is challenging. In the following we show that making available additional upper mind-bands spectrum would make FWA in the upper mid-bands a long-term solution for Very High-Capacity Networks (VHCN) in rural small towns and villages at a much lower cost compared to Fibre to the Home (FTTH).

- Comparing the cost of FTTH and 5G NR FWA with fibre-like speeds shows that in rural areas FWA in the mid-bands can reduce costs compared to FTTH;
- in many economies bringing 100 Mbit/s broadband to rural users is a challenge and copper-based access is nearing the end of its useful life. Copper networks, even with the latest upgrades, cannot provide modern broadband speeds of 100 Mbit/s or more – especially over wider areas. For example, upgrading the copper network to deliver up to 50 Mbit/s has been abandoned in Germany and subsidies now focus on FTTH. Several fixed network operators are in the process of retiring their copper network, such as BT in the UK by 2027.

The investment required to connect all premises to fibre would be extremely high. While the cost of connecting buildings in relatively densely populated areas may be manageable, deploying FTTH to rural premises is likely to require substantial subsidies.

5G FWA in Europe

Rural broadband connectivity subsidy schemes leave it up to the provider to build rural broadband access with either fibre or FWA, as evidenced by the following examples from Europe:

- The European Commission’s strategy on Connectivity for a European Gigabit Society sets a target of 100 Mbit/s connectivity available to 100% of households (see Exhibit 31). Fibre is playing a major role in reaching this target and FWA is recognised as one of the solutions. The European Electronic Communications Code (EECC) lists FWA as a technology to deliver Very High-Capacity Networks (VHCN), thus making FWA eligible for public subsidies.

- In the European Union, FWA is part of the solution to achieve the EU's target of offering Internet connectivity of at least 100 Mbit/s to all European households by 2025. The time frame to reach the 2025 goal is short. From a logistical and funding perspective it is not possible to reach the goal without FWA.
- The directives of the European Parliament and Council 2014/61/EU, 15.05.2014 refer to fixed wired and wireless to lower the costs for deploying broadband.
- The directives of the European Parliament and Council 2014/61/EU, 15.05.2014 refer to fixed (wired) and wireless to lower the costs for deploying broadband. Several national broadband development plans explicitly acknowledge the role of FWA, for example Sweden: "*Given the geographical aspects of Sweden, and the repartition of its population, a completely connected Sweden requires a combination of different technologies – fixed and wireless*." (A Completely Connected Sweden by 2025, a Broadband Strategy, page 11)

Exhibit 31: European broadband policy

The Commission's strategy on Connectivity for a European Gigabit Society, adopted in September 2016, sets a vision of Europe where availability and take-up of very high-capacity networks enable the widespread use of products, services, and applications in the Digital Single Market.

This vision relies on three main strategic objectives for 2025:

- Gigabit connectivity for all of the main socio-economic drivers,
- Uninterrupted 5G coverage for all urban areas and major terrestrial transport paths, and
- Access to connectivity offering at least 100 Mbit/s for all European households.

It confirms and builds upon the previous broadband objectives for 2020, to supply every European with access to at least 30 Mbit/s connectivity, and to provide half of European households with connectivity rates of 100 Mbit/s.

Source: https://ec.europa.eu/digital-single-market/en/broadband-europe

The recently published Communication "2030 Digital Compass – the European way for the digital decade" from the European Commission states the 2030 target for all European households to be covered by a Gigabit network, with all populated areas covered by 5G.

Source: https://digital-strategy.ec.europa.eu/en/policies/digital-compass

As of 2019, the FTTH Council indicated that the number of homes in the EU-28 passed by fibre were 88.1 million, equivalent to a coverage rate of 39.4%[25]. To reach the objective of bringing 100 Mbit/s connectivity to 100% of homes by 2025, a further 135 million homes will need to be reached by fibre within the six years 2020 to end 2025. The investment required to achieve this is estimated at around €120 billion[26], assuming that 100% of homes are covered and 50% actually connected. In mid-2019, rural FTTH coverage was only 18%.

[25] FTTH Council Panorama, 23 April 2020

[26] The Cost of Meeting Europe's Future Network Needs, FTTH Council Europe, March 2017 cite a cost of €137 billion. Taking account of progress made to mid-2020, we estimate the remaining investment cost at €120 billion

Depending on the local situation, the cost of connecting a building with fibre-like 5G FWA in upper mid-bands in rural areas is in order of 50%-80%[27] lower compared to fibre

The investment required to deliver the European broadband connectivity target in rural areas with FTTH would amount to around €53 billion. An additional 2,000 MHz of mid-band spectrum can reduce this cost by 79% thus delivering an investment saving of €42 billion[27].

5G FWA in North America

On the 9th of June 2020, the Federal Communications Commission of the US "*adopted procedures for Phase I of the Rural Digital Opportunity Fund auction (Auction 904), which will award up to $16 billion in support over 10 years for the deployment of fixed broadband networks to millions of unserved homes and businesses across rural America. The $20.4 billion Rural Digital Opportunity Fund is the FCC's most ambitious step ever toward bridging the digital divide*."[28] The programme is technology neutral provided minimum requirements are met. "*We've focused on maintaining technological neutrality and maximizing competition in our USF programs. And here, we do that by opening the door to new types of technologies to apply for different tiers in the auction. For example, we allow fixed wireless and DSL providers for the first time to apply to bid in the gigabit tier*."[29] This announcement also demonstrates that even in a high-income country such as the US, substantial amounts of public funds are required to bridge the digital divide.

In Canada, operators can obtain subsidies to build broadband connectivity to rural premises using either fibre or FWA depending on the local situation. The aim is to minimise the subsidy per premises connected. For example, on the 7th of February 2020, Xplornet a rural telecoms specialist announced that it will deploy fibre and FWA. "*To deliver this service, Xplornet will deploy fibre optic cable and 5G-ready wireless broadband infrastructure to its existing network, enabling the delivery of fibre-to-the-home and fixed wireless services. The project will cover 16,000 homes through the Nova Scotia Internet Funding Trust (NSIFT), along with an additional 8,000 homes outside of the scope of the program. … The result will be access to competitively priced Internet packages, unlimited data, and speeds up to 100 Megabits per second (Mbit/s), exceeding targets established by the CRTC. Better still, the network is designed to support future customer needs, with speed capabilities that exceed 1 Gbit/s*."[30]

5.6 5G FWA in countries with limited FTTH coverage in cities

5.6.1 Introduction

In theory, fibre can be built to all locations and thus provide "unlimited" access network capacity. However, this is not economically feasible where affordability is a key issue. In most countries, broadband will be wireless, including in the less dense areas of mega cities such as Mexico City, Lagos, Cairo, and Jakarta. Upper mid-band spectrum has a key role to play and is required to provide fibre like access at a cost that makes it affordable even for lower income groups.

In the case of countries with limited FTTH coverage in cities additional upper mid-band spectrum is not simply a technical issue but also an economic one. There are around 2 to 2.4 billion households worldwide. At the end of Q4 2019, the number of global fixed broadband connections stood at 1.11 billion[31] to 1.2 billion[32] (excluding mobile). Based on these figures, approximately 0.9 to 1.2 billion households have a broadband connection in the form of DSL, fibre, cable, or FWA. This leaves 1.1 to 1.2 billion households without broadband access.

[27] Further detail is contained in Appendix G
[28] FCC, press release, 9th of June 2020
[29] FCC, Statement of Chairman Ajit Pai, 9th of June 2020
[30] Xplornet, press release, 7th of February 2020, https://www.xplornet.com/about/news/xplornet-announces-fibre-expansion-in-nova-scotia/
[31] Point Topic, World Fixed Broadband Statistics – Q4 2019
[32] Ericsson Mobility Reporting, citing Omnia, June 2020

In countries with limited FTTH coverage in cities, internet access is synonymous with wireless access and fixed broadband connections account for less than 10% of all connections and this proportion is declining further. The predominant role of wireless for broadband in countries with lower ARPU is recognised in the United Nations Sustainable Development Goals (SDG). The indicator for SDG 9.c is to "*Significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet […] by 2020*" is the "*Proportion of population covered by a mobile network, by technology*".

Broadband connectivity in lower income countries goes hand in hand with affordability. The Broadband Commission[33] for Sustainable Development 2025 Targets make this explicit: "*By 2025, entry-level broadband services should be made affordable in developing countries, at less than 2% of monthly gross national income per capita.*"[34] 5G is an essential element to attain the SDGs and the Broadband Commission 2025 targets in the context of affordability

5.6.2 5G FWA to provide rural broadband connectivity

The rural connectivity gap

In this section, we place connectivity into the context of the rural small towns and villages – and the benefits that additional upper mid-band spectrum has to achieve rural broadband connectivity targets in terms of broadband speed and affordability. These areas typically have limited fixed network (copper, cable, or fibre) infrastructure with mobile networks being the prime method of delivering connectivity. As countries seek to bring more small towns and villages in rural areas online at good connectivity speeds, additional mid-band spectrum will facilitate increased capacity per mast. This will increase the number of households that can be addressed at an economic cost by an individual mast – a key driver in addressing these rural areas.

In small towns and villages in rural areas in lower-income countries the economic problem of providing broadband connectivity comes into sharp focus. The economics of using "fibre like speed" 5G FWA in upper mid-bands to close the rural connectivity gap are vastly better compared to fibre and using 5G FWA will reduce the time it takes to fulfil rural connectivity targets.

- Leverage mobile coverage obligations: Many countries attached coverage obligations to low-bands spectrum licences. This means many rural small towns and villages which do not have any fixed network access have a mobile cell tower in or near the settlement. While the available low-bands will be used for mobile connectivity, the same mast can be used to add fibre-like 5G FWA. If sufficient upper mid-band spectrum is available to deliver 100 Mbit/s broadband to home and businesses, then mobile operators are likely to have a business case to upgrade the cell tower and bring fibre to the cell towers instead of wireless backhaul.
- Scalability: Initially only some households may have terminals to make use of broadband or may not be able to afford it. Demand will grow over time. FWA has a large advantage over FTTH in terms of cost per home connected. The key metric for FTTH is homes passed and homes connected. Even if only one home in a street wants FTTH, fibre still has to pass all the other homes in the street thus pushing up the FTTH operator's cost per home connected. In contrast, a mobile operator can install, for example, a two-sector radio which covers the whole settlement

[33] ITU and UNESCO set up the Broadband Commission for Digital Development in response to UN call to step-up UN efforts to meet the Millennium Development Goals (MDGs). The Commission was established in May 2010 with the aim of boosting the importance of broadband on the international policy agenda and expanding broadband access in every country as key to accelerating progress towards national and international development targets.
[34] Broadband Commission for Sustainable Development 2025 Targets: "Connecting the Other Half", 2018

- Avoiding duplication: In rural areas, mobile coverage is ahead of fixed network coverage. This existing mobile network can serve both 5G NR mobile and fixed broadband needs provided sufficient spectrum is available. Bringing FTTH into a rural small town is in effect a duplication of infrastructure, network operations expenditure, and customer administration. These are avoidable costs which is hugely important for lower-income countries, for example.

Additional spectrum for a sustainable FWA business case in rural areas

There are two aspects to be considered:

- Is there sufficient spectrum to deliver the 5G mobile 100 Mbit/s DL and 50 Mbit/s UL user experience?
- And at the same time: Is there sufficient spectrum to deliver 100 Mbit/s FWA connectivity to all households and businesses in a rural small town or village?

With a small set of assumptions, we modelled capacity and demand in order to illustrate where additional mid-band spectrum could be effective in this regard. We analysed the maximum rural population density that could be supported in low bands and lower mid-band spectrum. We also assessed the number of 5G mobile users that could be supported from a single three sector cell tower. In such a scenario, any additional upper mid-band spectrum could then be dedicated to provisioning 5G broadband FWA connectivity by using existing mobile sites and without any detriment to the mobile service.

In contrast to urban areas, in rural small towns and villages the population density and hence demand for 5G mobile area traffic capacity (Gbit/s/km^2) is sufficiently low to be catered for by low bands and lower mid-band spectrum. With some variations between countries, typically 650 MHz of low bands and lower mid-band spectrum is available. Assuming in these low-density areas there is no offload to either high bands or indoor small cells, the maximum population density that can be served from a single 3 sector site with a 100 Mbit/s 5G mobile service is approximately 540 premises (see Exhibit 30 above).

Demand for 5G area traffic capacity will grow in line with the adoption of 5G. Due to affordability, 5G adoption in lower-income countries will be slower compared to higher-income countries, especially in rural areas. Low levels of 5G penetration translate into a low activity factor. By 2023, in rural areas of lower-income countries the activity factor is likely to be below 1% but may reach 10% by 2030. In other words, area traffic demand will increase over time.

Due to the low activity factor in the near term, 5G NR capacity using upper mid-band spectrum can be used to provide a 100 Mbit/s FWA connectivity. On day one of 5G FWA in rural population clusters only a few households will subscribe to it, but demand will grow over time. In the early years of 5G NR low-band and lower mid-bands will be sufficient to deliver the 5G NR area traffic capacity in a rural population cluster. A country may have already 400 MHz of upper mid-band spectrum available. Our 5G FWA modelling shows that with 400 MHz of upper mid-band spectrum 90 households could be supported. However, as 5G NR mobile penetration increases, within a few years this spectrum will be required for cater for the growing mobile area traffic demand.

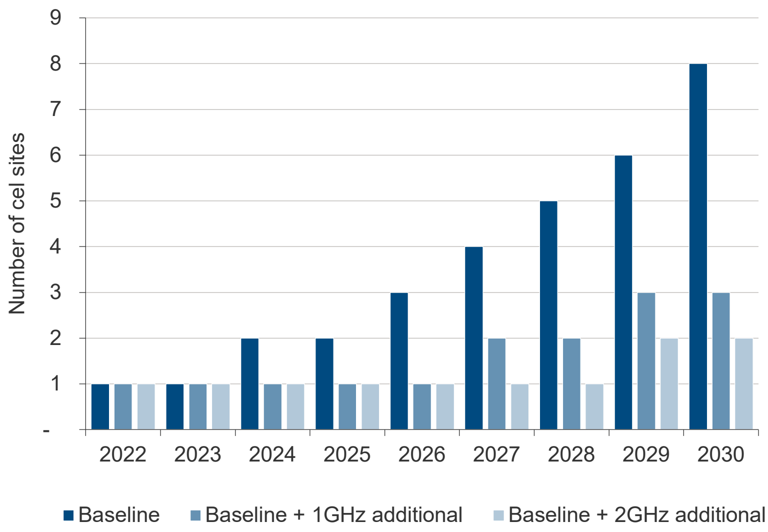
While initially FWA broadband demand in a rural population cluster may not exceed 90 households, in the longer term almost every household, business premises, school, and medical facility in the cluster will require 100 Mbit/s FWA and will be able to afford it. Clearly, as demand grows 400 MHz of spectrum will not be sufficient for a typical rural small town with 400 households and a population of 1,600. In other words, without additional spectrum the business case for FWA in upper mid-bands would not be sustainable in the longer term when most households and all business premises want broadband connectivity of at least 100 Mbit/s DL and 50 Mbit/s UL speeds.

However, if additional spectrum is made available, mobile operators can deliver the 5G NR 100 Mbit/s DL / 50 Mbit/s UL user experienced data to mobile users and at the same time provide a 100 Mbit/s DL / 50 Mbit/s UL 5G FWA service.

Exhibit 32 provides an illustration of how this might play out in a rural small town in the period 2022 to 2030.

- Initially, as 5G adoption and demand for 5G FWA broadband are low, the demand can be met from existing cells towers. As demand increases, either additional cell towers need to be built at great cost or additional radios can be installed on the existing cell tower. The latter is of course far cheaper.
- Assuming by 2030 the 5G mobile activity factor is 10% and 85% of households subscribe to 5G FWA, without additional upper mid-band spectrum eight cell towers are required for around 400 connected premises in a village. With an additional 2,000 MHz of upper mid-band spectrum only two cell towers are required, i.e., a 75% saving. This saving is extremely important because keeping costs down to deliver affordable broadband access is a key policy objective. Typically, such villages cover an area of 1 km^2. The range of upper mid-band spectrum is sufficient to cover a village from a single cell tower.

Exhibit 32: Cell site vs. spectrum trade off in rural population clusters



Source: Coleago

5.6.3 Case Study: The value of additional spectrum for rural FWA in India

In the sections below, we examine how these figures relate to the rural populations of India – to establish the potential magnitude of the rural population that could be addressed by such solutions. The population estimates are sizeable in each case indicating that additional upper mid-band spectrum could play a significant role in wider broadband provision.

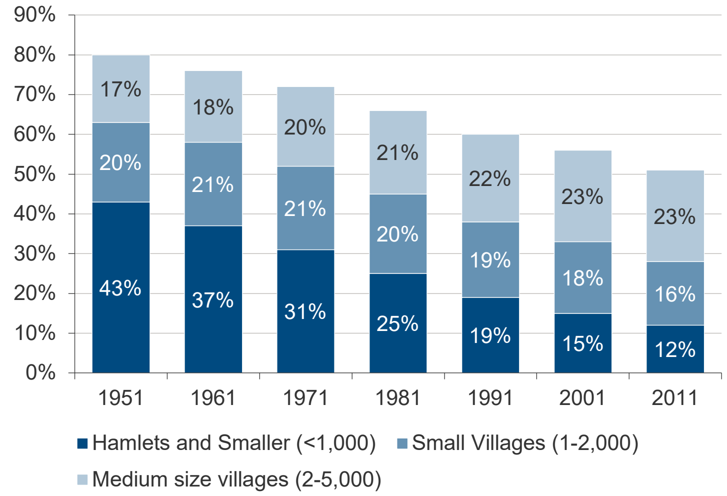
India has a sizeable rural population of 895.4 million, equivalent to 65.5% of the total population (2019, World Bank) – which has been increasing over time in absolute terms (from 845 million in 2009) but falling in percentage terms (from 69.4% in 2009). Average rural household size has also been falling and is currently estimated to be in the region of 4 to 4.5 people per household (falling from in excess of 5 in the early 2000's).

The rural population can be further broken down into those who live in 'very large' and 'large' villages, those in 'medium sized' villages, and those in 'small sized villages'. The 'small sized village' category is the one of interest here since, at a household ratio of 4 to 4.5, these villages are around 230 to 450 households in size – aligned with our mid-band calculation in Exhibit 30 for the FWA capacity of a site. If these households are served by a single site, then the population density is well below the 540 households limit calculated earlier.

Exhibit 33 shows that this population in the 'small sized village' category has been falling slowly – and is estimated to be 15% in 2021. Applying this to the current Indian population estimate of 1.39 billion (2021) implies that ~209 million people live in these small sized villages. At an average village size of 1,500 people, there are around 139,000 villages each with around 230 to 450 households. This is a sizeable portion of the population that could be addressed by the single-site solution discussed above and which could significantly benefit from additional mid-band spectrum both in terms of the capacity delivered, as well as helping to close the digital divide.

Many of these rural population clusters will also have schools, healthcare facilities and agricultural businesses. Bringing broadband connectivity to these facilities is a key development objective in and 5G FWA is the fastest and cheapest technology to realise this objective.

Exhibit 33: Indian population by settlement type (%)



Source: India's Missing Middle: 24,000 'Villages' with populations greater than towns lose Out on policies for urban areas, Arindam Jana Archita S, 23 Jan, 2019

5G FWA solutions minimise capital and operational expenditure. The latter point is particularly important because affordability is a key issue in rural areas of lower-income countries such as India. Exhibit 34 shows the key metrics for India, including the potential savings of 5G FWA in mid-bands vs. FTTH. The rural definitions are explained in more detail below in the country specific sections.

As regards the savings, the cost of building FTTH in rural areas varies substantially. The cost per home passed could be lower due, for example, to using pole mounted fibre. However, as a minimum, we estimate that if all households in a settlement are connected to broadband, the cost per connection would be at least $200 lower using 5G NR FWA with additional upper mid-band spectrum. This is a conservative estimate, and due to the differences in scalability, the cost of 5G FWA compared to fibre is likely to be significantly lower.

Exhibit 34: 5G FWA in “small size” rural areas in India

	India
Rural population (mn)	895.4
Of which in “small-size” rural cluster (mn)	209.0
Number of “small-size” rural clusters	139,000
Average population per “small-size” rural cluster	1,504
People per household	4.3
Households in “small-size” rural clusters (mn)	49.2
Average households per “small-size” cluster	354
Potential saving with fibre-like FWA vs. FTTH USD mn in “small-size” rural clusters	9,835

Source: Coleago

Note: A rural cluster is defined as a village or small rural town with between 200 and 600 households.

6 Mid-band spectrum to deliver 5G along motorways outside cities

Above we showed that additional upper mid-band spectrum is required in cities with a population density of 8,000 per km^2 or more. Additional upper mid-band spectrum is also required outside cities. The vision of a user experienced DL data rate of 100 Mbit/s and 50 Mbit/s UL everywhere means that this also has to be assured on major road and rail links outside cities.

Substantial capacity is required on roads to serve the connected car and smart road use cases. In January 2019, the 5G Automotive Association (5GAA) reported that "*At present, more than 100 million vehicles connected to cellular networks (V2N) are on the roads. This V2N connection is used for a wide variety of services including telematics, connected infotainment, real time navigation and traffic optimization, as well as for safety services including automatic crash notification (ACN) such as eCall, the recognition of slow or stationary vehicle(s) and informational alerts for events including traffic jams, road works and other traffic infrastructure related information, inclement weather conditions and other hazardous conditions. Several OEMs share safety related warnings between their vehicles and have started to exchange this information across OEMs*".[35]

Moving beyond such services into the future of connected cars implies a significant step change in the data generated and transmitted per car. 5GAA notes that the 5G NR standards "offer the features which are paramount to highly and fully automated and cooperative driving such as the exchange of:

- sensor data sharing for collective perception (e.g., video data);
- control information for platoons from very close driving vehicles (only a few meters gap); and
- vehicle trajectories to prevent collisions (cooperative decision making)."

As such, connected cars are expected to generate several Terabytes of data a day from the hundreds of on-vehicle sensors and large quantities of on-board processing which are essential to the functioning of the car:

Each autonomous car driving on the road will generate about as much data as about 3,000 people

- Google stated that in their self-driving car trials, a car generates around 1 terabyte of data in an 8 hour driving period (equivalent to a constant 35 Mbit/s, if transmitted in real-time).
- According to industry estimates, cameras deployed in such cars alone will generate 20 to 40 Mbit/s of traffic. "Each autonomous car driving on the road will generate about as much data as about 3,000 people. And just a million autonomous cars will generate 3 billion people's worth of data" (Brian Krzanich, CEO, Intel, 2019).

By no means all data generated by autonomous vehicles will be transmitted while mobile, but autonomous vehicles will add significantly to area traffic density demand.

In addition, smart road traffic management will add to area traffic capacity needs. The extensive deployment of smart devices and sensors along 5G-enabled roads will allow cars and physical road infrastructure to interact in real-time – as well as the real-time management of road networks.

A key for all these use cases is reliability and low latency, and thus having access to the required spectrum consistently is a prerequisite.

Many examples of densely occupied roads exist around the world. Here we consider an example of a four lane motorway in each direction is used. At 120 km/h, safe following distances of typically 40 meters to 60 meters are recommended.

[35] Timeline for deployment of C-V2X – Update, 5G Automotive Association, 22 January 2019,

If macro sites dedicated to road coverage are spaced every 6 km using 3.5 GHz (i.e., a 3 km site radius) then, in peak hours, one dedicated road site could be serving 800 to 1,200 cars – or 400 to 600 cars per sector (assuming two linear sectors pointing up and down the road). To provision 100 Mbit/s speed coverage to each car to entertain its passengers (an under-estimate of the 5G requirements which, arguably, could require 100 Mbit/s provision for each passenger as well as for the car) assuming 15% concurrent use by 2025-2030 would require a site sector downlink throughput of up to 6 to 9 Gbit/s.

If a 5G spectral efficiency of 6 bit/s/Hz is assumed (as used earlier, in our city analysis) then between 1,000 and 1,500 MHz of spectrum will be needed to deliver this throughput. Whilst a smaller portion of the traffic could be carried in below 3GHz spectrum, it will not have a significant impact on this overall requirement.

With only 400 MHz available at 3.4-3.8 GHz, it is clear that additional mid-band spectrum – or an alternative solution – is required.

With only 400 MHz available at 3.3-3.8 GHz, it is clear that additional mid-band spectrum – or an alternative solution – is required.

5GAA has also analysed the spectrum needs for automotive in rural and urban areas and concluded the following (5GAA TRS-200137, 20.06.2020):

"Furthermore, based on the results of our studies of the spectrum needs of C-V2X network-based (V2N) communications, we can draw the following conclusions:

- *c) At least 50 MHz of additional service-agnostic low-band (< 1 GHz) spectrum would be required for mobile operators to provide advanced automotive V2N services in rural environments with affordable deployment costs.*
- *d) At least 500 MHz of additional service-agnostic mid-band (1 to 7 GHz) spectrum would be required for mobile operators to provide high capacity city wide advanced automotive V2N services.*

In the above, the term "additional" means availability of spectrum in addition to the bands that are currently identified for IMT use by mobile communication networks."

7 The need for a wide-band assignment

7.1 Introduction

5G is not simply a new radio technology. To deliver 5G, a combination of factors is required:

- Additional spectrum;
- A contiguous wide-band assignment per operator of at least 100 MHz in the mid-bands and multiple 100 MHz wide channels in the 2025-2030 time frame;
- A contiguous wide-band assignment per operator of at least 1 GHz by 2020 in the high bands and even wider channels in the 2025-2030 time frame; and
- Higher presence of MIMO and beamforming.

5G NR is designed to exploit 100 MHz channel bandwidths in mid-bands. This is a significant improvement over 4G which only allows a channel bandwidth of up to 20 MHz. Exhibit 35 shows the 3GPP Release 16 spectrum bands that support 100 MHz channel bandwidth. This wide channel brings significant benefits in terms of spectral efficiency, signalling overhead, physical layer flexibility, latency performance, base station radio and UE implementation. The implication is that the more a single operator assignment is below 100 MHz, the more we move away from what 5G could deliver.

At least a contiguous block of 100 MHz of mid-band spectrum per operator is needed today and two to three 100 MHz blocks of mid-band spectrum per operator are needed in the longer term to deliver technical, economic and environmental benefits, and hence making available the widest possible contiguous amount of mid-band spectrum per operator should be a goal of spectrum management. This is only possible if additional upper mid-band spectrum is made available.

Exhibit 35: 3GPP FR-1 bands with 100 MHz wide channel

3GPP Band Number	Frequency – MHz
n40	2300 – 2400 (TDD)
n41	2496 – 2690 (TDD)
n48	3550 – 3700 (TDD)
n77	3300 – 4200 (TDD)
n78	3300 – 3800 (TDD)
n79	4400 – 5000 (TDD)
n90	2496 – 2690 (TDD)

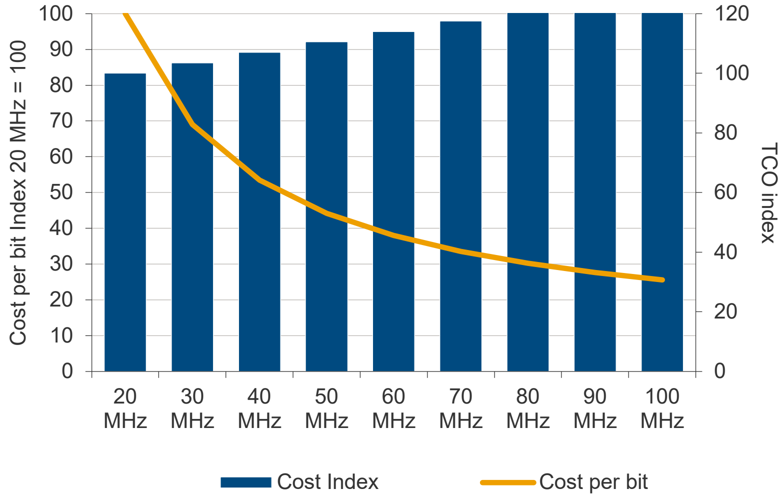
Source: 3GPP Release 16

7.2 Economic benefit of 100 MHz channel bandwidth

From a network cost perspective, the wider the channel that is deployed in a single radio the lower the cost per MHz deployed, and therefore implicitly the cost per bit. 5G is associated with much higher volumes of data traffic and higher speed at retail prices that are not higher than today’s mobile data retail prices. The required user experienced data rate for 5G is 10 times higher compared to 4G. If retail prices are to remain constant, then this is only possible if the cost per bit declines substantially. Deploying 5G in a channel bandwidth of at least 100 MHz of mid-band spectrum is an essential element to make the equation work.

Exhibit 36 below illustrates the cost per bit depending on the amount of spectrum deployed in a single radio. Coleago made the following assumptions with regards to the total cost of ownership (TCO) of deploying a 3.5 GHz radio on an existing cell site. We calculate this based on an index, comparing deployment in a 20MHz wide channel (index value = 100) with higher channel bandwidth. If 100 MHz is deployed in a single radio, the cost per MHz deployed can be up to 70% lower compared to, for example, a typical deployment in a 20 MHz wide channel. Deploying upper mid-band spectrum with massive MIMO in a 100 MHz wide channel maximises spectral efficiency which is a key objective for operators and regulators.

Exhibit 36: Cost per bit depending on channel bandwidth



Source: Coleago Consulting

7.3 Per operator contiguous assignments of more than 100 MHz

Equipment suppliers' efforts aim at allowing their 5G radios, including those implementing massive MIMO and beamforming, to operate with the widest possible channel bandwidth ("instantaneous bandwidth") and to make that "tunable" in the widest possible frequency range ("operating bandwidth").

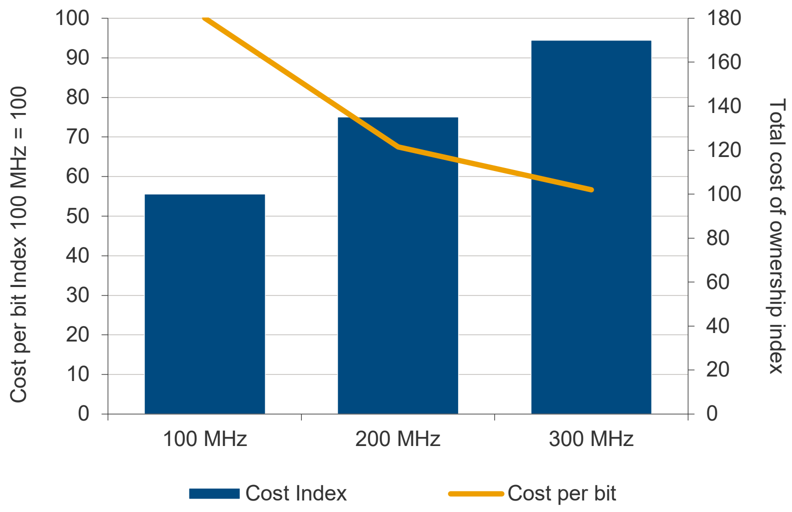
5G radios that are now deployed in 3400-3800 MHz band are starting to operate at an "instantaneous bandwidth" of 100 MHz within a 400 MHz "operating bandwidth".

The ongoing research (e.g., for filters and power amplifiers) will allow larger instantaneous and operating bandwidths by 2025-2030.This means that future radios will aim at larger instantaneous bandwidths (e.g., 200 to 400 MHz) [36] and at operating bandwidths that will be larger than 400 MHz. Operators will therefore be able to operate significantly larger instantaneous channel bandwidths (contiguous or non-contiguous) within the same mid-bands.

[36] Note that at the moment 3GPP specifications only support 100MHz channel bandwidth. Multiple 100MHz carriers can be aggregated (5G carrier aggregation of up to four 100MHz carriers is possible today). If such carriers are contiguous, carrier aggregation can be performed within the same single radio, cost effectively.

Exhibit 37 is similar to Exhibit 36, but the starting point is a 100 MHz wide channel (index value = 100). If 300 MHz is deployed in a single radio, the cost per bit is 43% lower compared to a deployment in only 100 MHz. Therefore, the assignment of 200 to 300 MHz of contiguous spectrum per operator would result in significant economic benefits.

Exhibit 37: Cost per bit with per operator allocation of over 100 MHz



Source: Coleago Consulting

7.4 Spectral efficiency benefit of a 100 MHz wide-band allocation

The wider the band in which 5G is deployed, the higher the spectral efficiency. Deploying 5G in a 100 MHz wide channel in upper mid-band spectrum delivers a 7% higher spectral efficiency compared to deploying it in only 20 MHz. Spectrum utilisation is less than 100% for all 5G NR channel bandwidth options because the resource blocks do not fully occupy the channel bandwidth. However, the utilisation decreases with the channel bandwidth as shown in the table below for 30 kHz sub-carrier spacing.

Exhibit 38: 5G NR utilisation of channel bandwidth

Channel BW	Number of resource blocks	Transmission BW (MHz)	Lost BW (MHz)	Utilisation
100 MHz	273	98.280	1.720	98.3%
80 MHz	217	78.120	1.880	97.7%
60 MHz	162	58.320	1.680	97.2%
50 MHz	133	47.880	2.120	95.8%
40 MHz	106	38.160	1.840	95.4%
20 MHz	51	18.360	1.640	91.8%

Source: ECC Report 287, Guidance on defragmentation of the frequency band 3400-3800 MHz, October 2018, page 41

7.5 Contiguous spectrum vs. carrier aggregation

While specifications allow for channels to be aggregated, there is a performance loss if two non-contiguous channels are aggregated, as summarised in Exhibit 39. The table presents a comparison between a 100 MHz wide channel using a contiguous 100 MHz block of spectrum vs. creating a 100 MHz wide channel by aggregating two non-contiguous 50 MHz blocks. This clearly shows that allocating at a minimum a contiguous 100 MHz per operator constitutes best practice in spectrum management.

Exhibit 39: Comparison 100 MHz contiguous vs two 50 MHz blocks

	100 MHz	50 + 50 MHz
Complexity	Single carrier	Needs intra-band CA
Channel utilisation	98.3%	95.8%
Physical layer signalling	6.3% overhead	Approx. 12% overhead
Physical layer configuration	A single 100 MHz carrier offers more flexibility than 2x50 MHz carriers to configure sub-bands within the carrier	
Carrier activation / deactivation delay	2ms	10ms
BS implementation	Requires one radio unit only	May need two radio units
Spectrum management	Guard bands may be required if networks are unsynchronised	Two additional guard bands if networks are unsynchronised
UL support	No CA required in the UL	Uplink CA may not be supported by all UEs
UE consumption		30mA additional power consumption for the second CC (50-90% RF power increase over the non-CA case)

Source: ECC Report 287, Guidance on defragmentation of the frequency band 3400-3800 MHz, October 2018, page 44

7.6 Impact of awarding less than 100 MHz per operator

This report explores the amount of additional spectrum required to achieve the IMT-2020 requirements. The results show that typically more than 1 GHz of additional upper mid-band spectrum is required to cater for area traffic demand in cities. Assuming there are four operators in a country, this means 250 MHz per operator is required. The impact of not having sufficient mid-bands spectrum available is discussed under heading Trade-off between additional spectrum and network densification above.

Furthermore, from a spectral efficiency perspective and from an economic perspective it is more advantageous to allocate a wide contiguous channel to MNOs as explained above

Additionally, where 5G take up is still low and is not standalone, lower contiguous bandwidth may allow a small number of users in a cell to achieve 5G performance, however as demonstrated in the report, additional mid band spectrum will be required to meet the demand of a growing number of users.

7.7 The importance of service-neutral licenses

Best practice in spectrum licensing calls for service-neutral spectrum licences. Mobile operators would deploy additional upper mid-band spectrum in their network to serve mobile, FWA or other use cases where needed:

- In cities, the additional mid-band spectrum is essential to produce the IMT-2020 user experienced data rate across the city. In sub-urban areas the capacity provided could be used for eMBB and FWA for premises which do not have a wired broadband connection.
- Secondly, additional mid-bands are also required to deliver smart cities.
- Even in rural areas there are locations with high mobile traffic density, such as a train station, a rural airport, or some other place where people congregate. In these locations the network will benefit from additional mid-band spectrum.
- Lastly, additional mid-band spectrum could be used to deliver network slices to help serving the demand from industrial or similar facilities, as well as transport routes (highways and railways).

Considering the above, it is clear that service neutral nationwide licencing of additional mid-band spectrum would produce the most efficient outcome, i.e., deliver the greatest socio-economic benefit.

As stated above, mid-band spectrum would be deployed selectively in rural areas, for example a village or rural small town. However, given the lesser propagation characteristics of upper mid-band spectrum compared to low bands (sub-1 GHz) spectrum, it is not economically feasible to build wide geographic coverage with mid-band spectrum.

Appendices

Appendix A: **Frequently asked questions**

How can you justify the activity factors?

The activity factor includes uses from 5G smartphones as well new use cases. Smartphone usage will include much longer periods of video streaming leading to very long periods of bandwidth demand rather than the peaky usage pattern common today. New use cases include IoT (particularly smart city), connected cars, body cams, and many more as well as services delivered with a predictable quality of service by means of network slicing. Several of these use cases stream data continuously i.e., they are demanding a high bit rate 24 hours a day. In some cities 5G FWA will also contribute to the activity factor. For further detail please refer to chapter 6.

How do you factor in Wi-Fi offload?

Undoubtedly there will be a lot of Wi-Fi traffic, however, the effect of Wi-Fi offload is implicitly included in the model through a “5G activity factor” (when the device has an active 5G connection), as in developed telecommunications markets the activity factor would be significantly higher without Wi-Fi offload. To be also noted, 5G networks must deliver the user experienced speed of 100/50 Mbit/s “on the move”, not only indoors. For further detail please refer to chapter 3.3.2.

How do you factor in mmWave offload?

We assume that it will make economic sense to deploy high bands in areas with traffic density well above the average across an urban area, and up to 10 Mbit/s/m^2. Hence mmWave will carry high-traffic where deployed and effectively offload traffic from other bands. This reduces the demand for additional upper mid-band spectrum. For further detail please refer to chapter 3.3.2.

How did you factor in higher order MIMO and 5G tech advancements?

We assume that within the 2030 all spectrum resources will be used by 5G with a high order of MIMO which increase spectral efficiency. These assumptions ensure that demand for additional IMT spectrum is not overstated. For further detail please refer to chapter 3.3.2.

Why are your population density numbers for cities higher than others I’ve seen and aren’t the very high population densities squeezed into very small areas that could easily be covered with more densification?

The population density is the average in a dense area of a city. We focused on cities which have a sizeable area with a population density of at least 8,000 per km^2. In many cases the high-density area is not the same as the administrative area of a city or the build-up area of a city. The high-density area in the cities in our sample is typically at least 100 km2 and in many instances several hundred km2. It would not be economically feasible to provide contiguous 100 Mbit/s DL and 50 Mbit/s UL speed coverage over such large areas by densification instead of upper mid-bands. For further detail please refer to Appendix C

Appendix B: **Additional spectrum needs**

In the report we show the total amount of upper mid-band spectrum needed in Exhibit 14, including the baseline spectrum. Baseline spectrum includes spectrum already used by mobile operators or already identified to be used. The table below shows the difference between the total spectrum needs and the baseline to bring the additional spectrum needs:

Exhibit 40: Additional spectrum needs (MHz) for DL and UL

DL and UL additional spectrum need [MHz]

City	Popn density per km^2	Base line Low Band MHz	Base Line Mid Band MHz	Base Line Total MHz	Activity factor 10% High bands offload			Activity factor 15% High bands offload			Activity factor 20% High bands offload			Activity factor 25% High bands offload		
					30%	20%	10%	35%	25%	15%	40%	30%	20%	45%	35%	25%
Tehran	8,000	130	620	750	110	190	270	290	400	520	420	580	730	520	710	910
Amsterdam	8,386	190	935	1,125	0	30	70	70	190	320	210	380	540	320	520	720
Munich	8,836	190	835	1,025	30	100	190	210	340	460	360	530	700	460	680	890
Marseille	9,035	190	935	1,125	10	50	100	120	260	390	280	450	630	390	600	820
Hamburg	9,289	190	835	1,025	50	130	220	240	380	510	400	580	760	510	740	960
Minsk	9,541	190	765	955	150	240	330	350	490	630	520	700	880	630	860	1090
Baku	9,636	190	765	955	150	240	340	360	500	640	520	710	900	640	870	1110
Makkah	10,070	240	1,145	1,385	0	40	80	90	210	360	240	430	630	360	600	850
Milan	10,162	190	935	1,125	40	90	190	210	360	510	390	580	780	510	750	1000
Lyon	10,595	190	935	1,125	50	120	220	250	400	560	430	630	840	560	810	1070
Rome	10,955	190	935	1,125	60	150	250	280	440	600	460	670	890	600	860	1120
Berlin	11,859	190	835	1,025	190	310	420	450	620	790	650	880	1110	790	1080	1370
Amman	11,930	190	1,045	1,235	80	180	300	330	500	670	530	760	990	670	960	1250
Tashkent	14,088	190	765	955	410	550	680	720	920	1130	950	1230	1500	1130	1470	1810
Johannesburg	14,681	196	674	870	480	620	760	800	1010	1220	1050	1330	1620	1220	1580	1930
Bangkok	14,696	170	900	1,070	340	480	630	660	880	1090	910	1200	1480	1090	1440	1800
Riyadh	15,000	240	1,145	1,385	140	280	430	460	680	900	720	1010	1300	900	1260	1620
Barcelona	15,576	190	935	1,125	310	460	610	650	870	1100	910	1210	1510	1100	1470	1850
Madrid	15,773	190	935	1,125	320	470	620	660	890	1120	930	1230	1540	1120	1500	1880
Bogotá	16,240	210	950	1,160	340	500	650	690	930	1160	970	1280	1600	1160	1560	1950
Mexico City	16,640	210	940	1,150	440	600	760	800	1040	1280	1080	1400	1720	1280	1680	2090
Istanbul	17,316	190	1,035	1,225	380	550	720	760	1010	1260	1050	1390	1720	1260	1680	2100
Jakarta	17,439	160	850	1,010	520	690	860	900	1150	1410	1190	1530	1870	1410	1830	2250
Beijing	18,185	150	1,115	1,265	350	520	700	740	1010	1270	1050	1400	1760	1270	1710	2150
Paris	18,400	190	935	1,125	470	650	830	870	1140	1410	1180	1540	1890	1410	1850	2290
Nairobi	18,758	190	660	850	710	900	1080	1120	1390	1670	1440	1800	2160	1670	2120	2570
Cairo	18,934	130	660	790	740	920	1100	1150	1420	1700	1470	1840	2200	1700	2160	2610
Tokyo	19,440	150	1,270	1,420	180	350	540	580	860	1150	910	1290	1660	1150	1620	2090
Ho Chi Minh City	20,087	180	955	1,135	560	760	950	1000	1290	1580	1340	1730	2120	1580	2070	2550
New York	20,770	180	950	1,130	580	780	980	1030	1330	1630	1380	1780	2180	1630	2130	2640
Moscow	20,975	190	755	945	820	1020	1230	1280	1580	1880	1630	2040	2440	1880	2390	2900
Sao Paulo	21,542	140	970	1,110	650	860	1070	1120	1440	1750	1490	1900	2320	1750	2270	2790
Mumbai	24,773	137	588	725	1020	1260	1500	1560	1920	2280	1980	2460	2940	2280	2880	3480
Hong Kong	25,327	245	830	1,075	900	1150	1390	1450	1820	2190	1880	2370	2860	2190	2800	3410
Yangon	25,327	160	835	995	1060	1300	1550	1610	1970	2340	2030	2520	3010	2340	2950	3570
Lagos	30,968	170	640	810	1500	1800	2100	2170	2620	3070	2700	3300	3900	3070	3820	4570

Additional spectrum need	< 10 MHz	10 to 500 MHz	500 - 1000 MHz	1000-2000 MHz	> 2000 MHz

Source: Coleago

Appendix C: **Population density analysis**

Focus on urban areas with a high population density

The need for additional upper mid-band spectrum for 5G is driven by the need to cater for high demand densities in cities. As stated above, we use population density as a proxy for demand density.

Demand for area traffic capacity is of course only a problem in areas with a high population density. In our analysis (based on publicly available data[37]) of specific cities we focus on areas within a city with a population density of at least 8,000 people per km^2. In principle, the higher the density, the greater the demand per km^2.

Given that population density is an average over an area, one must define the level of analysis and it is appropriate to look at population density clusters rather than dividing a city's population by the area within its administrative boundary. The area considered needs to be reasonably large, i.e., not just a 1 km^2 hotspot, for the issue to be material. The reason for this is that from an economic perspective it would be feasible to provide area traffic capacity in hotspot areas using just 4 or 5 high bands sites. However, it would not be economically feasible to build consistent speed coverage with high bands sites over a larger area with high area traffic demand. In other words, in the context of analysing demand for upper mid-band spectrum, the high-density area must be reasonably large. From a materiality perspective, Coleago considers that the minimum size is 40 km^2 in a single area or several such areas within an urban area.

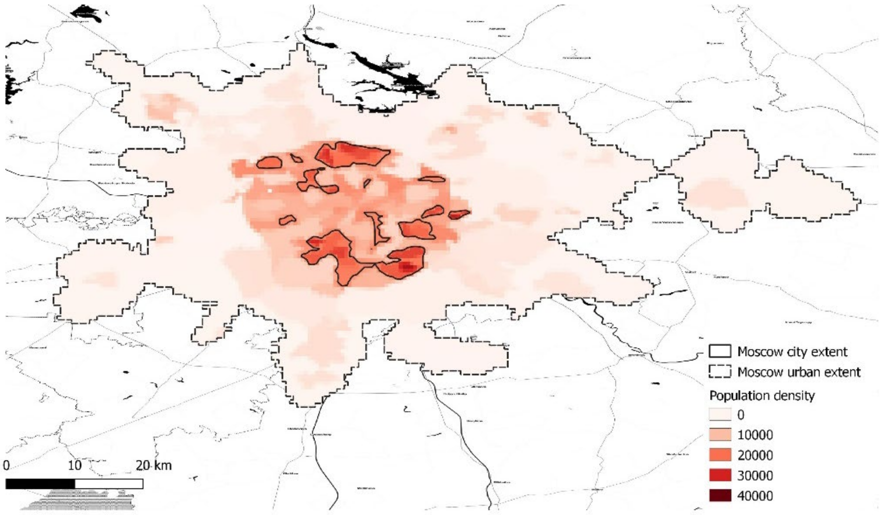
From a network dimensioning perspective, administrative city boundaries are irrelevant and what matters are areas with a high population density. We identify high population density areas over a reasonably large urban area which may or may not be within the administrative boundaries of a city or may not encompass the whole city.

When looking at statistics for population density in urban areas, there is an extremely wide range in terms of the total population, the area, and the population per km^2. At first glance, some cities may not look that dense. Upon closer inspection, it becomes apparent that large cities which show a population density below, say, 5,000 people per km^2 are often associated with a large area of, for example, more than 1,000 km^2. The larger the urban area that is considered the lower the average population density.

For example, the 16th Annual Demographia World Urban Areas, June 2020 shows that the average population density for Moscow is 2,908 pops / km^2 considering a built-up area of 5,891 km^2 encompassing a population of 17,125,000. 2,908 pops / km^2 is of course not sufficiently dense but this is misleading because the average density is calculated over a very large area. Our analysis is based on high population density clusters. For Moscow, we used a contour line of 17,500 people/km^2 to identify the central region(s) of Moscow. This is illustrated in Exhibit 41 and delivers a large number of distinct distributed areas. The urban extent of Moscow is also shown for reference. For Moscow, these central regions aggregate to an area of 204.3 km^2 with an average population density of 20,975 people/km^2, i.e., a population of 4.3 million across all the identified areas. 204.3 km^2

[37] https://sedac.ciesin.columbia.edu/data/set/grump-v1-urban-extents

Exhibit 41: Moscow, Russia: Population density and central region(s)



Source: Coleago Consulting

As explained above, when looking at population density it is appropriate to look at population density clusters rather than simply dividing a city's population by the area within its administrative boundary. In a selection of cities from different ITU regions, we have identified a similar reasonably sized high-density area. Exhibit 42 shows the analysis for the selected cities with their high-density area (km^2), the population in the high-density area, and the population density in the high-density area (pop/km^2). Population densities are sourced mainly from SEDAC[38 39]. Where SEDAC data was not sufficiently detailed we used other sources such as local data population density statistics with a sufficient level of granularity to identify high-density areas.

38 Center for International Earth Science Information Network - CIESIN - Columbia University, International Food Policy Research Institute - IFPRI, The World Bank, and Centro Internacional de Agricultura Tropical - CIAT. 2011. Global Rural-Urban Mapping Project, Version 1 (GRUMPv1): Urban Extents Grid. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4GH9FVG. Accessed May 2020 YEAR

39 Center for International Earth Science Information Network - CIESIN - Columbia University. 2018. Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H49C6VHW. Accessed May 2020.

Exhibit 42: Population and areas of sample cities

City	Country	World Bank Income Group	ITU Regional Group	Popn density per km^2	Dense Area km^2	Population 000
Tehran	Iran	Upper Middle	APT	8,000	1,704	13,632
Amsterdam	Netherlands	High	CEPT	8,386	117	982
Munich	Germany	High	CEPT	8,836	92	817
Marseille	France	High	CEPT	9,035	43	390
Hamburg	Germany	High	CEPT	9,289	69	642
Minsk	Belarus	Upper Middle	RCC	9,541	192	1,827
Baku	Azerbaijan	Upper Middle	RCC	9,636	115	1,106
Makkah	KSA	High	ASMG	10,070	434	4,366
Milan	Italy	High	CEPT	10,162	141	1,432
Lyon	France	High	CEPT	10,595	73	769
Rome	Italy	High	CEPT	10,955	171	1,868
Berlin	Germany	High	CEPT	11,859	163	1,939
Amman	Jordan	Upper Middle	ASMG	11,930	109	1,294
Tashkent	Uzbekistan	Lower middle	RCC	14,088	164	2,315
Johannesburg	South Africa	Upper Middle	ATU	14,681	222	3,262
Bangkok	Thailand	Upper Middle	APT	14,696	513	7,542
Riyadh	KSA	High	ASMG	15,000	145	2,175
Barcelona	Spain	High	CEPT	15,576	179	2,784
Madrid	Spain	High	CEPT	15,773	303	4,779
Bogotá	Colombia	Upper Middle	CITEL	16,240	584	9,484
Mexico City	Mexico	Upper Middle	CITEL	16,640	864	14,379
Istanbul	Turkey	Upper Middle	CEPT	17,316	698	12,087
Jakarta	Indonesia	Upper Middle	APT	17,439	515	8,980
Beijing	China	Upper Middle	APT	18,185	953	17,327
Paris	France	High	CEPT	18,400	243	4,468
Nairobi	Kenya	Lower middle	ATU	18,758	241	4,521
Cairo	Egypt	Lower middle	ASMG	18,934	961	18,202
Tokyo	Japan	High	APT	19,440	176	3,417
Ho Chi Minh City	Vietnam	Lower middle	APT	20,087	484	9,721
New York	USA	High	CITEL	20,770	348	7,221
Moscow	Russia	Upper Middle	RCC	20,975	204	4,279
Sao Paulo	Brazil	Upper Middle	CITEL	21,542	266	5,739
Mumbai	India	Lower middle	APT	24,773	944	23,386
Hong Kong	China	High	APT	25,327	291	7,370
Yangon	Myanmar	Lower middle	APT	25,327	291	7,370
Lagos	Nigeria	Lower middle	ATU	30,968	215	6,664

Source: Coleago GIS analysis based on data from, https://sedac.ciesin.columbia.edu/data/set/grump-v1-urban-extents, Demographia, local Statistical Offices

Relationship between a city area and population density

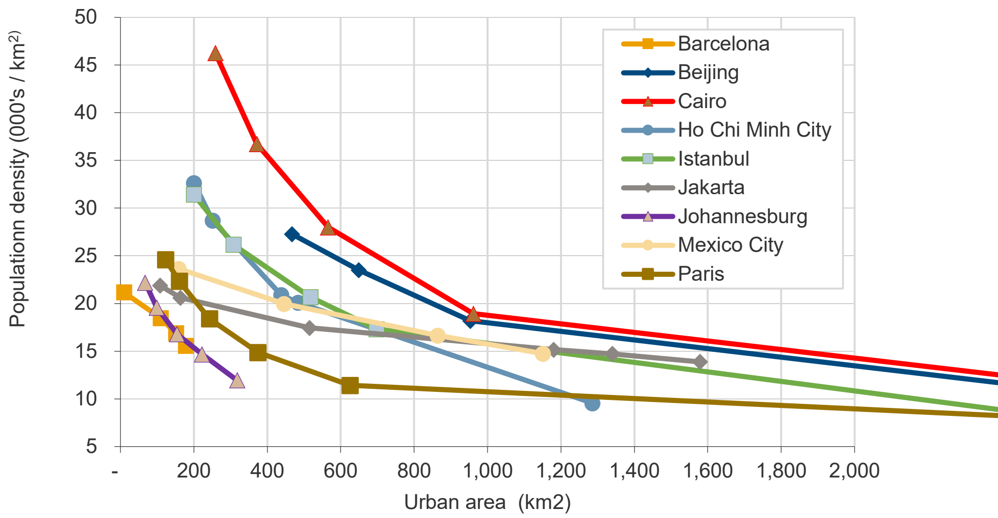
The foundation of the city analysis contained in this report is the average population density of each city across an associated area. By using this average population density, we are effectively assuming that each city is homogenous across the area. However, we recognise that this is not the case. Both population density and traffic will have localised peaks and troughs across the area considered. The deployment of macro cells and small cells will align with these and so will also be non-homogeneous.

Undertaking a detailed radio planning exercise for each city would account for this variation but would require considerably more data (particularly data forecasting the peaks and troughs) and time than was available for the project. Our chosen modelling approach seeks to be simple whilst remaining valid (for the outcome) when considering these issues.

A single pairing of population density and area has been chosen for each city. The chosen figures are intended to be indicative of the 5G capacity issues that might be faced in the coming years – by presenting a reasonably equitable balance between population density and area. Alternative pairings could have been chosen and here we provide some insight into the relationship by illustrating it for a selection of cities in different regions.

Exhibit 43 below shows population density/ area pairings calculated for a selection of cities. As expected much lower densities occur when considering larger areas and much higher densities when considering smaller areas – due to the averaging that takes place. From this it is also clear that Jakarta and Mexico City are considerably larger in area and total population than both Barcelona and Johannesburg – as expected. However, all cities have sizeable areas where population density exceeds 20,000 people per square kilometre.

Exhibit 43: Population density versus urban area examples



Source: Coleago

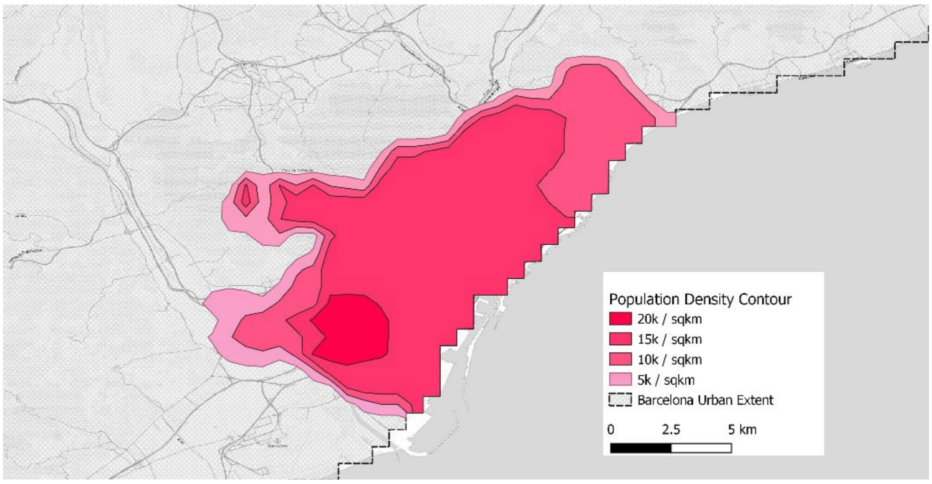
Below we provide further details and maps for four cities from which the above data is derived. These maps illustrate the further differences between the cities in terms of how population is distributed and how that data is recorded in the sources used for population density data.

Barcelona

The urban extent containing Barcelona extends a considerable way up and down the coast from Figueres to Amposta. Barcelona's population also follows the coast with the densest area slightly inland.

The lowest density contour analysed encompasses an area of 178.7 km^2 with an average population density of 15,600 people per km^2, whilst the highest density contour encloses just 9.7km^2 at an average density of 21,200 people per km^2.

Exhibit 44: Barcelona Population Distribution



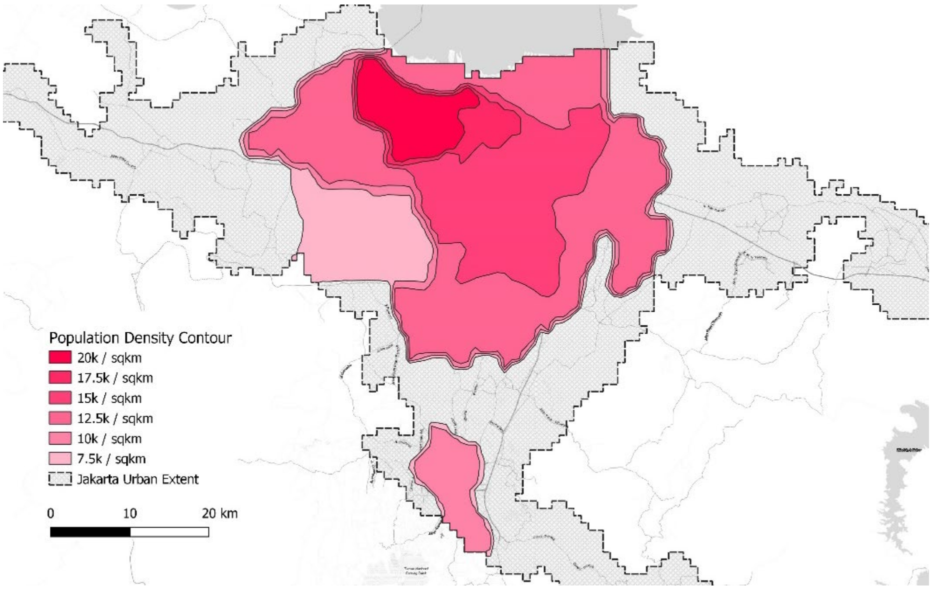
Source: Coleago, based on SEDAC data

Jakarta

Jakarta has a high population density which extends over a considerable portion of its urban extent. The densest area is close to the coast, although there is also a second separate relatively dense area to the south of this.

Several contours were produced to more fully explore the population distribution as the data showed limited variation in some areas at lower population densities. The largest contour analysed extends across a considerable area of 1,579km^2 with an average population density of 13,900 people per km^2. The smallest contour examined extends across 108km^2 at a population density of 21,900 people per km^2. Jakarta is not one of the densest cities examined in this report but it is one of the largest.

Exhibit 45: Jakarta Population Density



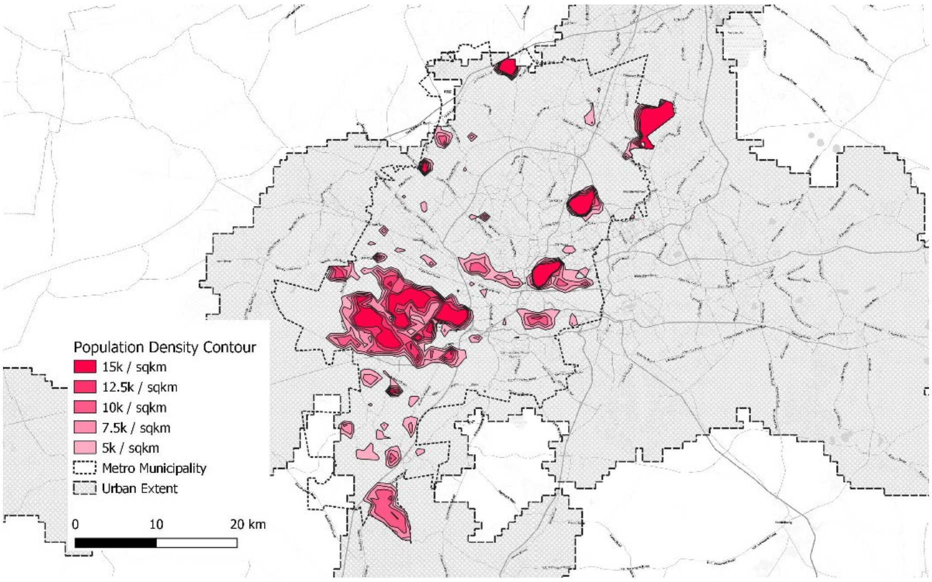
Source: Coleago, based on SEDAC data

Johannesburg

Johannesburg has several areas of high-density spread across its urban extent (but within the metro municipality). There is also a clear dense centre.

In aggregate, the lowest density contour examined spans an area of 318km^2 at an average population density of 11,900 people per km^2. Conversely the highest density contour examined aggregates to 67km^2 at an average density of 22,200 people per km^2. These figures bear some similarity to those for Barcelona although very clear differences in overall distribution can be seen between the two cities.

Exhibit 46: Johannesburg Population Density



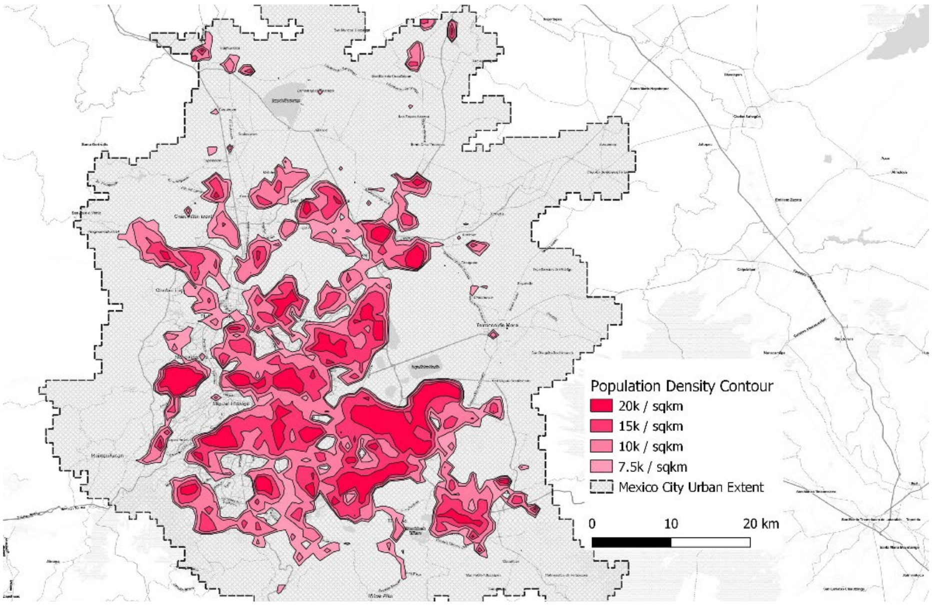
Source: Coleago, based on SEDAC data

Mexico City

The source data for Mexico City contains good resolution which results in multiple distributed centres of population across the full area of Mexico's urban extent.

In aggregate, the lowest density contour examined encloses 1,151km^2 at an average of 14,700 people per km^2. This is a large area in comparison to many of the other cities analysed and a high population density. The highest density contour analysed encompasses a total area of 159km^2 at an average density of 23,600 people per km^2.

Exhibit 47: Mexico City Population Density



Source: Coleago, based on SEDAC data

Exhibit 48: High-density areas in sample cities

City	Urban extent (km^2)	Population data source	Urban centre area(s) definition	Urban centre area (km^2)	Urban centre avg pops per km^2
Lyon	3,379	SEDAC/ Coleago	5k pop/km^2 contour	73	10,595
Lyon	3,379	SEDAC/ Coleago	10k pop/km^2 contour	36	13,568
Lyon	3,379	SEDAC/ Coleago	15k pop/km^2 contour	9	17,590
Marseille	5,456	SEDAC/ Coleago	5k pop/km^2 contour	43	9,035
Marseille	5,456	SEDAC/ Coleago	10k pop/km^2 contour	12	18,489
Marseille	5,456	SEDAC/ Coleago	15k pop/km^2 contour	8	20,893
Hamburg	2,065	SEDAC/ Coleago	Urban extent	2,065	1,212
Hamburg	2,065	SEDAC/ Coleago	2.3k pop/km^2 contour	661	2,390
Hamburg	2,065	Statistical handbook	N/A	75	8,999
Hamburg	2,065	Statistical handbook	N/A	69	9,289
Hamburg	2,065	Statistical handbook	N/A	52	10,281
Hamburg	2,065	Statistical handbook	N/A	24	12,884
Hamburg	2,065	Statistical handbook	N/A	1	19,193
Munich	1,479	SEDAC/ Coleago	Urban extent	1,479	1,553
Munich	1,479	SEDAC/ Coleago	4.5k pop/km^2 contour	265	4,854
Munich	1,479	Statistical handbook	N/A	124	8,017
Munich	1,479	Statistical handbook	N/A	92	8,836
Munich	1,479	Statistical handbook	N/A	73	9,635
Munich	1,479	Statistical handbook	N/A	64	10,013
Munich	1,479	Statistical handbook	N/A	47	10,952
Munich	1,479	Statistical handbook	N/A	4	15,811
Milan	6,292	SEDAC/ Coleago	5k pop/km^2 contour	141	10,162
Milan	6,292	SEDAC/ Coleago	10k pop/km^2 contour	53	15,239
Milan	6,292	SEDAC/ Coleago	15k pop/km^2 contour	20	18,044
Milan	6,292	SEDAC/ Coleago	17.5k pop/km^2 contour	8	20,365
Milan	6,292	SEDAC/ Coleago	20k pop/km^2 contour	2	21,670
Rome	3,519	SEDAC/ Coleago	5k pop/km^2 contour	171	10,955
Rome	3,519	SEDAC/ Coleago	10k pop/km^2 contour	69	15,839
Rome	3,519	SEDAC/ Coleago	15k pop/km^2 contour	22	20,569
Rome	3,519	SEDAC/ Coleago	17.5k pop/km^2 contour	11	23,852
Rome	3,519	SEDAC/ Coleago	20k pop/km^2 contour	5	26,214
Amsterdam	5,141	SEDAC/ Coleago	4.2k pop/km^2 contour	146	4,282
Amsterdam	5,141	EEA / Coleago	5k pop/km^2 contour	117	8,386
Amsterdam	5,141	EEA / Coleago	7.5k pop/km^2 contour	72	9,788
Amsterdam	5,141	EEA / Coleago	10k pop/km^2 contour	70	9,788
The Hague	5,141	SEDAC/ Coleago	6.2k pop/km^2 contour	59	6,494
Madrid	4,690	EEA / Coleago	EEA; 5k pop/km^2 contour	303	15,773
Madrid	4,690	EEA / Coleago	EEA; 7.5k pop/km^2 contour	226	18,646
Madrid	4,690	EEA / Coleago	EEA; 10k pop/km^2 contour	113	24,246
Madrid	4,690	EEA / Coleago	EEA; 15k pop/km^2 contour	86	26,047
Barcelona	6,985	SEDAC/ Coleago	5k pop/km^2 contour	179	15,576
Barcelona	6,985	SEDAC/ Coleago	10k pop/km^2 contour	151	16,881
Barcelona	6,985	SEDAC/ Coleago	15k pop/km^2 contour	110	18,456
Barcelona	6,985	SEDAC/ Coleago	17.5k pop/km^2 contour	98	18,661
Barcelona	6,985	SEDAC/ Coleago	20k pop/km^2 contour	10	21,175
Berlin	2,730	SEDAC/ Coleago	3.8k pop/km^2 contour	753	3,791
Berlin	2,730	EEA / Coleago	EEA 5k pops/km^2 contour	506	6,498
Berlin	2,730	EEA / Coleago	EEA 7.5k pop/km^2 contour	41	12,654
Berlin	2,730	Statistical handbook	N/A	301	8,885

City	Urban extent (km^2)	Population data source	Urban centre area(s) definition	Urban centre area (km^2)	Urban centre avg pops per km^2
Berlin	2,730	Statistical handbook	N/A	290	9,058
Berlin	2,730	Statistical handbook	N/A	232	10,088
Berlin	2,730	Statistical handbook	N/A	163	11,859
Berlin	2,730	Statistical handbook	N/A	86	13,917
Berlin	2,730	Statistical handbook	N/A	2	17,129
Bogotá	584	Demographia		584	16,240
Bogotá	3,004	SEDAC/ Coleago	Urban extent	3,004	1,925
Bogotá	3,004	SEDAC/ Coleago	5k pop/km^2 contour	568	6,316
Sao Paulo	4,435	SEDAC/ Coleago	17.5k pop/km^2 contour	266	21,542
Sao Paulo*	3,116	Demographia		3,116	7,076
Mexico City	2,386	Demographia		2,386	8,802
Mexico City	4,496	SEDAC/ Coleago	Urban extent	4,496	4,930
Mexico City	4,496	SEDAC/ Coleago	7.5k pop/km^2 contour	1,151	14,746
Mexico City	4,496	SEDAC/ Coleago	10k pop/km^2 contour	864	16,640
Mexico City	4,496	SEDAC/ Coleago	15k pop/km^2 contour	446	19,963
Mexico City	4,496	SEDAC/ Coleago	20k pop/km^2 contour	159	23,630
New York	12,093	Demographia		12,093	1,700
New York	25,948	SEDAC/ Coleago	Urban extent	25,948	1,157
New York	25,948	SEDAC/ Coleago	10k pop/km^2 contour	348	20,770
New York	25,948	SEDAC/ Coleago	15k pop/km^2 contour	218	25,170
Nairobi	851	Demographia		851	7,065
Nairobi	1,190	SEDAC/ Coleago	Urban extent	1,190	4,936
Nairobi	1,190	SEDAC/ Coleago	5k pop/km^2 contour	241	18,758
Nairobi	1,190	SEDAC/ Coleago	7.5k pop/km^2 contour	179	23,155
Nairobi	1,190	SEDAC/ Coleago	10k pop/km^2 contour	143	27,183
Johannesburg	2,542	Demographia		2,542	3,737
Johannesburg	7,839	SEDAC/ Coleago	Urban extent	7,839	1,908
Johannesburg	7,839	SEDAC/ Coleago	5k pop/km^2 contour	318	11,949
Johannesburg	7,839	SEDAC/ Coleago	7.5k pop/km^2 contour	222	14,681
Johannesburg	7,839	SEDAC/ Coleago	10k pop/km^2 contour	154	16,791
Johannesburg	7,839	SEDAC/ Coleago	12.5k pop/km^2 contour	99	19,555
Johannesburg	7,839	SEDAC/ Coleago	15k pop/km^2 contour	67	22,193
Lagos*	1,965	Demographia		1,965	7,772
Lagos	1,435.4	SEDAC/ Coleago	Urban extent	1,435.4	9,061
Lagos	1,435.4	SEDAC/ Coleago	5k pop/km^2 contour	683.4	16,698
Lagos	1,435.4	SEDAC/ Coleago	10k pop/km^2 contour	498.0	20,391
Lagos	1,435.4	SEDAC/ Coleago	12.5k pop/km^2 contour	414.2	22,256
Lagos	1,435.4	SEDAC/ Coleago	15k pop/km^2 contour	215.2	30,968
Lagos	1,435.4	SEDAC/ Coleago	17.5k pop/km^2 contour	195.3	31,813
Lagos	1,435.4	SEDAC/ Coleago	20k pop/km^2 contour	162.8	34,162
Mumbai	944	Demographia		944	24,773
Mumbai	2,180	SEDAC/ Coleago		2,180	9,674
Mumbai	2,180	SEDAC/ Coleago		616	27,775
Jakarta	3,540	Demographia		3,540	9,756
Jakarta	4,124	SEDAC/ Coleago	Urban extent	4,124	6,997
Jakarta	4,124	SEDAC/ Coleago	7.5k pop/km^2 contour	1,579	13,885
Jakarta	4,124	SEDAC/ Coleago	10k pop/km^2 contour	1,340	14,720
Jakarta	4,124	SEDAC/ Coleago	12.5k pop/km^2 contour	1,180	15,152
Jakarta	4,124	SEDAC/ Coleago	15k pop/km^2 contour	515	17,439
Jakarta	4,124	SEDAC/ Coleago	17.5k pop/km^2 contour	163	20,612
Jakarta	4,124	SEDAC/ Coleago	20k pop/km^2 contour	108	21,879
Hong Kong	291	Demographia		291	25,327

City	Urban extent (km²)	Population data source	Urban centre area(s) definition	Urban centre area (km²)	Urban centre avg pops per km²
Hong Kong	905	SEDAC/ Coleago	Urban extent	905	7,639
Hong Kong	905	SEDAC/ Coleago	5k pop/km² contour	148	32,207
Tokyo	38,893	SEDAC/ Coleago	17.5k pop/km² contour	176	19,440
Tokyo*	4,614	Demographia		4,614	8,230
Ho Chi Minh City	1,638	Demographia		1,638	8,132
Ho Chi Minh City	1,286	SEDAC/ Coleago	Urban extent	1,286	9,554
Ho Chi Minh City	1,286	SEDAC/ Coleago	7.5k pop/km² contour	484	20,087
Ho Chi Minh City	1,286	SEDAC/ Coleago	10k pop/km² contour	438	20,891
Ho Chi Minh City	1,286	SEDAC/ Coleago	12.5k pop/km² contour	251	28,694
Ho Chi Minh City	1,286	SEDAC/ Coleago	15k pop/km² contour	200	32,626
Beijing	4,172	Demographia		4,172	4,658
Beijing	3,487	SEDAC/ Coleago	Urban extent	3,487	6,762
Beijing	3,487	SEDAC/ Coleago	5k pop/km² contour	953	18,185
Beijing	3,487	SEDAC/ Coleago	10k pop/km² contour	649	23,514
Beijing	3,487	SEDAC/ Coleago	15k pop/km² contour	467	27,282
Yangon	291	Demographia		291	25,327
Yangon	806	SEDAC/ Coleago	Urban extent	806	6,731
Yangon	806	SEDAC/ Coleago	10k pop/km2 contour	186	17,230
Cairo	2,010	Demographia		2,010	9,639
Cairo	3,741	SEDAC/ Coleago	Urban extent	3,741	6,472
Cairo	3,741	SEDAC/ Coleago	5k pop/km² contour	961	18,934
Cairo	3,741	SEDAC/ Coleago	10k pop/km² contour	566	27,986
Cairo	3,741	SEDAC/ Coleago	15k pop/km² contour	372	36,730
Cairo	3,741	SEDAC/ Coleago	20k pop/km² contour	259	46,266
Istanbul	1,375	Demographia		1,375	11,019
Istanbul	3,279	SEDAC/ Coleago	Urban extent	3,279	4,470
Istanbul	3,279	SEDAC/ Coleago	5k pop/km² contour	698	17,316
Istanbul	3,279	SEDAC/ Coleago	10k pop/km² contour	517	20,678
Istanbul	3,279	SEDAC/ Coleago	15k pop/km² contour	308	26,160
Istanbul	3,279	SEDAC/ Coleago	20k pop/km² contour	200	31,431
Tehran	1,704	Demographia		1,704	8,000
Tehran	5,838	SEDAC/ Coleago	Urban extent	5,838	1,579
Tehran	5,838	SEDAC/ Coleago	5k pop/km² contour	1,092	5,594
Tehran	5,838	SEDAC/ Coleago	Modified 5k + 7.5k contours	575	8,568
Tehran	5,838	SEDAC/ Coleago	7.5k pop/km² contour	53	9,285
Moscow	4,834	SEDAC/ Coleago	17.5k pop/km² contour	204	21,170
Moscow*	5,891	Demographia		5,891	2,908
Paris	2,509	Demographia		2,509	4,247
Paris	5,791	SEDAC/ Coleago	Urban extent	5,791	2,148
Paris	5,791	SEDAC/ Coleago	5k pop/km² contour	625	11,420
Paris	5,791	SEDAC/ Coleago	7.5k pop/km² contour	375	14,869
Paris	5,791	SEDAC/ Coleago	10k pop/km² contour	243	18,400
Paris	5,791	SEDAC/ Coleago	12.5k pop/km² contour	161	22,325
Paris	5,791	SEDAC/ Coleago	15k pop/km² contour	123	24,605
Paris	5,791	SEDAC/ Coleago	Within Boulevard Périphérique	85.3	25,018
Baku		Demographia	Built-Up Land Area	1,135	2,586
Baku	1,630	SEDAC/ Coleago	Urban extent	1,630	1,701
Baku	1,630	SEDAC/ Coleago	5k pop/km² contour	154	8,828
Baku	1,630	SEDAC/ Coleago	7.5k pop/km² contour	115	9,636
Baku	1,630	SEDAC/ Coleago	10k pop/km² contour	17	17,794
Minsk		Demographia	Built-Up Land Area	313	6,682
Minsk	1,246	SEDAC/ Coleago	Urban extent	1,246	1,716

City	Urban extent (km^2)	Population data source	Urban centre area(s) definition	Urban centre area (km^2)	Urban centre avg pops per km^2
Minsk	1,246	SEDAC/ Coleago	7.5k pop/km^2 contour	192	9,541
Tashkent		Demographia	Built-Up Land Area	1,075	3,249
Tashkent	1,919	SEDAC/ Coleago	Urban extent	1,919	1,470
Tashkent	1,919	SEDAC/ Coleago	5k pop/km^2 contour	182	13,670
Tashkent	1,919	SEDAC/ Coleago	10k pop/km^2 contour	164	14,088
Riyadh	906	UN Habitat	15,000 density	145	15,000
Makkah	433	UN Habitat, during Hajj	n/a	433	10,070
Amman	1,459	SEDAC/ Coleago	Urban extent	1,459.4	2,198
Amman	1,459	SEDAC/ Coleago	5k pop/km^2 contour	108.6	11,930
Amman	1,459	SEDAC/ Coleago	10k pop/km^2 contour	73.2	13,289
Bangkok		Demographia	Built-Up Land Area	3,199	5,336
Bangkok	5,868.6	SEDAC/ Coleago	Urban extent	5,869	3,204
Bangkok	5,868.6	SEDAC/ Coleago	2.5k pop/km^2 contour	2,072	7,379
Bangkok	5,868.6	SEDAC/ Coleago	5k pop/km^2 contour	1,115	10,685
Bangkok	5,868.6	SEDAC/ Coleago	7.5k pop/km^2 contour	787	12,495
Bangkok	5,868.6	SEDAC/ Coleago	10k pop/km^2 contour	513	14,696
Bangkok	5,868.6	SEDAC/ Coleago	12.5k pop/km^2 contour	320	16,437
Bangkok	5,868.6	SEDAC/ Coleago	15k pop/km^2 contour	195	18,592

Source: As shown in table

Appendix D: **ITU-R definition of the user experienced data rate**

From Report ITU-R M.2410-0 – page 5

4.3 User experienced data rate

User experienced data rate is the 5% point of the cumulative distribution function (CDF) of the user throughput. User throughput (during active time) is defined as the number of correctly received bits, i.e., the number of bits contained in the service data units (SDUs) delivered to Layer 3, over a certain period of time.

In case of one frequency band and one layer of transmission reception points (TRxP), the user experienced data rate could be derived from the 5th percentile user spectral efficiency through equation (3). Let W denote the channel bandwidth and SE_{user} denote the 5th percentile user spectral efficiency. Then the user experienced data rate, R_{user} is given by:

$R_{user} = W \times SE_{user}$ (3)

In case bandwidth is aggregated across multiple bands (one or more TRxP layers), the user experienced data rate will be summed over the bands. This requirement is defined for the purpose of evaluation in the related eMBB test environment.

The target values for the user experienced data rate are as follows in the Dense Urban – eMBB test environment:

– Downlink user experienced data rate is 100 Mbit/s.

– Uplink user experienced data rate is 50 Mbit/s.

These values are defined assuming supportable bandwidth as described in Report ITU-R M.2412-0 for each test environment. However, the bandwidth assumption does not form part of the requirement. The conditions for evaluation are described in Report ITU-R M.2412-0.

Appendix E: **ITU-R definition of area traffic capacity**

From Report ITU-R M.2410-0 – page 7

4.6 Area traffic capacity

Area traffic capacity is the total traffic throughput served per geographic area (in Mbit/s/m^2). The throughput is the number of correctly received bits, i.e., the number of bits contained in the SDUs delivered to Layer 3, over a certain period of time. This can be derived for a particular use case (or deployment scenario) of one frequency band and one TRxP layer, based on the achievable average spectral efficiency, network deployment (e.g., TRxP (site) density) and bandwidth.

Let W denote the channel bandwidth and ρ the TRxP density (TRxP/m^2). The area traffic capacity C_{area} is related to average spectral efficiency SE_{avg} through equation (6).

$C_{area} = \rho \times W \times SE_{avg}$ (6)

In case bandwidth is aggregated across multiple bands, the area traffic capacity will be summed over the bands. This requirement is defined for the purpose of evaluation in the related eMBB test environment. The target value for Area traffic capacity in downlink is 10 Mbit/s/m2 in the Indoor Hotspot – eMBB test environment. The conditions for evaluation including supportable bandwidth are described in Report ITU-R M.2412-0 for the test environment.

Appendix F: **Selected use cases requiring citywide speed coverage**

We are considering the future evolution of 5G over the next ten years. Today not all applications or use cases that will be developed to make use of the capabilities of 5G are known. However, in the following section we provide illustrations of some of the use cases that drive the need for citywide speed coverage.

Video everywhere and “on the move”

Much of the increase in demand for area traffic capacity is driven by increased use of video and advanced forms of video. Exhibit 49 shows the speed requirement for different types of videos, which increase as video capabilities advance. Advanced video includes augmented reality (AR) and virtual reality (VR) with higher resolutions and frame rates. Large screen devices, where higher resolution video is more relevant, will also use 5G streaming.

Immersive gaming not only requires high resolution video but also low latency. The low latency of 5G networks allows offload of the heavy computational work from devices to data centres which allows simplification of end user devices and wearables. Gaming content can be streamed just like video streaming services for example Netflix or Amazon Prime. The new gaming platforms such as Microsoft (with Project xCloud) and Google (with Stadia) are developed with 5G in mind.

Advanced video over 5G is already a reality. For example, in December 2019 Korea Telecom launched Real 360 app, a platform for 360-degree live-streaming, video sharing and video chat. Real 360 app users can initiate a 4K 360-degree video chat from a smartphone. Because of the vast quantity of data involved in transmitting high-resolution 360-degree video in real time, 5G technology is essential for this new communication tool.

Exhibit 49: Speed requirement for video

AR/VR level	Nominal data rate
1080p	4 Mbit/s
2K	5 Mbit/s
4K	20 Mbit/s
8K	80 Mbit/s
AR/VR 4K 2D	50 Mbit/s
AR/VR 8K 2D	100 Mbit/s
AR/VR 8K 3D	150 Mbit/s
AR/VR 12K 3D	500 Mbit/s

Source: Coleago Consulting, Qualcomm, Ericsson, Huawei

FWA in cities in countries with limited wired broadband infrastructure

In addition to 5G mobile connectivity, Fixed Wireless Access (FWA) is an important 5G use case. Traffic volumes on FWA are five times higher compared to mobile use and a video streaming to large screens creates a demand for high data rates of 300 Mbit/s.

While FWA provided with 4G is already experiencing some growth, the use of 5G means that particularly in countries with less developed wired (FTTH, xDSL, cable) broadband networks, 5G FWA is a major driver for an increase in mid-band spectrum demand. Therefore, in such countries, while demand for advanced 5G applications such as connected cars may take time to develop, demand from FWA is much higher compared to countries with good wired broadband infrastructure.

More information on the 5G FWA market and trends available in Section 5.

Connected cars in cities

In the long-term, substantial capacity is required on roads to serve the connected car and smart road use cases. Exhibit 50 shows the data rates for connected cars which in a ten year time frame will require substantial capacity. A study by the 5G Automotive Association published in June 2020[40] found that "*At least 500 MHz of additional service-agnostic mid-band (1 to 7 GHz) spectrum would be required for mobile operators to provide high capacity city wide advanced automotive V2N services*."

Exhibit 50: Data rates for car automation sensors

Sensor type	Quantity per vehicle	Data rate per sensor
Radar	4 – 6	0.1 – 15 Mbit/s
LIDAR	1 – 5	20 – 100 Mbit/s
Camera	6 - 12	500 – 3500 Mbit/s
Ultrasonic	8 - 16	< 0.01 Mbit/s
Vehicle motion, GNSS, IMU	-	< 0.1 Mbit/s

Source: Flash Memory in the emerging age of autonomy Stephan Heinrich, Lucid Motors

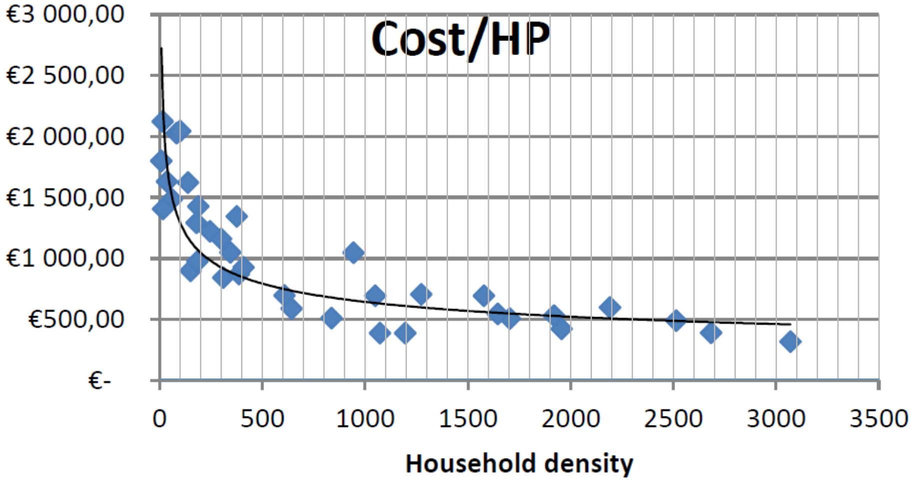
[40] 5GAA TRS-200127 Working Group Standards and Spectrum Study of spectrum needs for safety related intelligent transport systems, page 5.

Appendix G: **Comparing the cost of FTHH and 5G FWA in Europe**

The cost of bringing fibre to households varies considerably with household density. Areas with a population density below 300 per km^2 equivalent to a household density of 125 per km^2, are considered rural. The FTTH Council Europe cost study provides insight into the cost of bringing fibre to rural households:

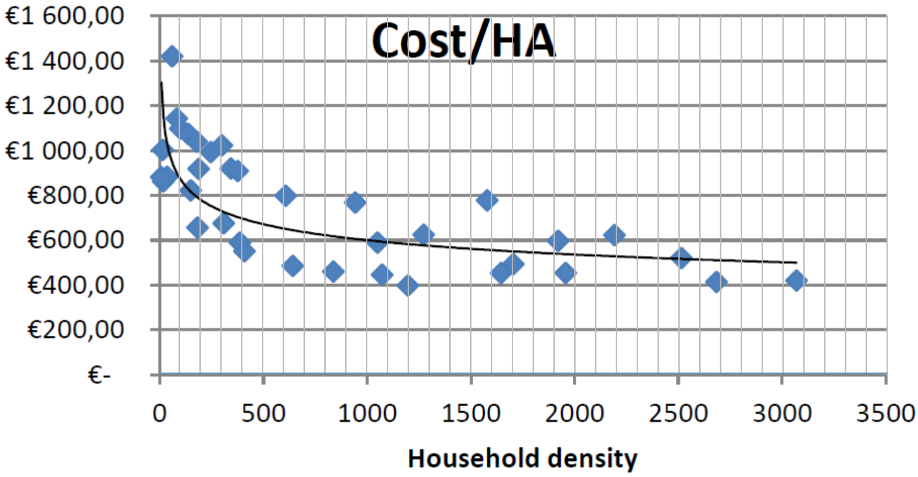
- In areas with a household density of 100 to 200 per km^2, the cost per household passed is €1,000 to €1,500 based on modelling by the FTTH Council Europe (see Exhibit 51). The additional cost to activate the connection per household amounts to circa €800 (see Exhibit 52). On this basis the average cost of connecting a rural household with FTTH amounts to circa €2,000 (see Exhibit 54).
- To examine the cost of connecting isolated homes, the FTTH Council Europe study breaks down the cost into areas where 95% of households are located and where the remaining 5% are. For the 5% of households in the least dense areas, the cost per connected household is estimated at €7,000.

Exhibit 51: Fibre cost per home passed



Source: The Cost of Meeting Europe's Future Network Needs, FTTH Council Europe, 3/2017

Exhibit 52: Fibre activation cost per home



Source: The Cost of Meeting Europe's Future Network Needs, FTTH Council Europe, 3/2017

We calculated the cost per household to bring 100 Mbit/s DL connectivity using 5G FWA using the following assumptions:

- Where mobile coverage already exists, incremental investment is required for the 5G radio but not the mast. We estimate the cost of adding mid-band radios to existing sites in rural areas at around €25,000. The number of radios required will depend on the instantaneous bandwidth (IBW) accommodated by the radio (typ. 300-400 MHz) as well as the possibility to access contiguous spectrum. For example, in the event that 2,000 MHz of additional spectrum is made available (2400 MHz in total), and assuming an IBW of 300 MHz, then up to eight radios may be required on the cell tower.
- Civil works may amount to €20,000 per site.
- Depending on whether the site is already connected by fibre or whether fibre is required, this may add a further €10,000 to the cost. The figure of €7,000 is quoted in the FTTH Council Europe study as the cost per FTTH home connected in a remote location.
- The cost per home connected using a self-installed CPE is in the order to of €250.
- The number of households that can be supported at different speeds is a function of the amount of spectrum deployed on an FWA site.

Exhibit 53: Rural FWA cost assumptions

	Baseline	+ 1 GHz	+2 GHz
MHz of spectrum for FWA	400	1,400	2,400
Number of radios per site	2	5	8
MHz per radio	200	280	300
Radio cost per site - €	50,000	125,000	200,000
Fibre cost per site - €	10,000	10,000	10,000
Civil works cost - €	20,000	20,000	20,000
Total cost per site - €	80,000	155,000	230,000

Source: Coleago Consulting

Exhibit 55 below summarises the result of the FWA cost modelling. Using only the baseline spectrum, the investment cost per household to reach the 100 Mbit/s target is €889. However, if an additional 2 GHz of upper mid-band spectrum is used, the cost per household decreases to €426, which is 79% lower compared to the €2,000 cost using FTTH as shown in Exhibit 56.

If, in the longer term, a speed of 1 Gbit/s is required, the cost per household passed using FWA in an additional 2 GHz of mid-band spectrum is higher than using fibre, and high bands become crucial.

Exhibit 54: Cost per rural household connected using FTTH

FTTH Connectivity	Cost per home passed	Cost per home connected	Total FTTH cost per home
Investment per home	€ 1,000 to 1,500	€ 800	Circa € 2,000

Source: Coleago estimates based on The Cost of Meeting Europe's Future Network Needs, FTTH Council Europe, 3/2017

Exhibit 55: Cost per rural household covered using FWA

	Base Line	Plus 1 GHz	Plus 2 GHz
Households supported @ 100 Mbit/s	90	315	540
Households supported @ 150 Mbit/s	60	210	360
Households supported @ 300 Mbit/s	30	105	180
Households supported @ 1 Gbit/s	9	32	54
Cost per household covered @ 100 Mbit/s - €	889	492	426
Cost per household covered @ 150 Mbit/s - €	1,333	738	639
Cost per household covered @ 300 Mbit/s - €	2,667	1,476	1,278
Cost per household covered @ 1 Gbit/s - €	8,889	4,921	4,259

Source: Coleago Consulting

Exhibit 56: FWA deployment cost saving vs. FTTH in rural areas

Relative cost difference FWA vs FTTH	Base Line	Plus 1 GHz	Plus 2 GHz
Cost per household covered @ 100 Mbit/s	56%	75%	79%
Cost per household covered @ 150 Mbit/s	33%	63%	68%
Cost per household covered @ 300 Mbit/s	-33%	26%	36%
Cost per household covered @ 1 Gbit/s	-344%	-146%	-113%

Source: Coleago Consulting

Based on the above data, we can calculate the reduction in the investment required to reach the European Commission's target of covering 100% of households with a broadband speed of at least 100 Mbit/s. As indicated earlier, the total investment required to cover 100% of households in the EU with FTTH is estimated at €123 billion. An estimated €53 billion of this investment needs to be made in rural areas.

Exhibit 56 shows the investment cost savings if FWA instead of FTTH is used to bring 100 Mbit/s connectivity to rural households.

- For an additional 2GHz of spectrum, an investment saving of 79% on €53 billion amounts to €42 billion. 5G IMT has a capital expenditure avoidance value of €42 billion, for FWA alone, i.e., not counting the capex avoidance value for mobile 5G.
- If only 1 GHz of additional mid-band spectrum is made available, the investment cost saving is 75% amounting to €40 billion.

Although providing rural coverage using FWA is much cheaper compared to FTTH, in most rural locations there will be no business case to provide 100 Mbit/s or higher speeds. This means the €42 billion saving is a reduction in the subsidies and not an indication that 100 Mbit/s FWA might be turned into a spectrum licence obligation.

In assessing the cost savings of FWA in upper mid-bands vs. FTTH we have not added in any spectrum licence fees. The reason for this is our objective to calculate the difference in the network investments comparing FWA with the FTTH solution. This would translate into real savings in public subsidies regardless of whether there is any cost of spectrum.

Appendix H: **Small Cell Densification Calculations**

We have completed an illustrative analysis of the number of additional small cells needed to deliver the citywide capacity required for 5G should additional upper mid-band spectrum not be available. This analysis is illustrative in that it is only intended to show the potential magnitude of the issue. As such, several caveats apply:

- The analysis is based on the thesis that the macro cell density (i.e., given by the assumed 400 meter inter-site distance) is already at (or approaching) the densest it can be, limited by needing to manage interference and by the difficulty in finding new sites in many cities. Hence any additional sites are assumed to be outdoor small cells.
- Potential interference issues between macro cells and outdoor small cells, and between small cells themselves, are discounted as we are simply seeking to understand the potential magnitude of the issue.
- Only the downlink requirement / spectrum need has been examined. If the additional spectrum needed to address uplink requirements is also considered then the number of additional small cells may be higher.
- Any additional outdoor small cells use upper mid-band TDD spectrum in the same manner as our previous calculations – with the same sector numbers, spectral efficiencies, loading factors and TDD duplexing ratio leading to an overall downlink throughput of 2.4 b/s/Hz per outdoor small cell.

The foundation of our analysis is the amount of additional spectrum that is needed to satisfy demand – and an assumption that this is not met. We have presented a range of values for each of the cities in our report and have chosen mid-point values for the specific example cities considered in our densification analysis. However, a more general case is to propose several incremental values of additional spectrum need which are not met: 500 MHz, 1,000 MHz, 1,500 MHz and 2,000 MHz.

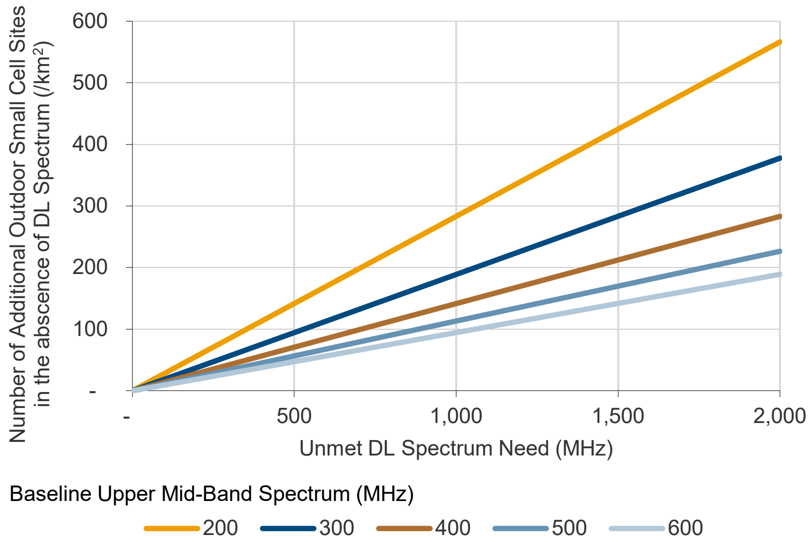
If these additional spectrum requirements are not met then there is an associated amount of demand that remains unsatisfied by the baseline of macro cells (400m-spaced) and outdoor small cells (3 per macro). Our spectrum model shows that the capacity of these baseline sites, with respect to mid band spectrum, is 133.6 Mbit/s/km^2/MHz. This capacity is calculated from the density of sites (per km^2) and the various mid band site parameters assumed for macro and outdoor small cell sites (sector numbers, spectral efficiencies, loading factors and TDD duplexing ratio). The unmet demand associated with each above increment of spectrum is therefore: 66,803 Mbit/s/km^2, 133,606 Mbit/s/km^2, 200,409 Mbit/s/km^2 and 267,212 Mbit/s/km^2.

The number of additional small outdoor small cells to meet this unmet demand will vary by city due to the differing existing mid band spectrum allocations available. A general case is therefore to propose several incremental values for existing spectrum availability: 200 MHz, 300 MHz, 400 MHz, 500 MHz and 600 MHz.

The capacity delivered by each additional small cell is simply the earlier outdoor small cell spectral efficiency (2.4 b/s/Hz) multiplied by each of these incremental spectrum values – leading to capacities of: 472 Mbit/s, 708 Mbit/s, 944 Mbit/s, 1,179 Mbit/s and 1,415 Mbit/s respectively.

The number of small cells needed for each combination of unmet demand and additional small cell capacity can then be calculated by division of one by the other. This delivers the curves shown inExhibit 20– showing the number of additional outdoor small cells needed, per square kilometre, to deliver 100 Mbit/s citywide downlink speed coverage if a given calculated additional mid-band spectrum need cannot be provided.

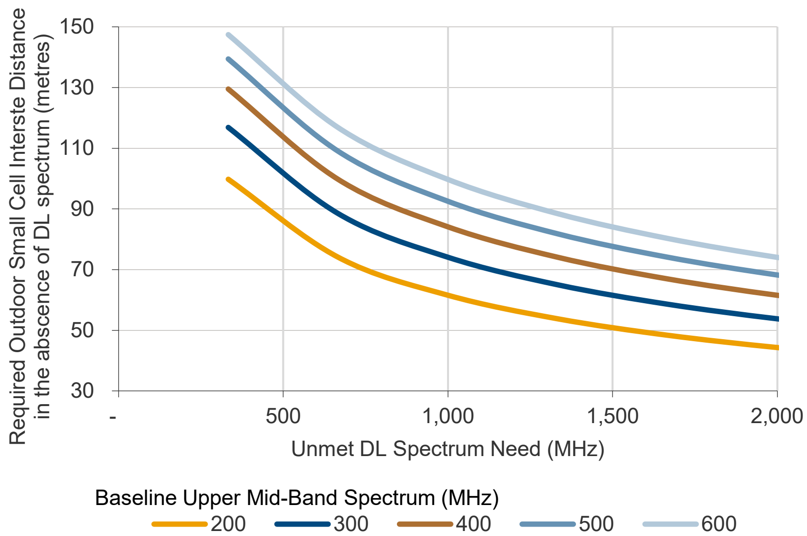
Exhibit 57: Additional outdoor small cells vs. unmet DL spectrum need



Source: Coleago

As these figures are on a per square kilometre basis, they can easily be converted to a small cell inter-site distance. However, before undertaking this calculation, it is important to also add in the baseline small cell density assumed (of 3 small cell per macro). Once this is done, the curves can be calculated. These curves show the resulting small cell inter-site distance if a given calculated additional mid-band spectrum need cannot be provided.

Exhibit 58: Small cell inter-site distance vs. unmet DL spectrum need



Source: Coleago

For more information, please visit the GSMA website at www.gsma.com

GSMA HEAD OFFICE
Floor 2
The Walbrook Building
25 Walbrook
London EC4N 8AF
United Kingdom
Tel: +44 (0)20 7356 0600
Fax: +44 (0)20 7356 0601