GSMA Intelligence

The economics of mmWave 5G

An assessment of total cost of ownership in the period to 2025

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Executive summary

5G is now a commercial reality. Despite the Covid-19 pandemic, adoption of 5G will reach 200 million connections by the end of 2020; this is forecast to grow to more than 1 billion connections by the end of 2023 and nearly 2 billion globally by the end of 2025. 5G can deliver 10× faster data rates and 100× more capacity, at latencies up to 10× shorter, compared to 4G networks, allowing it to handle growing mobile data traffic. The 5G opportunity for enterprise digital transformation is massive and includes industrial applications, automotive, robotics and healthcare, to cite a few examples. But 5G will also have a profound impact on consumers. It will enable higher-quality services, such as in video streaming and video conferencing, the possibility of fast home broadband services through fixed wireless access (FWA), and new consumer and business services such as edge computing and augmented and virtual reality (AR/VR).

In this study, we evaluate the cost effectiveness of deploying millimetre wave (mmWave) 5G solutions in six different scenarios, including dense urban areas, FWA and indoor deployments. The results have clear implications for all actors in the mobile ecosystem. Operators that underestimate the role of mmWave in the short term run the risk of finding themselves at a disadvantage to competitors when offering 5G services. Governments looking to capitalise on 5G as a catalyst of economic growth need to make clear plans for the assignment of mmWave bands to mobile services. As broader economic benefits are realised and mmWave 5G solutions achieve greater scale, a wider choice of consumer devices and equipment is poised to further reduce deployment costs, increase the choice of affordable devices available and facilitate greater adoption.

Most 5G launches globally so far have relied on mid-band spectrum, with very few exceptions. But as adoption increases and more consumers and diverse services migrate to 5G networks, these will need spectrum across low (e.g. 700 MHz), mid (e.g. 3.5 GHz) and high (e.g. mmWave) bands in order to deliver enough capacity to support the full 5G experience. In particular, due to the massive spectral bandwidth available, mmWave bands are key to meeting high traffic demand and at the same time maintaining the performance and quality requirements of 5G services. So far, mobile operator bids in auctions for mmWave bands have not been as high as for lower frequency bands. This means that mmWave bands are at present generally cheaper in $/MHz/pop terms.

Despite its potential, the utilisation of mmWave in mobile has had to overcome major technical challenges: mmWave signals travel relatively short distances compared to signals of lower-frequency bands; can be susceptible to attenuation from trees and other obstacles; and have difficulties in penetrating concrete building walls (often necessary to reach indoors). However, the continued growth of mobile data traffic plays to the strengths of mmWave bands, as mmWave can accommodate more capacity and bandwidth than any other band.

While commercial mmWave 5G networks have already been launched in three countries as of the end of Q3 2020 (US, Japan and South Africa),[1] mmWave 5G solutions are poised to achieve more scale.

Two important signs of market readiness are as follows:

- **mmWave spectrum is now becoming more widely available.** Countries such as the US, Italy, Finland, Japan and South Korea have already released mmWave spectrum for 5G, and a number of other countries are about to follow suit. This is particularly remarkable considering that mmWave spectrum was only internationally allocated to mobile services at the recent World Radiocommunication Conference in November 2019 (WRC-19).
- **A sufficiently wide choice of consumer devices and equipment.** Reliable network solutions are already available today, with almost all tier-1 and tier-2 equipment vendors offering mmWave equipment products as part of their portfolio of solutions to mobile operators. Consumer devices in particular have recently seen remarkable growth, with the launch of the new mmWave-capable iPhone 12 series in 2020 giving a boost to the wider adoption of the technology. While only a few mmWave handsets and FWA customer premise equipment units (CPEs) were available in 2019, consumers can expect more than 100 mmWave 5G handsets and more than 50 FWA CPEs to be available in 2021.

As 5G rollouts and adoption progress quickly, and with the mmWave ecosystem showing signs of readiness, the main question that the mobile industry faces today is where and when mmWave solutions can be cost effective. In this report, we focus on the critical question of its deployment costs.

We identify a range of scenarios where the high throughput and network capacity of mmWave, both downlink and uplink, can lead to cost-effective targeted deployments in the period between now and 2025. We then explore and dissect the conditions under which these deployments could be cost effective. In particular, we evaluate the cost effectiveness of deploying mmWave 5G solutions in six different scenarios:

- Two scenarios consider the deployment of outdoor sites in a hypothetical dense urban area in Greater China and Europe.
- Three scenarios consider the deployment of FWA in a hypothetical urban area in China, suburban area in Europe and a rural town in the US.
- One scenario considers the deployment in a hypothetical enterprise office space.

1 Since then, a mmWave 5G network has been launched in Italy and a launch has been announced in Singapore.

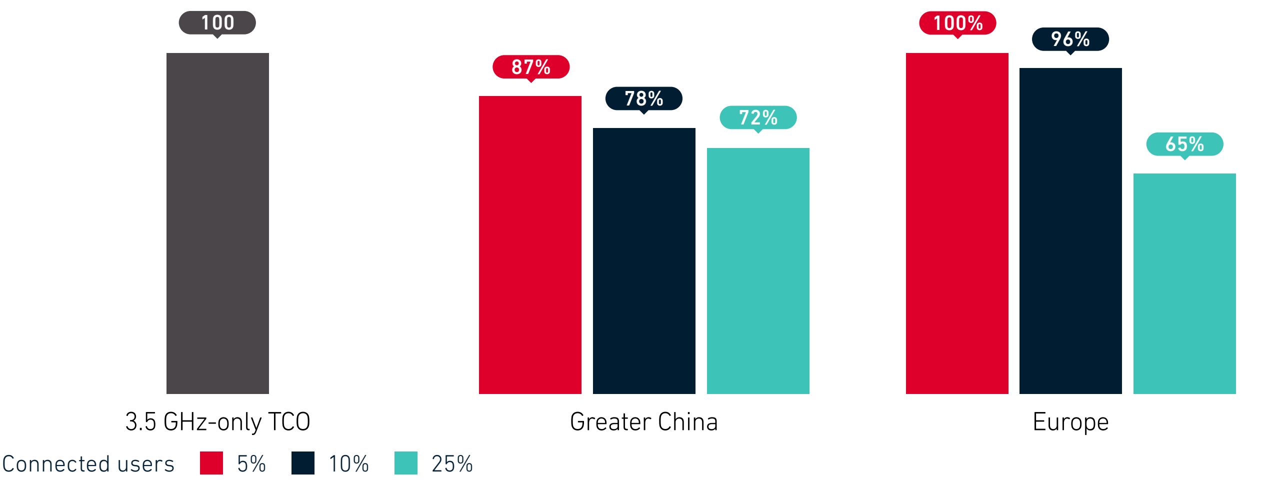
The modelling exercise shows the following:

- **Dense urban scenarios (Greater China and Europe):** We find that a mixed 3.5 GHz and mmWave network can be cost effective in delivering at least 100 Mbps download speeds for 5G services in this period, when compared to a 3.5 GHz-only network. As soon as mmWave spectrum becomes available in Greater China and large-scale deployments take place, we estimate that deploying mmWave solutions to deliver this additional capacity layer could bring cost efficiencies, compared to the use of only 3.5 GHz in central scenarios. This is assuming the percentage of connected users is above 5% at the peak demand hour and that 800 MHz of mmWave and 100 MHz of 3.5 GHz spectrum are available per operator. In Europe, assuming that 400 MHz of mmWave and 80 MHz of 3.5 GHz spectrum are available per operator, we estimate that a mixed 3.5 GHz and mmWave 5G solution could be cost effective if the percentage of connected users at peak in the area is 10% or above in central scenarios.

Figure i

Net present value (NPV) of total cost of ownership (TCO) for a 3.5 GHz plus mmWave 5G network

Base 100: 3.5 GHz-only TCO



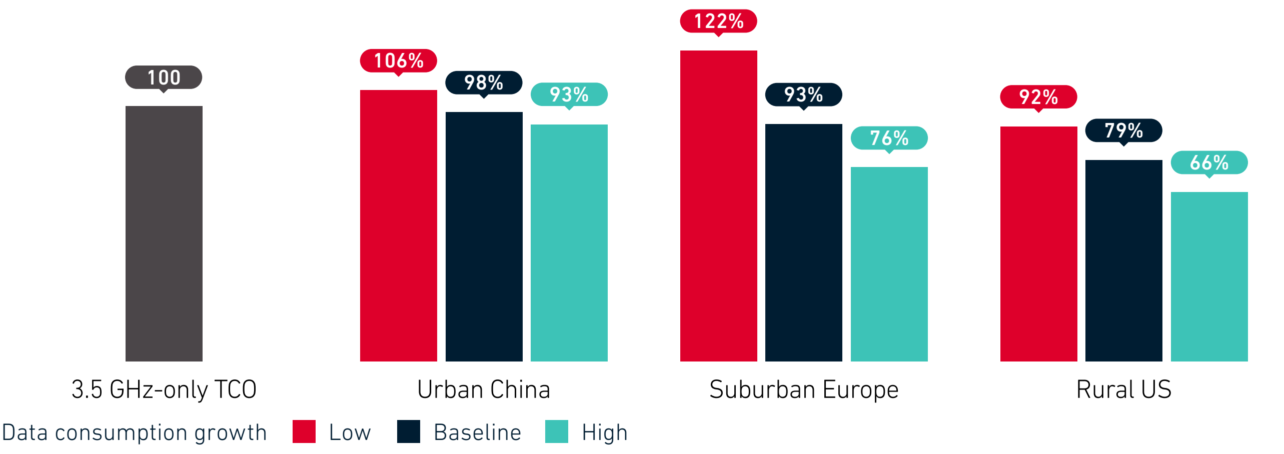
Source: GSMA Intelligence

- **FWA scenarios:** Deploying a 5G FWA network using mmWave spectrum can also be cost effective in this period when compared to a 3.5 GHz 5G FWA network. The cost effectiveness of mmWave networks is sensitive to assumptions on traffic demand and the ratio of uplink to downlink traffic. Under central assumptions, mmWave FWA deployments in urban China, suburban Europe and a rural US town are a cost-effective strategy if 5G FWA is able to capture a good percentage of the residential broadband market demand (see Figure ii). The results are particularly sensitive to overall traffic demand and the share of downlink and uplink in total traffic at the peak demand hour. For example, fast growth in the share of uplink in total traffic during the period would result in a material increase in the cost savings from deploying a mmWave-only FWA network when compared to a 3.5 GHz-only FWA network. An alternative scenario where mmWave is used as a capacity layer alongside a 3.5 GHz coverage layer is also a possible deployment strategy for 5G FWA. Our sensitivity analysis shows that the cost savings could be greater in this case: 16% in urban China, 15% in suburban Europe and 27% in a rural US town for the baseline sensitivity case, compared to a 3.5 GHz-only network (see Figure 12). The validity of the assumptions underlying this sensitivity will vary for different cases though, as the results are only valid where capacity gaps emerge in a few localised spots in the area.

Figure ii

NPV of TCO for a mmWave FWA network

Base 100: 3.5 GHz-only TCO



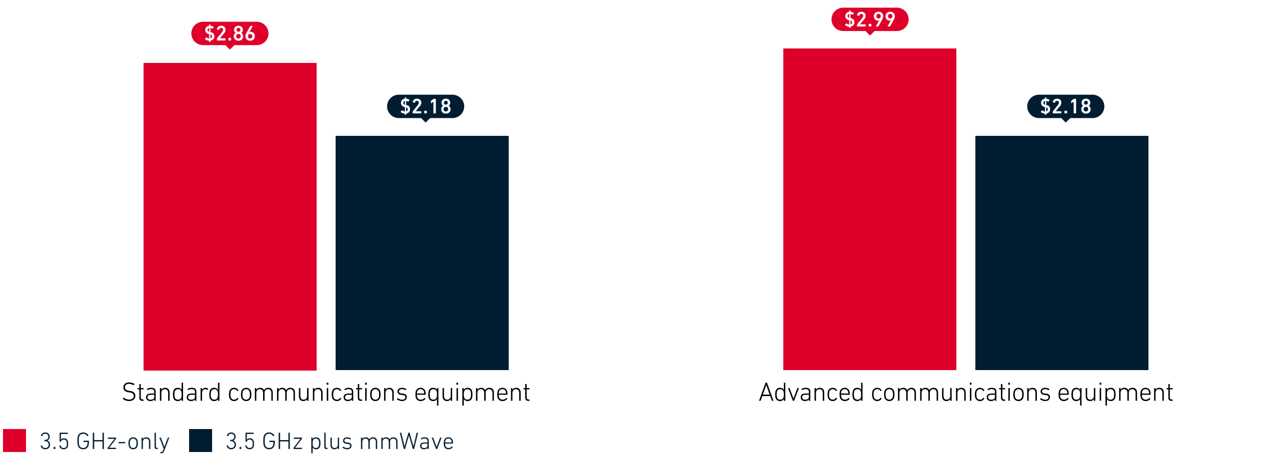
Source: GSMA Intelligence

- **Indoor office scenario:** On central assumptions a mmWave indoor 5G network is cost effective and generates cost savings for operators between 5% and 20%. We also find that when a significant share of data traffic from devices is supported by indoor 5G services, a mmWave network could generate cost savings of up to 54%. The precise value in the range depends on the share of devices concurrently active and on whether and to what extent there is the need to provide connectivity to next-generation video communications equipment.

Figure iii

Cost per square metre in an indoor office space scenario

TCO per square metre (USD)



Source: GSMA Intelligence

While our TCO analysis looks at the period to 2025, we expect mmWave 5G deployments to further accelerate in the second half of the decade as equipment and devices with higher performance and lower costs proliferate. By 2030, we estimate that 5G will generate an annual boost to global GDP of 0.6%, adding approximately $600 billion annually to the global economy,[2] with mmWave playing an increasingly important role in the delivery of these benefits. mmWave solutions will therefore be key to 5G deployments, both in the short and longer term.

2 Mobile Technology and Economic Growth, GSMA, 2020

1 Entering the 5G era: the role of mmWave

5G services are now a reality

At the end of Q3 2020, 107 operators in 47 markets had launched commercial 5G services, including both mobile and FWA. Adoption is growing quickly, with around 135 million connections[3] registered by mobile operators worldwide at the end of Q3 2020, a number that we expect to reach almost 235 million by the end of 2020. By 2025, we project nearly 2 billion global 5G connections (see Figure 1).

3 5G unique SIM cards (or phone numbers, where SIM cards are not used) that have been registered on the mobile network at the end of the period.

Figure 1

5G at a glance: global outlook, Q3 2020

	In Q3 2020	To end of Q3 2020	Q4 2020	2020	2025
Spectrum auctions	NLD, USA, 3 others	121 operators** in 35 markets	USA, GRC, ARE, 4 others	44 countries completed auctions	
Trials	17 trials, 2 new operators	217 operators** in 100 markets			
Commercial launches*	18 operators in 13 markets	107 operators in 47 markets	LUX, FRA	149 operators in 57 markets	410 operators in 123 markets
Adoption		135 million connections	234 million connections	234 million connections (3% adoption)	1.8 billion connections (21% adoption)

*Launches of commercial mobile and FWA 5G services **Excludes regional US and Canadian operators For updates, see gsmaintelligence.com
Source: GSMA Intelligence

While operators all over the world have either launched or have firm plans to launch 5G services (see Figure 1), most of the initial launches and growth in adoption in the next few years will be accounted for by North America, Europe and Asia Pacific, where China will play a central role. These three regions will represent 90% of 5G mobile connections forecast globally by 2025, with North America representing 218 million 5G connections (of which 200 million connections will be in the US), Asia Pacific representing 1.2 billion 5G connections (of which 800 million connections will be in China) and Europe representing 233 million 5G connections. In order to accommodate this rapid growth in adoption, operators are investing heavily in 5G networks. In the period 2020–2025, operators globally are expected to invest $1.1 trillion in networks, of which nearly 80% will be on 5G.

The Covid-19 pandemic has highlighted the robustness and resilience of mobile networks as it has accelerated the digitisation of many activities and the reliance on mobile communications and video streaming. This will likely generate an even greater demand for advanced mobile services in the medium term. According to Ericsson, mobile data traffic will grow by around 30% annually between 2019 and 2025. 5G networks will play a critical role in delivering the networks and capacity to meet that demand. 5G can deliver between 10× faster data rates and 100× more capacity, at signal response times up to 10× shorter, compared to 4G networks, allowing it to handle growing mobile data traffic. This will enable higher-quality services, such as in video streaming and video conferencing, the possibility of fast home broadband services through FWA, and new consumer and business services such as edge computing and AR/VR.

5G networks need low-, mid- and high-band spectrum

Most 5G launches globally so far have relied on 3.5 GHz spectrum, with very few exceptions. This is because the initial services and adoption required bandwidth and speeds that can be adequately supported by this type of spectrum. But as adoption increases and more consumers and diverse services migrate to 5G networks, these will need spectrum across low, mid and high bands in order to deliver widespread coverage and enough capacity to support the delivery of 5G.

All three spectrum band ranges have important roles to play in offering 5G services. Low-band spectrum (sub-1 GHz) supports widespread coverage across urban, suburban and rural areas and helps support IoT services. 5G services will struggle to reach beyond urban centres and deep inside buildings without this spectrum. Mid-band spectrum (1–6 GHz) typically offers a good mix of coverage and capacity benefits. The majority of commercial 5G networks so far are relying on spectrum within the 3.3–3.8 GHz range. Other mid-band spectrum that may be assigned to, or refarmed by, operators for 5G, includes 1800 MHz, 2100 MHz, 2.3 GHz and 2.6 GHz.

Because of the massive amount of spectrum that they can offer, mmWave bands (24 GHz and above) will be crucial to meet high traffic demand at high network speeds to maintain the performance and quality requirements of 5G services. In particular, mmWave can be a robust solution for meeting demand for enhanced mobile data services as well as new use cases that would be challenging or very costly to deliver using alternative spectrum. Currently, 26, 28 and 40 GHz have the most international support and momentum. In 2019, the World Radiocommunication Conference (WRC-19) revised the international treaty that governs the use of spectrum frequencies to include several mmWave frequency bands for use in 5G mobile services, with around 17 GHz of spectrum identified in total globally or regionally for 5G in the 26 GHz (24.25–27.5 GHz), 40 GHz (37–43.5 GHz), 50 GHz (45.5–47 GHz and 47.2–48.2 GHz) and 66 GHz (66–71 GHz) ranges.

The pros and cons of mmWave

Despite its potential, the utilisation of mmWave for mobile has had to overcome major technical challenges: mmWave signals travel relatively short distances; can be susceptible to attenuation from trees and other obstacles; and have difficulties in penetrating through material, in particular concrete but also glass and wood. This means that they may not be a good solution for reaching indoors or dealing with severe obstacles. These challenges differ considerably to those that the mobile industry has had to deal with in previous generations of mobile networks and have led to some concerns about the potential for mmWave 5G in the short term.

However, as mobile data traffic continues to grow rapidly, with demand for higher data rates to serve new applications along with a potential need for more uplink capacity, the need for mmWave bands is only becoming more apparent. mmWave bands can accommodate more capacity and bandwidth than any other band. And since spectrum in these bands is abundant, mmWave spectrum is ideally placed to deliver high speeds, low latency and high capacity, all at the same time. The short wavelength of mmWave allows for very small antennas, which helps with beam forming for enhanced coverage and spectral efficiency. mmWave can also be a good solution indoors where the propagation characteristics become an advantage to avoid inter-cell interference. For the industry, the main question is where and when these solutions will be cost effective – which this report addresses.

Can mmWave be cost effective?

We look at the critical question of deployment costs in depth in section 3. We identify a range of scenarios where the short range and high throughput and capacity of mmWave could lead to targeted deployments in the period to 2025, and we explore and dissect the conditions under which these deployments could be cost effective. Three scenarios are modelled in detail: A) the use of mmWave to provide additional capacity in dense urban areas; B) providing home broadband through FWA; and C) an indoor solution that can accommodate high traffic demand in an office space.

While commercial mmWave 5G networks have already been successfully launched in some countries, mmWave 5G solutions need to achieve more scale to reduce deployment costs, increase the choice of affordable devices available and facilitate greater adoption. The scale that any technology solution reaches is critical to determining its success and adoption. As we discuss in section 2, momentum for mmWave is building across the three areas that are needed for any 5G band to gain the necessary scale and adoption: spectrum availability, a sufficient choice of consumer devices, and reliable and cost-effective network equipment. This should help inform mobile operators' considerations of the role that mmWave will play a role in their deployments and when to initiate or accelerate investments in the technology.

2 Ecosystem readiness for 5G mmWave solutions

Spectrum, devices and equipment are vital to achieve the necessary scale

In mobile communications, the scale that any technology solution reaches is critical. Because of the existence of significant economies of scale and the need for interoperability for networks and devices, greater scale can reduce deployment costs and increase the number of affordable devices available, facilitating greater overall adoption.

Three main conditions are needed for any specific 5G spectrum band to achieve scale and provide the benefits of low costs and wide availability to all stakeholders in the 5G ecosystem:

1. Sufficient spectrum in globally harmonised bands needs to be available for a given band across a significant number of countries.
2. Consumers need to have a broad choice of affordable devices that support the band to stimulate consumer demand and achieve economies of scope and scale in the production and manufacturing of handsets and other devices connected to mobile networks, such as CPEs or hotspots.
3. A wide set of competitive network equipment options needs to be available to facilitate the technological and economic case for mobile operators to roll out networks using a specific band.

The 3.5 GHz band is clearly emerging as the most commonly used frequency across most markets currently deploying 5G. However, the readiness of the ecosystem for mmWave 5G is rapidly catching up, as we illustrate in this section.

5G spectrum is required across multiple bands

As 5G is ultimately fuelled by low-, mid- and high-band spectrum, operators in different countries will make network investment decisions based on the spectrum that is available. The different bands support different features and functions, with mmWave generally powering applications that benefit from speed or high traffic volumes in a localised area. However, as more spectrum becomes available, the new bands available for mobile services will complement existing ones by providing the capacity or coverage required.

As of Q3 2020, new spectrum for mobile services specifically earmarked for 5G had been assigned in 35 markets. 121 operators had received spectrum across low, mid and high bands to date (excluding US and Canadian regional operators): 48 operators in low band; 91 operators in mid band; and 35 operators in high band.

Figure 2

5G spectrum assignments pipeline by frequency range

	Up to Q1 2020	Q2 2020	Q3 2020	Q4 2020	Q1 2021+*
<1 GHz	DNK, DEU, FRA, FIN, 8 others		AUT, LUX, ISR, NLD	PRT, GRC	GBR, IRL, CZE, IND, ROU, ESP
1–6 GHz	HKG, TWN, KOR, OMN, 19 others	NZL, SGP	NLD, LUX, AUT, USA, ISR	SWE, GRC, PRT, FRA, CHL, USA	GBR, BRA, CZE, THA, ROU
>6 GHz	THA, USA, TWN, HKG, 3 others	FIN, SGP		GRC, CHL, ARE	BRA, AUS

*Q1 2021+ data not exhaustive; preference by date
Source: GSMA Intelligence

26 countries have already assigned spectrum in the 3.5 GHz band. Meanwhile, a more limited number of markets have released mmWave spectrum for 5G as of October 2020: the US, Finland, Hong Kong, Italy, Japan, South Korea, Taiwan, Singapore, Russia and Thailand. However, more countries have already announced plans to release spectrum in mmWave bands soon: the UAE, Australia, Malaysia, Denmark, Norway, Luxembourg and Slovenia. It is important to note that mmWave spectrum was only allocated for mobile services at the recent World Radiocommunication Conference in November 2019 (WRC-19), while the 3.5 GHz band had already been identified in some regions as early as 2007. So far, mobile operator bids in auctions for mmWave bands have not been as high as for lower-frequency bands. This means that mmWave bands are at present generally cheaper in $/MHz/pop terms.

Another important indication of the readiness of a particular spectrum band is the number of trials that has been conducted on it. In 2020, the overall number of trials in all spectrum bands reduced compared to in 2019 because of the Covid-19 crisis. However, mmWave trials as a share of trials on all spectrum bands increased slightly from 9% in 2019 to 13% in 2020. The overall number of trials in mmWave bands now exceeds 100,[4] demonstrating that the technology is reaching a mature stage.

US: leading the development of the mmWave ecosystem

The US market is a global leader in the use of mmWave spectrum for 5G, with all major US operators already offering commercial 5G services using the band. This has been driven by the Federal Communications Commission (FCC) making mmWave spectrum available for mobile services earlier than in most countries, making it a good option for mobile operators that want to make use of the ultra-high speed, low latency and high capacity of these spectrum bands.

Table 1

mmWave spectrum assignments in the US

Band*	Date	Amount (MHz)
28 GHz	January 2019	850
24 GHz	May 2019	700
37 GHz	March 2020	1000
39 GHz	March 2020	1400
47 GHz	March 2020	1000

*Previous assignments of mmWave spectrum and secondary market transactions are also relevant for 5G, as spectrum licences are technology neutral in the US
Source: GSMA Intelligence

4 116 trials on mmWave bands have been conducted globally as of Q3 2020.

China: gearing up for mmWave, with deployments firmly planned for the 2022 Winter Olympics

Unlike the US, China has yet to make mmWave spectrum available to operators for commercial deployments. Current 5G bands in China are mid-band (2.6, 3.3, 3.5 and 4.9 GHz) and low band (700 MHz).

China's Ministry of Industry and Information Technology (MIIT) is reportedly exploring mmWave for 5G in the 26 GHz band (24.75–27.5 GHz). While there is no set timeline for the allocation to operators yet, there is recognition that mmWave spectrum will have a significant impact on the country's 5G opportunity. In the meantime, China Mobile, China Unicom and China Telecom are conducting trials and building pilot networks using 26 GHz, in preparation for a large-scale demonstration of mmWave 5G at the Beijing Winter Olympics in 2022.

Europe: not many mmWave assignments yet, but momentum is building

In Europe, the focus to date has been on the 3.5 GHz band, with 12 countries that have already assigned frequencies and 34 mobile networks that are making use of the band. As of the end of Q3, only two countries had assigned mmWave spectrum[5] and no operators had launched commercial 5G networks using mmWave spectrum in Europe.

However, the EU is taking significant steps to promote availability of new spectrum bands for 5G, including mmWave. This is likely to increase and accelerate the number of 5G mmWave deployments in the near future. In May 2019, the European Commission adopted an implementing decision to harmonise radio spectrum in the 24.25–27.5 GHz (26 GHz) band that enables member states to set common technical conditions for use of the band. Regulators in the member states have also been mandated to award at least 1 GHz of spectrum in the 26 GHz band for mobile use by 31 December 2020. Although most regulators will not meet this ambitious deadline and the Covid-19 pandemic may further slow the process, many countries in Europe are already consulting on the release of this spectrum (e.g. Sweden, France, Germany, Netherlands). In an additional effort to further accelerate deployment of 5G networks across the EU, in June 2020 the European Commission adopted an implementing regulation on small-area wireless access points (small cells). The new regulation specifies the physical and technical characteristics of 5G small cells, which will be exempt from any individual planning permission requirements. Small cells are crucial for the timely deployment of 5G networks that can deliver high capacity and increased coverage as well as advanced connection speeds.

5 Greece has now also assigned mmWave spectrum.

In other regions, mmWave spectrum licensing conditions are diverse

There is a lot of variation in the amount of mmWave spectrum awarded to mobile operators: for example, Italy released just 1000 MHz of spectrum in the 26 GHz band, while in Singapore mobile operators already have access to more than three times that amount of spectrum in the same band.

Currently, there are seven operators that have already launched commercial 5G networks using mmWave bands: NTT Docomo and Rakuten (Japan); MTN (South Africa); Asia Pacific Telecom (Taiwan); and AT&T, T-Mobile and Verizon (US). As the technology matures, the number of commercial networks launched using mmWave bands is expected to increase significantly in the next few years, with commercialisation expected soon in South Korea, Thailand and Hong Kong.

Table 2

Amount of spectrum assigned in mmWave bands per country as of Q3 2020

Country	Date	Band	Bandwidth
Korea	June 2018	28 GHz	2400 MHz
Italy	October 2018	26 GHz	1000 MHz
US	January 2019	28 GHz	850 MHz
Hong Kong	March 2019	28 GHz	1200 MHz
Japan	April 2019	28 GHz	1600 MHz
US	May 2019	24 GHz	700 MHz
Taiwan	January 2020	28 GHz	1600 MHz
Thailand	January 2020	26 GHz	2600 MHz
US	March 2020	37/39/47 GHz	3400 MHz
Singapore	April 2020	26 GHz	3200 MHz
Finland	June 2020	26 GHz	2400 MHz

Source: GSMA Intelligence

mmWave 5G consumer devices are becoming more widely available

A fair amount of scepticism surrounded the potential use of mmWave in mobile telecommunications until very recently. A number of mobile network operators successfully carried out field trials on mmWave services at the beginning of 2017 and vendors and OEMs started to develop 5G CPEs and network equipment. In October 2018, a leading operator in the US launched a commercial pre-5G FWA internet service in a few cities.

The growth in the number of available mmWave handsets and CPEs in these last few years has been remarkable. A few mmWave handsets and FWA CPEs were launched in 2019, and we expect that more than 30 handsets and 35 CPEs will be available by the end of 2020. Additionally, despite the uncertainty caused by the Covid-19 crisis and the potential economic downturn, the 5G mmWave device ecosystem is continuing to grow and expand. Consumers can expect more than 100 mmWave handsets and more than 50 FWA CPEs to be available in the market in 2021.

With scale comes lower prices for devices. In general, 5G device costs have already started to fall as scale economies are realised and the range of vendors supplying 5G devices grows. The use of global standardised variants of key smartphone components brings major benefits, as the increased scale in production and the need for fewer design teams outweigh certain higher upfront costs, such as the need to support multiple spectrum bands. The US market in particular is currently at the forefront in the availability of mmWave devices – with the new mmWave-capable iPhone 12 series a good example of that – giving an additional boost for wider adoption of the technology.

5G mmWave network equipment has experienced rapid technological progress

Today, all major tier-1 and tier-2 network equipment vendors are offering mmWave equipment products to mobile operators. This follows an intense initial phase of mmWave product development between 2017 and 2020, when most vendors focused on the development and testing of appropriate coverage and beam management[6] robustness. Most of the technical challenges were about beam failure recovery and coverage extension. Today, however, many of these challenges have been addressed and some of these new first-generation mmWave massive multiple-input multiple-output (MIMO) solutions can handle UEs[7] moving at high speeds of up to 100 km/h.

We expect that between 2020 and 2022, mmWave equipment will experience a significant cost reduction and incorporate marked technical and operational improvements – these include advanced beam management, higher peak rates, multi-user MIMO, higher effective isotropic radiated power (EIRP), lower noise-figure, and fronthaul sharing. In the longer term, new flexible solutions are expected to add more capacity when traffic grows and boost performance around a given cell. As more and more mmWave devices are used by consumers, new massive MIMOs will be able to handle progressively more UEs and rely on novel multi-user scheduling technologies.[8] 3GPP R16 specifications completed in 2020 include a number of improvements for mmWave operation, showing a concrete evolution path for the technology. Further, a wide range of products are expected to become available in various radio access network (RAN) split options.

6 Beam management harmonises multiple antennas and supports them to create directional transmissions that must accurately point at the receiving UEs.
7 User equipment
8 Multiple users can be scheduled simultaneously either in uplink or in downlink and successive interference cancellation is employed.

mmWave equipment categories

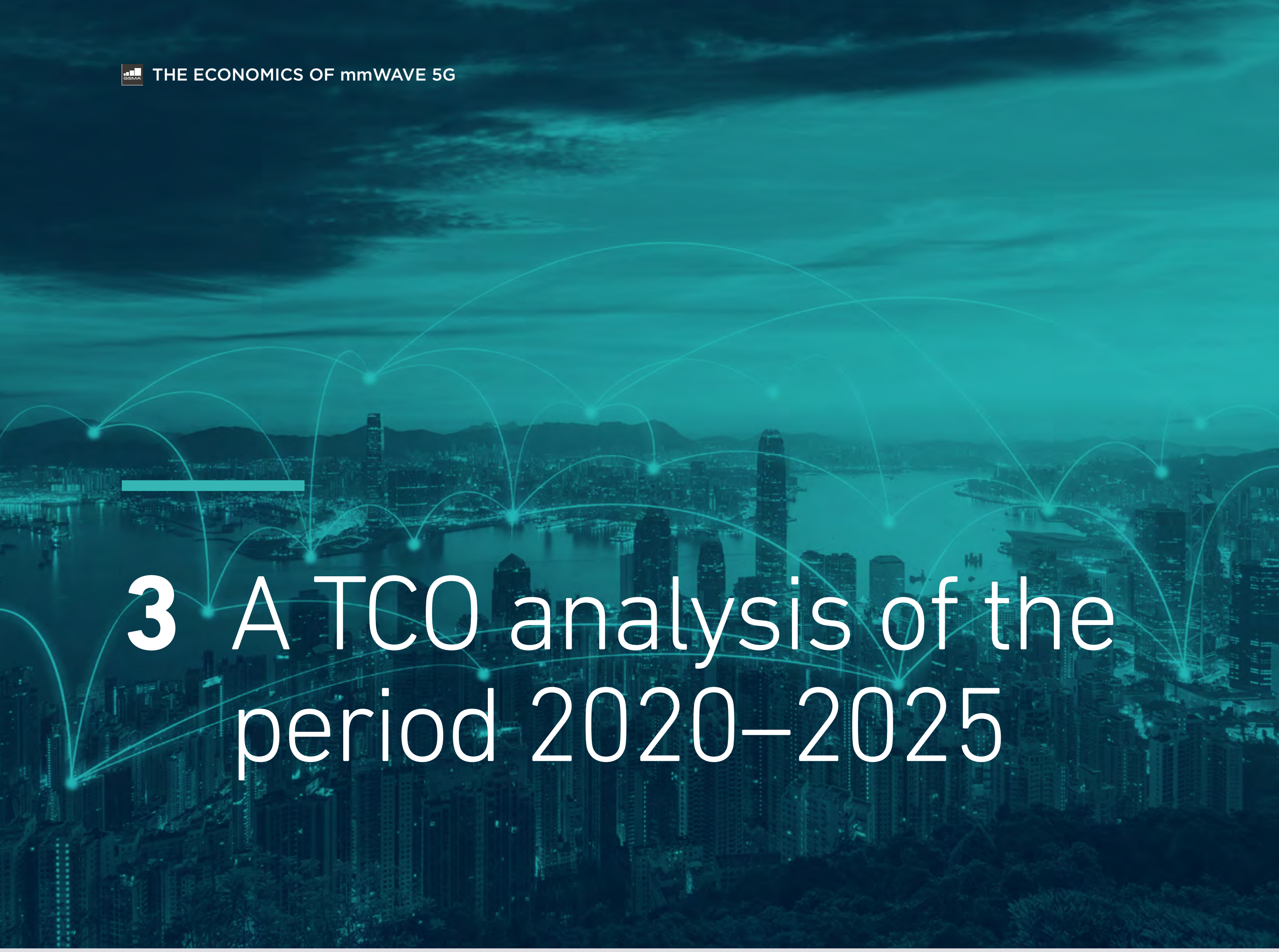
- **High-capacity macro site active antenna units (AAUs):** These active antenna units can provide enough capacity in densely populated areas for a large number of subscribers and are focused on spectrum between 24.25 and 29.5 GHz.
- **Microsites, lamp sites and pole sites:** Most of these serve the 26 GHz or the 28 GHz spectrum in a 2T2R 800 MHz or a 4T4R 400 MHz set-up. These compact and energy-efficient small cells help to provide coverage in outdoor hotspots.
- **Indoor 5G small cell solutions:** Vendors started to release indoor 5G small cells using mmWave to make sure operators can provide continuous 5G mmWave coverage. These small cells can ensure fibre-like speed in the mmWave spectrum with compact, lightweight equipment. Leveraging existing Ethernet cabling, and weighing less than 4 kg, they can generally be easily installed by one engineer.

The cost of mmWave equipment

Currently, mmWave radio-equipment infrastructure is more expensive relative to existing low-band and mid-band solutions. This is primarily because it is a newer technology and equipment vendors have not yet reached similar economies of scale in production. Bill of materials (BoM) costs are also a factor that currently add to this price differential. However, the cost gap between sub-6 GHz and mmWave solutions is decreasing and will continue to do so in the next few years.

There is much innovation around mmWave AAUs, with the ecosystem offering increasingly more affordable solutions. Newer equipment is expected to have purpose-designed mmWave radio-frequency integrated circuits (RFICs), lower energy consumption and a more compact design with lower wind load and smaller weight. Furthermore, higher EIRP should enable larger coverage areas and enhanced user throughput. The new mmWave AAUs will also rely more on natural cooling, and enhanced common public radio interface (eCRPI) used in the fronthaul transmission will reduce energy consumption. The vendor ecosystem has heavily focused on solutions that can further increase the cost effectiveness of mmWave network solutions.

As we explore in section 3, even with higher costs for the equipment in the short term, mmWave already has the potential to be a cost-effective solution across a range of deployment scenarios, since it is able to accommodate significantly higher bandwidth and traffic capacity than lower spectrum bands.



3 A TCO analysis of the period 2020–2025

In this section, we evaluate the cost effectiveness of deploying mmWave 5G solutions in six different scenarios where mmWave has the potential to be cost effective in this period:

- Two scenarios consider the deployment of outdoor sites in a hypothetical dense urban area in Greater China and Europe.
- Three scenarios consider the deployment of FWA in a hypothetical urban area in Greater China, suburban area in Europe and rural town in the US.
- One scenario considers deployment in a hypothetical enterprise office space.

In the dense urban and FWA scenarios, we construct the hypothetical areas of deployment by averaging three different real-world areas based on the analysis of satellite and granular population data, while for the indoor scenario, our analysis is based on a hypothetical large and dense office space.

3.1 Dense urban scenarios

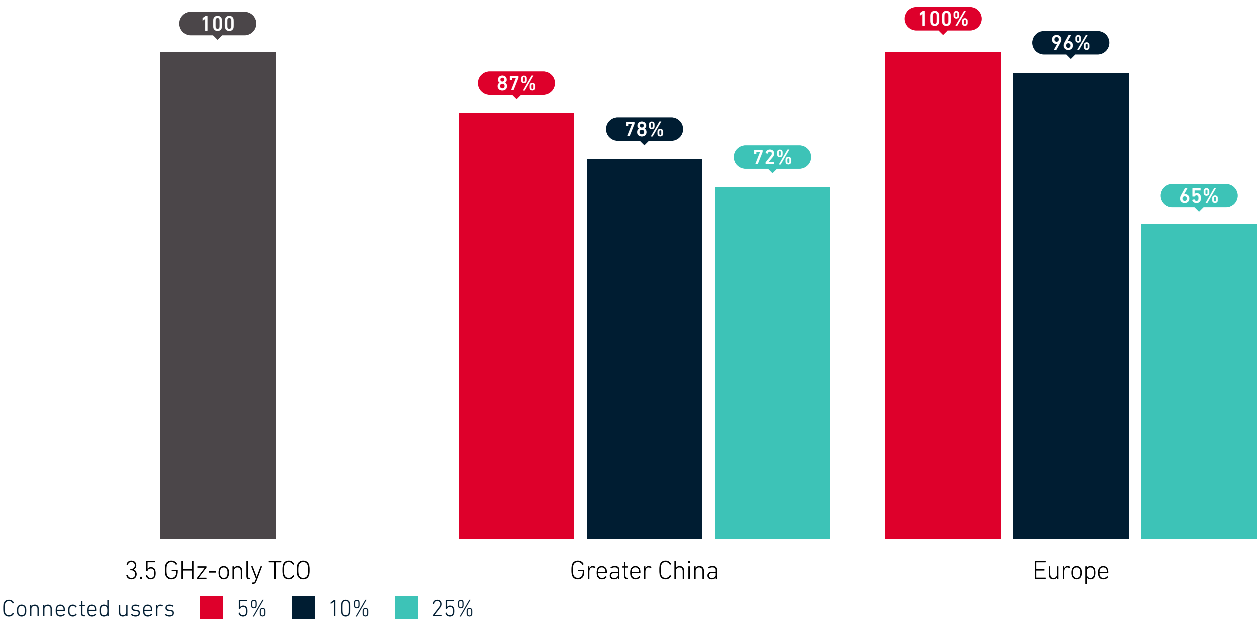
Considering a requirement of at least 100 Mbps download speeds everywhere, we find that in densely populated areas in Greater China and Europe there will be a need for additional capacity layers in the period to 2025, over and above the initial deployment of 5G networks. Adding this capacity layer with mmWave 5G networks can be cost effective in both scenarios. In Greater China, this is the case, for instance, when both connected users exceed 10% of total subscribers at peak and operator market share is above 10%. In Europe, this occurs, for instance, when both connected users are above 25% of total subscribers and operator market share is above 10%.

The economics of 5G mmWave differ between China and Europe because the former presents higher estimated traffic demand and technology adoption, increased population density and wider bandwidth availability in high bands (800 MHz versus 400 MHz, for example) – all conditions that augment the cost effectiveness of 5G mmWave deployment.

Figure 3

NPV of TCO for a 3.5 GHz plus mmWave 5G network

Base 100: 3.5 GHz-only TCO



Source: GSMA Intelligence

Our scenarios only consider mobile data demand generated outdoors and compare two alternative 5G deployment strategies:

- **5G networks rely on mid-band sites only for coverage and capacity:** We assume that a given operator would first provide a 5G 'coverage' layer of mid-band spectrum covering the whole area, and would subsequently densify the network with new mid-band sites (macro and small sites) wherever traffic demand exceeds deployed capacity.
- **5G networks rely on mid-band sites for coverage and mmWave sites for additional capacity:** As in the first deployment strategy, we assume that a given operator would first provide a 5G 'coverage' layer of mid-band spectrum covering the whole area, and would subsequently densify the network with mmWave-only sites (macro and small sites), instead of mid-band sites, wherever traffic demand exceeds deployed capacity.

The cost effectiveness of the second deployment strategy of a mid-band plus an mmWave-enabled 5G network in a dense urban area depends on two main factors. On the one hand, the higher capacity enabled by large mmWave bandwidths and superior spectral efficiency translate into a lower number of base stations required to fill capacity gaps, whenever these gaps arise. On the other hand, there are higher costs per site associated with mmWave equipment.

We assume that traffic demand follows population density[9] and evaluate the cost effectiveness of these two alternative deployment strategies under a range of values to reflect uncertainty in three main areas:[10]

- We consider several possible levels of intensity of traffic demand in a given area, proxied by an assumption on the share of connected users[11] at peak hours.
- We also consider different levels of operator market share values, reflecting different levels of subscribers (and traffic demand) captured by the operator.
- Finally, given the heterogeneity of spectrum assignments in Europe, we consider the results sensitivity to the amount of spectrum assigned per operator.

mmWave 5G in a dense urban scenario in Greater China could be cost effective as soon as spectrum is made available

In Greater China, we consider the two alternative deployment strategies presented above in a hypothetical dense urban area that is constructed as an average of different dense urban areas located in Greater China. It is important to note that, on average, the dense urban areas considered cover nearly 50% of the total population in these cities but only 16% of the geographical urban area.[12]

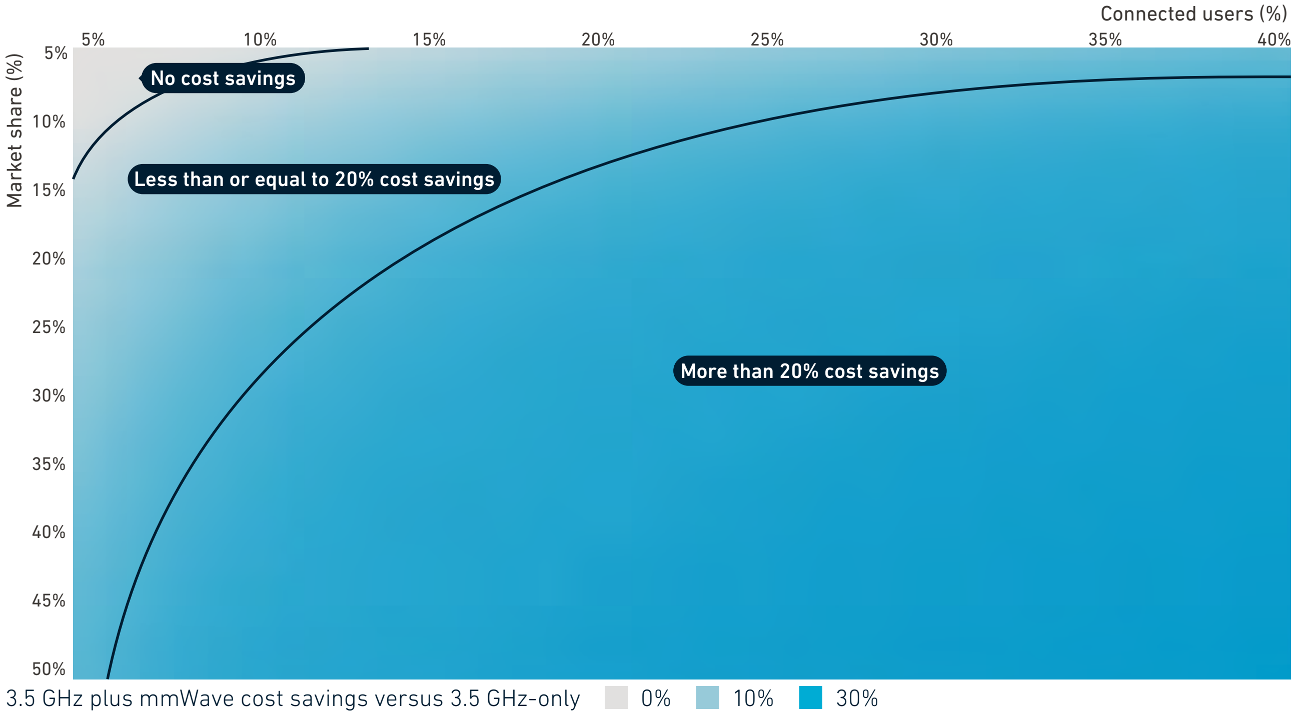
Under a central case where the 5G network enables at least 100 Mbps download speeds everywhere, 25% of users are connected at peak and the operator has a market share of 30%, we estimate that a deployment strategy of adding mmWave sites alongside mid-band sites could result in cost savings of up to 28%.

Operators' market shares and the share of connected users can vary significantly from one dense urban area to another. Figure 4 presents the cost savings associated with a range of 5% to 50% market share and a range of 5% to 40% of connected users. We also estimate that mmWave could bring cost efficiencies, for instance, when both the share of connected users exceeds 8% and operator market share is above 7%.

9 This is a conservative assumption since traffic per user remains constant over the period and 5G is expected to enable new use cases that would generate additional non-human data traffic.
10 The Annex provides a thorough overview of the modelling assumptions and sources.
11 Assuming 10% of connected users are active and that these users experience the same download speeds at any point in time.
12 The Annex provides an overview of the areas considered and their population densities.

Figure 4

Cost savings in the dense urban scenario in Greater China – at least 100 Mbps download speeds



Source: GSMA Intelligence

In Europe, mmWave 5G solutions could be cost effective in dense urban areas during the period if high outdoor traffic demand materialises

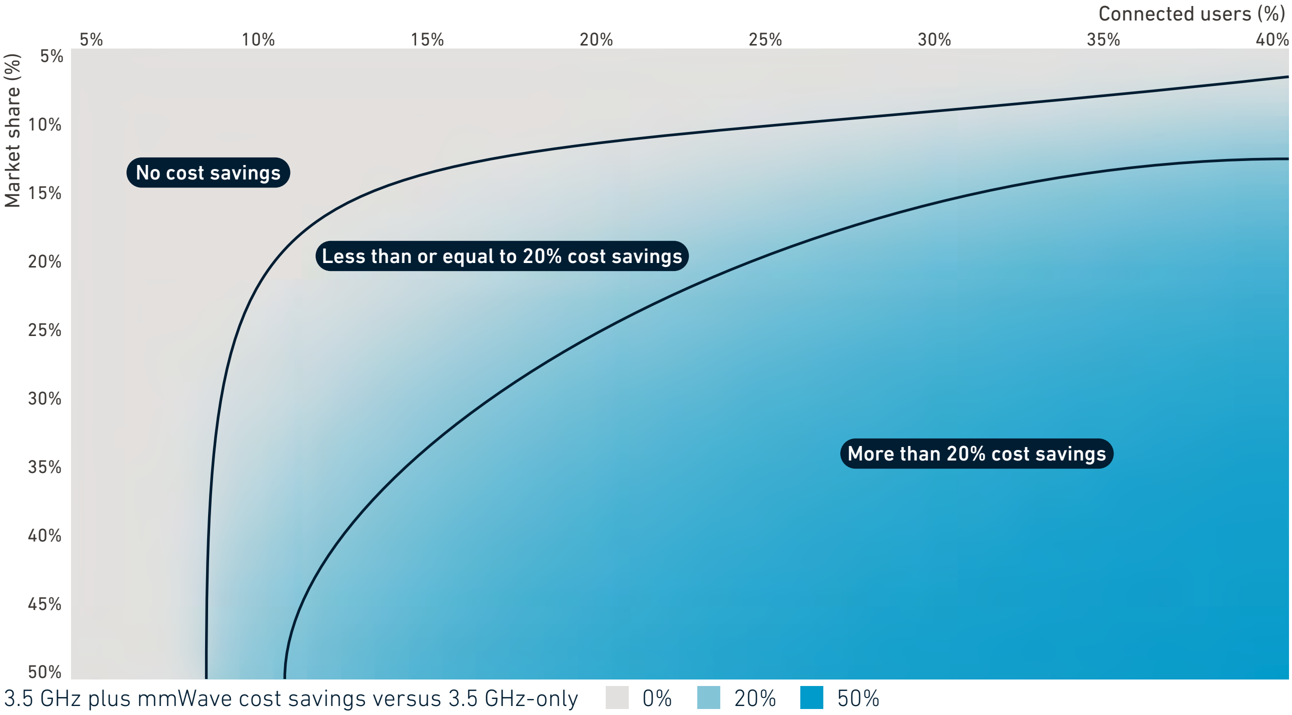
In Europe, we consider the deployment strategies presented above in a hypothetical dense urban area based on real-world dense urban areas located in three European capital cities. It is important to note that on average the dense urban areas cover nearly 45% of the total population in these cities but only 6% of the geographical urban area.

Under a central case where the 5G network enables at least 100 Mbps download speeds everywhere, 25% of users are connected and the operator has a market share of 30%, we estimate that a deployment strategy of adding mmWave sites alongside mid-band sites could result in cost savings of up to 35%. Under this central case, the need for a mmWave-enabled capacity layer would arise only in the densest parts of the dense urban area we study.

Operators' market shares and the share of connected users can vary significantly from one dense urban area to another across Europe. Figure 5 presents the cost savings associated with a range of 5% to 50% market share and a range of 5% to 40% of connected users. Based on 100 Mbps download speeds everywhere, adding a mmWave capacity layer would bring cost savings of up to 53%. We estimate that these cost efficiencies would arise, for instance, when both the share of connected users exceeds 10% and operator market share is above 23%. Under the assumption that only 10% of users are connected and the operator has a market share of 30%, mmWave could still deliver an overall cost saving of 4% and the need for a mmWave capacity layer would arise in 2025.

Figure 5

Cost savings in the dense urban scenario in Europe – at least 100 Mbps download speeds



Source: GSMA Intelligence

The results above are based on spectrum assignments per operator of 80 MHz in the 3.5 GHz band and 400 MHz in the 26 GHz band. However, there is considerable heterogeneity in spectrum assignments per operator across the continent.[13] We explore the results sensitivity to an alternative spectrum assignments profile of either 100 MHz for a given operator in the 3.5 GHz band or 800 MHz in the 26 GHz band. We find the following:

- Providing more bandwidth in the 3.5 GHz band enables more capacity in the 3.5 GHz network so that there is relatively less need for a mmWave capacity layer. Increasing the amount of spectrum in the 3.5 GHz band to 100 MHz reduces cost savings to 27% from 35% in the baseline.
- Providing more bandwidth in the 26 GHz band enables more capacity in the mmWave network so that fewer mmWave sites are needed to meet traffic demand, improving the cost savings associated with mmWave. Increasing the amount of spectrum in the 26 GHz band to 800 MHz increases cost savings to 37%.

13 For instance, in Finland some operators have 800 MHz in the 26–28 GHz bands and 100 MHz in the 3.5–3.8 GHz bands, while in Italy some operators have 400 MHz in the 26–28 GHz bands and 80 MHz in the 3.5–3.8 GHz bands.

3.2 Fixed wireless access scenarios

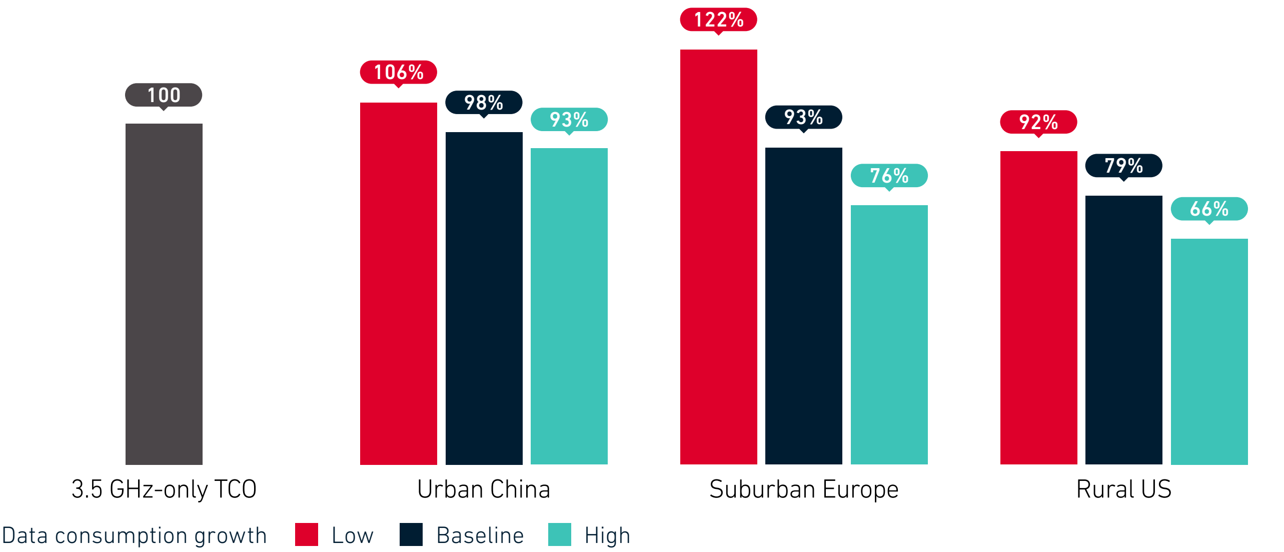
We find that deploying a 5G FWA network using mmWave spectrum can be cost effective. The results are, however, particularly sensitive to overall traffic demand,[14] mmWave propagation performance and the share of downlink and uplink in total traffic at the peak demand hour.

In a rural US town, suburban Europe and urban China, mmWave FWA can be a cost-effective strategy if 5G FWA is able to capture a good percentage of the residential broadband market demand, traffic demand during the busy hour is relatively high and data consumption does not slow down.

Figure 6

NPV of TCO for a mmWave FWA network

Base 100: 3.5 GHz-only TCO



Source: GSMA Intelligence

In the FWA scenarios, we consider two alternative deployment strategies. It should be noted, however, that these two deployment strategies for FWA are not the only ones possible. Other relevant deployment strategies would involve, for instance, deploying a mixed FWA network including both 3.5 GHz sites and mmWave sites. The two alternative deployment strategies we consider are as follows:

- **Deploying an FWA network on 3.5 GHz spectrum for coverage and capacity:** We assume that a given operator would deploy a 'coverage' layer of 3.5 GHz FWA sites and would eventually deploy additional mid-band sites whenever traffic demand exceeds throughput capacity.
- **Deploying an FWA network on mmWave spectrum for coverage and capacity:** We assume that a given operator would deploy a 'coverage' layer of mmWave FWA sites and would eventually deploy additional mmWave sites whenever traffic demand exceeds throughput capacity.

14 See Annex for the detailed assumptions used in the analysis.

We assume that traffic demand follows household density and is a function of average data consumption. For both strategies, we assume FWA networks would be primarily deployed as brownfield sites of an existing outdoor 5G network and that CPEs will be window-mounted indoors.[15]

The cost effectiveness of these two alternative deployment strategies is evaluated assuming the FWA network enables at least 100 Mbps download speeds and 50 Mbps upload speeds everywhere, under a range of assumptions to reflect uncertainty in five main regards:[16]

- **The data consumption scenario:** We construct a forecast for household data consumption for the period to 2025 according to three alternatives:[17]
  - Low case: data consumption growth slows down (compound annual growth rate (CAGR) between 6% and 11%, depending on the scenario).
  - Baseline case: data consumption linearly grows over the period at a similar rate experienced in recent years (CAGR between 13% and 18%, depending on the scenario).
  - High case: data consumption exponentially grows over the period (CAGR between 17% and 22%, depending on the scenario).
- **The busy hour share of traffic:** We set a central assumption of 10% busy hour share and explore mmWave cost effectiveness under higher and lower values.
- **The share of households with an FWA subscription in the area (FWA penetration):** We set a central assumption of 30% FWA penetration by 2025 and explore mmWave cost effectiveness under higher or lower subscription rates.
- **The number of sites initially required to provide for coverage:**[18] We assume more mmWave than mid-band sites are needed to provide for initial coverage. However, we also study an alternative deployment scenario where fewer mmWave than 3.5 GHz sites are needed when using high-power rooftop-mounted CPEs.[19]
- **The share of uplink traffic to total traffic during the busy hour:** We assume a baseline downlink/uplink split of 85%/15% at peak hour and we explore the cost effectiveness of a mmWave FWA network under higher shares of uplink peak hour traffic.

The cost effectiveness of mmWave-enabled FWA networks, compared to 3.5 GHz FWA networks, depends on several factors. The number of sites needed to provide 5G FWA coverage is important. There are also higher costs associated with mmWave equipment. However, the superior throughput and capacity characteristics of mmWave translate into a lower number of base stations needed to fill gaps in downlink and uplink capacity.

15 Other possible strategies would include, for instance, outdoor rooftop-mounted CPEs.
16 See Annex for a thorough overview of the modelling assumptions and sources.
17 Actual values used are discussed in the Annex.
18 See Annex for our assumption on coverage inter-site distances.
19 Providing for initial coverage could require more 3.5 GHz sites than mmWave sites when UEs are high-power rooftop-mounted CPEs that enable good line of sight or when terrain characteristics present fewer obstacles to propagation.

mmWave is cost effective in urban areas in China if 5G FWA is able to capture a good percentage of the residential broadband market demand and data consumption growth does not slow down

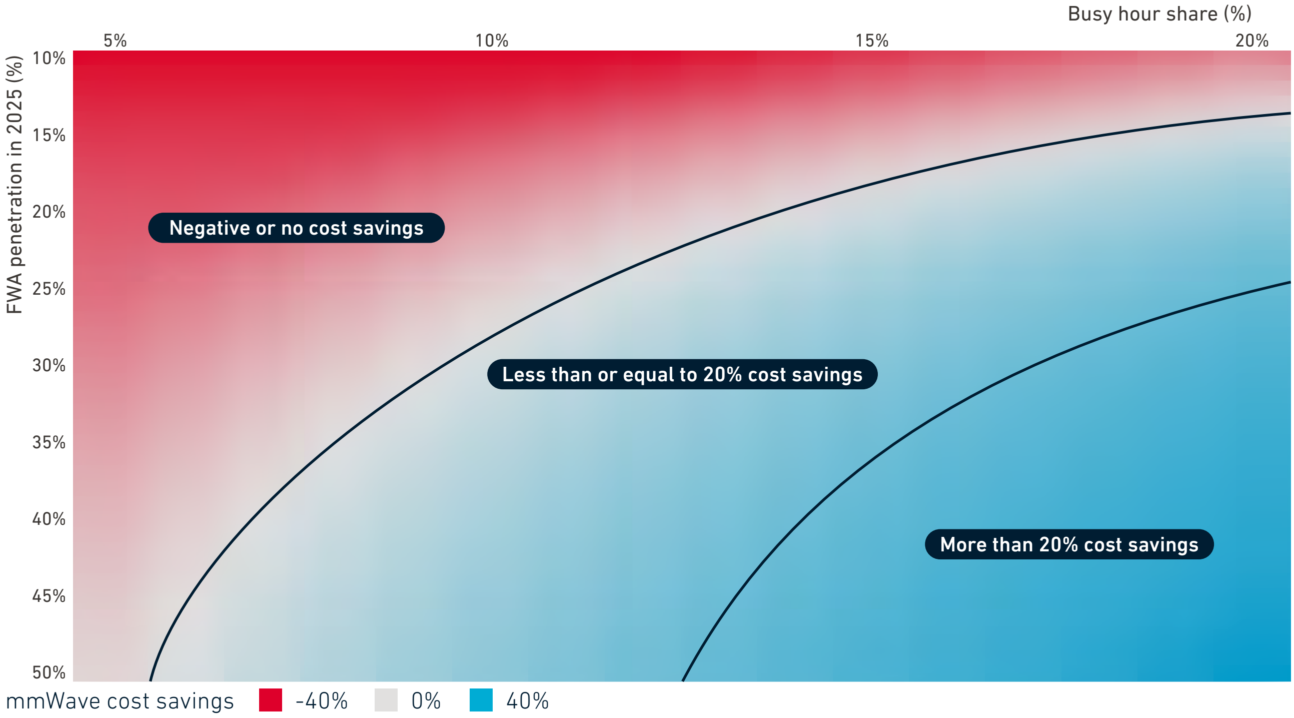
Assuming FWA deployment would start in 2023, in our central case we find a mmWave-enabled FWA network would cost:

- 6% more than a 3.5 GHz one under low data consumption growth
- 2% less than a 3.5 GHz one under baseline data consumption growth
- 7% less than a 3.5 GHz one under high data consumption growth.

Figure 7 presents estimated cost savings under a range of values for FWA penetration and busy hour share for baseline data consumption growth. Under central assumptions on busy hour share of traffic (10%), a mmWave-enabled FWA network would be cost efficient assuming FWA penetration reaches 28% or more by 2025 in a given area. Under the range of values considered, 5% to 20% busy hour share and 10% to 50% FWA penetration, cost savings associated with a mmWave-enabled network would be in the range of -40% to +38%.

Figure 7

Cost savings in an FWA scenario in urban China – baseline data consumption growth



Source: GSMA Intelligence

In suburban Europe, mmWave 5G is a cost-effective strategy for FWA where uptake and traffic demand are expected to be high and if data consumption growth does not slow down

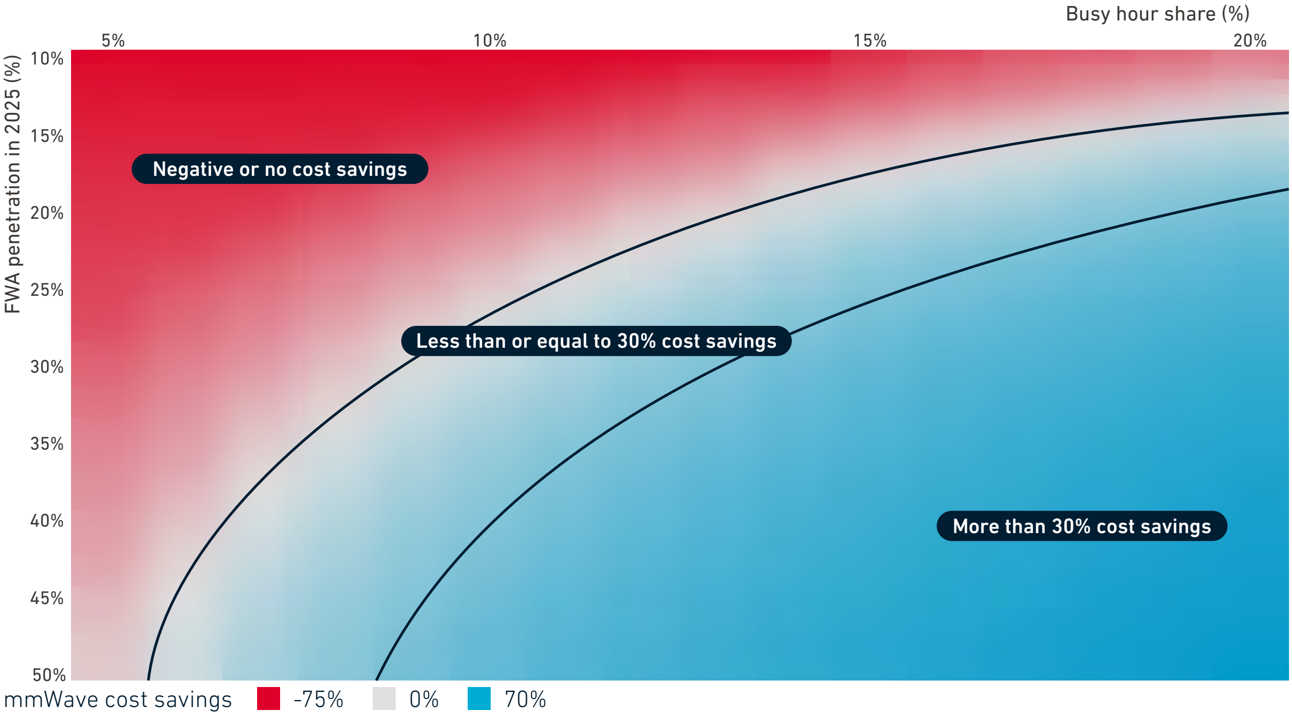
Under our central assumptions we find a mmWave enabled FWA network would cost:

- 22% more than a 3.5 GHz one under low data consumption growth
- 7% less than a 3.5 GHz one under baseline data consumption growth
- 24% less than a 3.5 GHz one under high data consumption growth.

Figure 8 presents estimated cost savings under a range of values for FWA penetration and busy hour share assuming baseline data consumption growth. Under central assumptions on busy hour share of traffic (10%), a mmWave FWA network would be cost efficient if FWA penetration reaches 27% or more by 2025. Considering a range of busy hour share between 5% and 20% and FWA penetration between 10% and 50%, cost savings associated with a mmWave FWA network would be in the range of -75% to +68%.

Figure 8

Cost savings in an FWA scenario in suburban Europe – baseline data consumption growth



Source: GSMA Intelligence

mmWave FWA deployments in rural US towns are also cost effective if busy hour traffic is high, data consumption growth does not slow down and a good percentage of the residential broadband market subscribes to the FWA service

We study the deployment of an FWA network in a hypothetical rural town in the US, constructed using three real-world rural towns We assume FWA deployment would start in 2022.

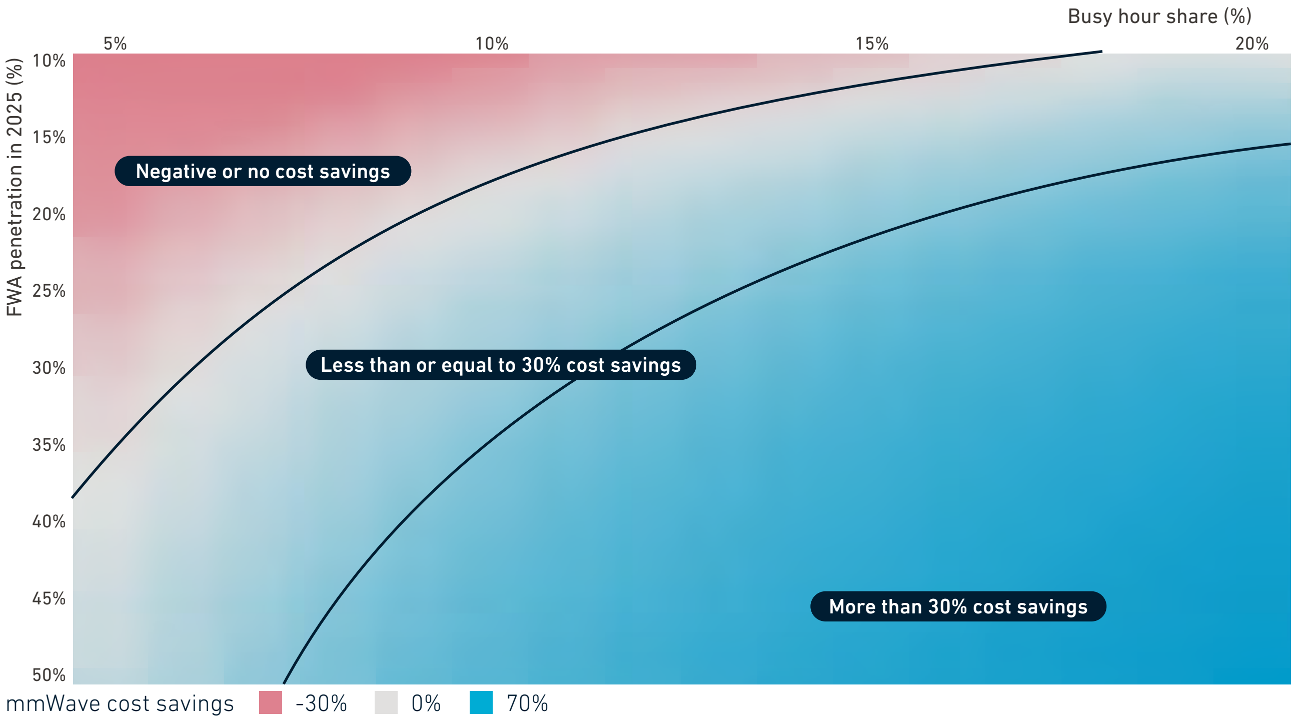
Under our central assumptions, we find that a mmWave enabled FWA network would cost:

- 8% less than a mid-band one under low data consumption growth
- 21% less than a mid-band one under baseline data consumption growth
- 34% less than a mid-band one under high data consumption growth.

Figure 9 presents estimated cost savings under a range of values for FWA penetration and busy hour share, assuming baseline data consumption growth. Under baseline data consumption growth and central busy hour share of traffic (10%), a mmWave FWA network would be cost efficient relative to a 3.5 GHz network if FWA penetration reaches 18% or more by 2025. Under a range of busy hour share between 5% and 20% and FWA penetration between 10% and 50%, cost savings associated with a mmWave enabled network would be in the range of -30% to +71%.

Figure 9

Cost savings in an FWA scenario in rural US



Source: GSMA Intelligence

Sensitivity analysis shows that mmWave cost effectiveness improves for higher shares of uplink busy hour traffic, and mmWave can also become cost effective under low traffic demand scenarios when deployed in areas with better propagation conditions for the band

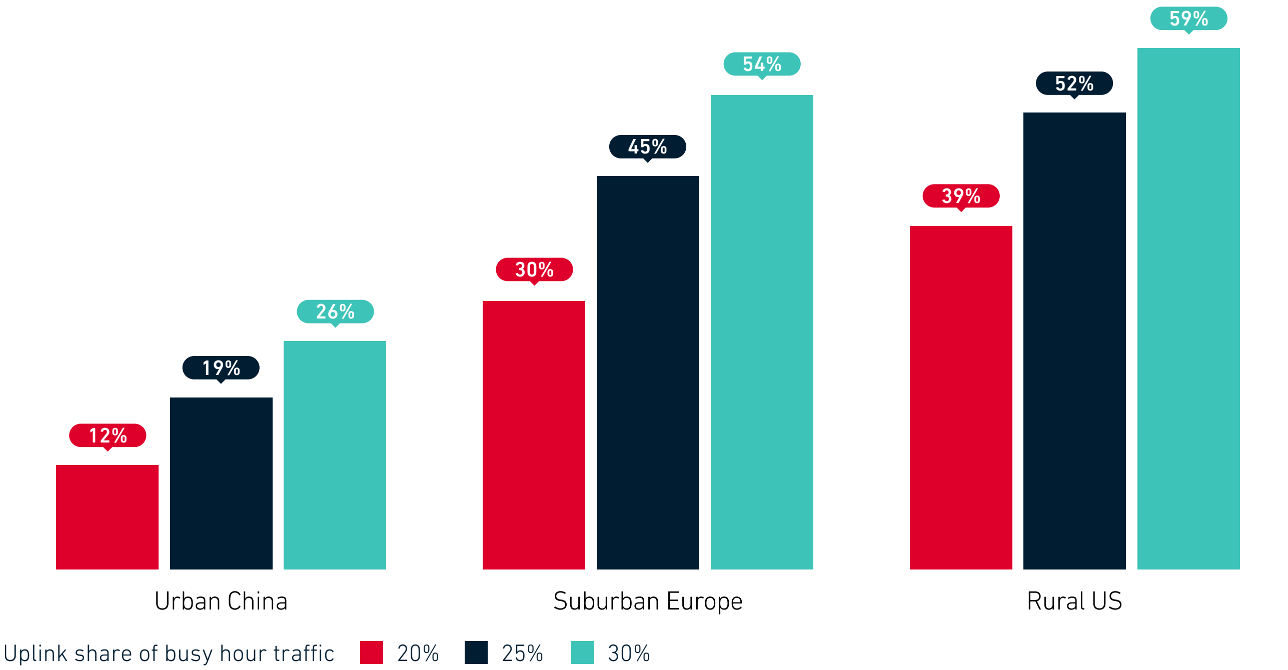
We analyse the results sensitivity to higher shares of uplink busy hour traffic. Use cases such as gaming and video conferencing typically feature high shares of uplink traffic and these use cases may experience faster growth than the traditional downlink-oriented use cases (e.g. video streaming). With high uplink busy hour traffic shares, we find that a mmWave FWA network is more cost effective relative to the baseline case because of its superior capacity characteristics in the uplink, relative to the 3.5 GHz band.

Figure 10 presents cost savings associated with a mmWave FWA network for 80%/20%, 75%/25% and 70%/30% downlink/uplink busy hour traffic splits, assuming 10% busy hour share of traffic, baseline data consumption growth and 30% FWA penetration by 2025. Under a 75%/25% downlink/uplink busy hour traffic split, cost savings associated with a mmWave FWA network amount to 19% in China, 45% in Europe and 52% in the US.

Figure 10

Cost savings in an FWA scenario for different downlink/uplink traffic splits

mmWave cost savings (%)



Source: GSMA Intelligence

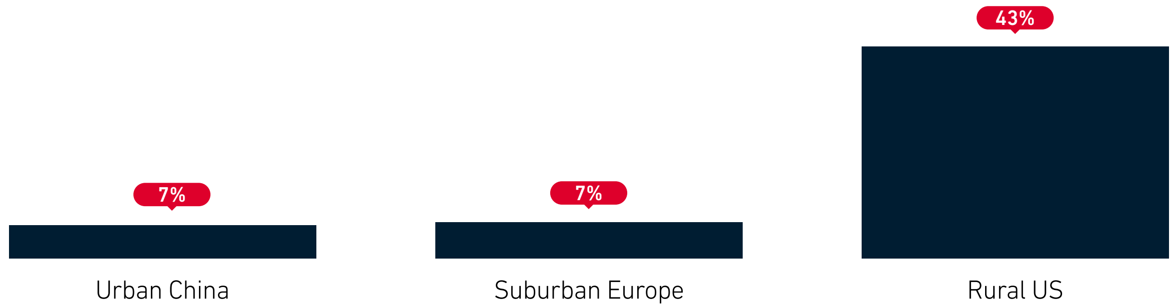
We also analyse the results sensitivity to an alternative coverage profile that would require fewer mmWave sites than 3.5 GHz sites to cover a given area. This could happen, for instance, with a high-power rooftop-mounted CPE that would enable good line of sight and/or in areas where terrain characteristics present few obstacles to propagation. Under these conditions, mmWave is cost effective even when assuming low traffic demand and low data consumption growth.

Figure 11 presents cost savings associated with a mmWave FWA network assuming mmWave sites required for coverage would represent approximately 70% of 3.5 GHz sites required for coverage in urban China and suburban Europe and 33% in rural US. These assumptions lead to cost savings that are larger in rural US. Under low data consumption growth, 20% FWA penetration and 5% busy hour share of traffic mmWave cost savings would amount to approximately 7% in China and Europe and 43% in rural US.

Figure 11

Cost savings in an FWA scenario assuming fewer mmWave than 3.5 GHz sites for coverage by using high-power rooftop-mounted mmWave CPEs

mmWave cost savings (%)



Source: GSMA Intelligence

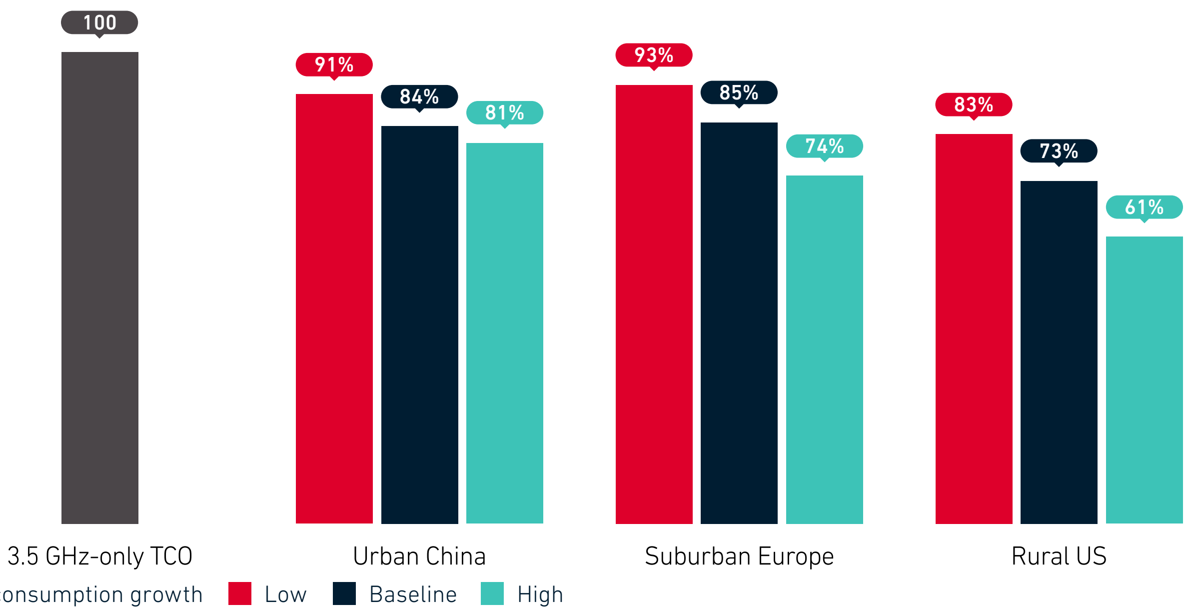
We also present additional sensitivity analysis of the results to an alternative strategy where mmWave is used to provide a capacity layer on top of a 3.5 GHz coverage layer for FWA

Our sensitivity analysis shows that the cost savings could be greater in this case: in central scenarios, cost savings could be 16% in urban China, 15% in suburban Europe and 27% in a rural US town for the baseline sensitivity case, compared to a 3.5 GHz-only network (Figure 12). However, the results are illustrative and are only valid where capacity gaps emerge in a few localised spots in the area. Figures 13, 14 and 15 provide further detail about the results of this sensitivity for urban China, suburban Europe and a rural US town by plotting the potential cost savings across a range of potential values of FWA penetration in the area and the busy hour share of total traffic.

Figure 12

NPV of TCO for a 3.5 GHz plus mmWave FWA network

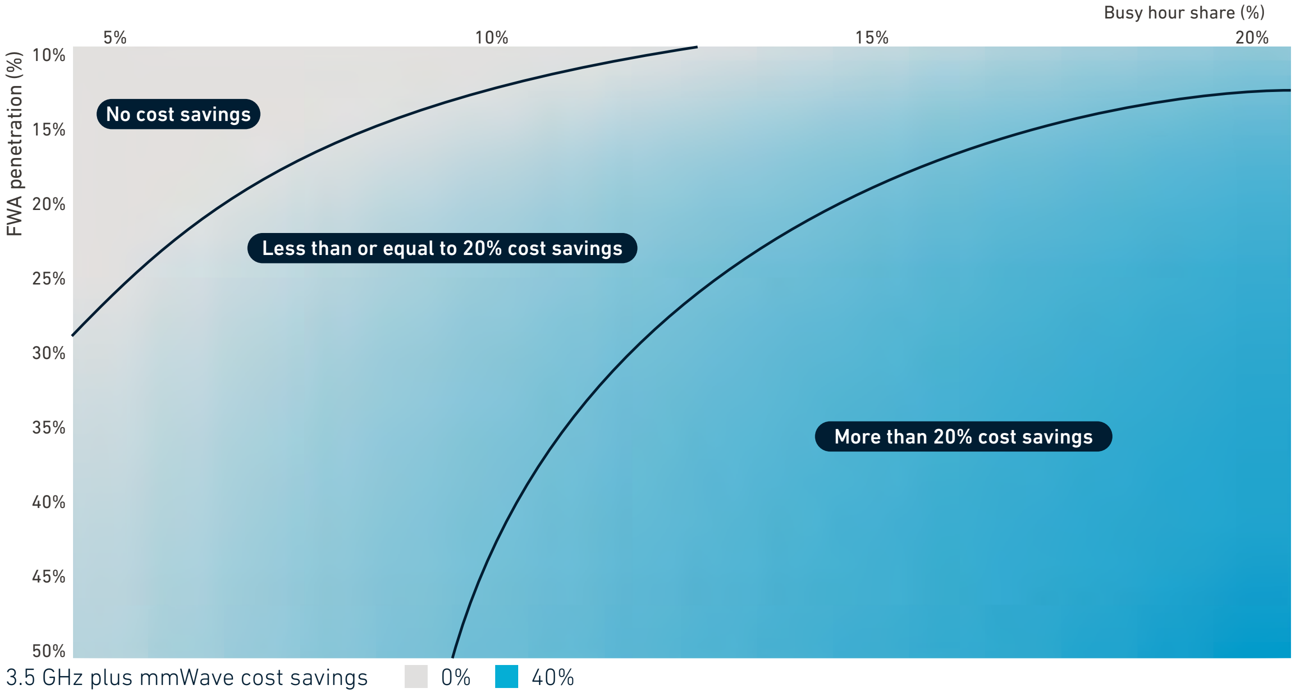
Base 100: 3.5 GHz-only TCO



Source: GSMA Intelligence

Figure 13

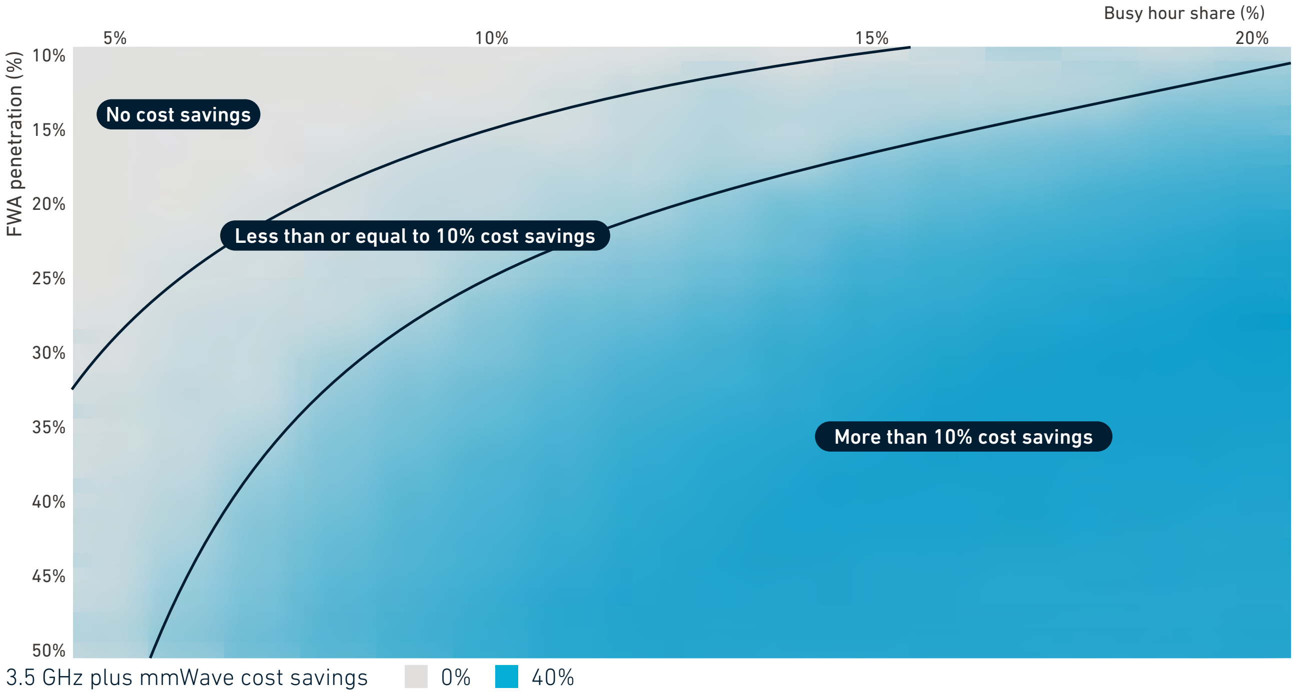
Cost savings in an FWA scenario in urban China – a 3.5 GHz-only network versus a 3.5 GHz plus mmWave network



Source: GSMA Intelligence

Figure 14

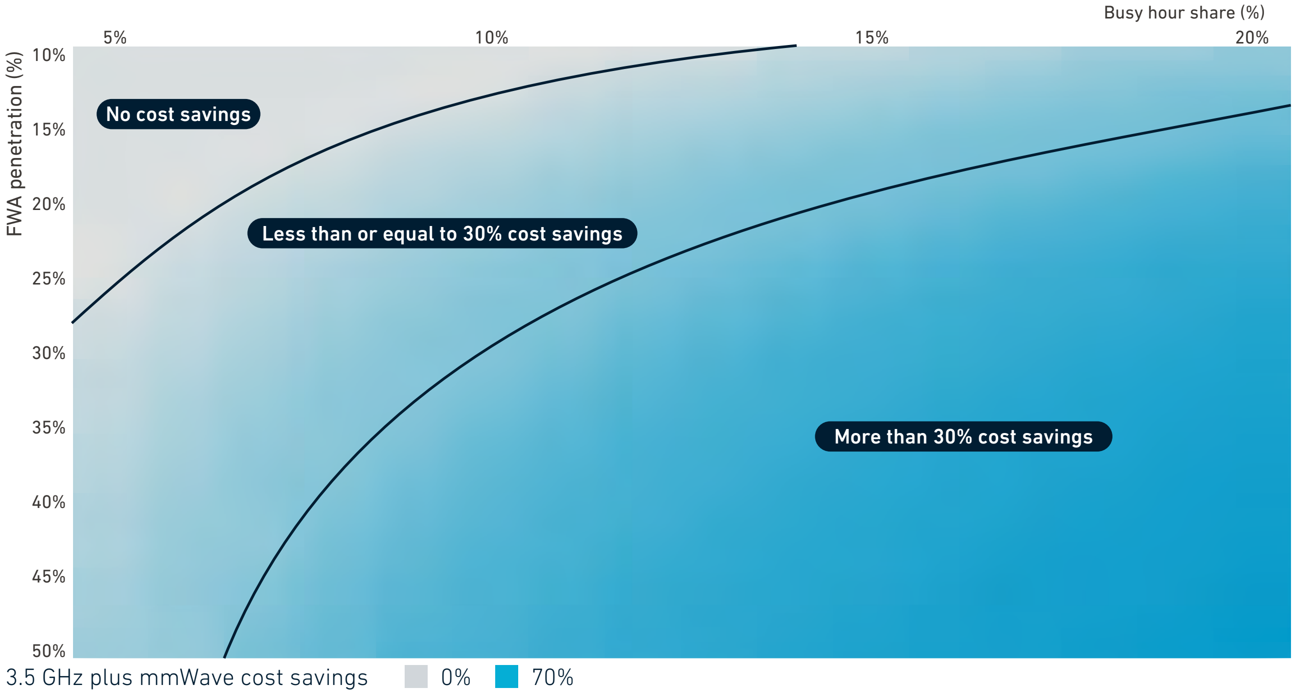
Cost savings in an FWA scenario in suburban Europe – a 3.5 GHz-only network versus a 3.5 GHz plus mmWave network



Source: GSMA Intelligence

Figure 15

Cost savings in an FWA scenario in rural US – a 3.5 GHz-only network versus a 3.5 GHz plus mmWave network



Source: GSMA Intelligence

3.3 Indoor scenario

We explore the cost effectiveness of deploying mmWave indoor small cells along with mid-band small cells in a hypothetical office building:

- The office is 15,000 square metres and hosts 1,875 open plan workstations.
- On an average working day, 80% of the work stations are occupied by employees.
- It also features 38 conference rooms, one every 50 workstations.
- We assume the office features multiple connected devices: smartphones, laptops, security cameras and video communications equipment in conference rooms. Some of these devices are assumed to be on Wi-Fi and Ethernet and some are assumed to be connected to an indoor 5G network.
- We also assume that indoor coverage is limited so that only a small share of traffic on 5G (just 10% of downlink traffic and 5% of uplink traffic) can be offloaded to outdoor sites.
- Finally, we consider the cost savings that could be generated by deploying advanced communications equipment in conference rooms, such as VR equipment, holographic communications equipment, and material utilisation of edge computing services or cloud-based applications.

We assume 15 3.5 GHz indoor small cells are deployed to provide complete indoor 5G coverage, assuming a coverage area per cell of around 1,000 square metres.

In this scenario, the cost effectiveness of adding mmWave indoor small cells to a mid-band coverage layer depends on two main factors: the superior capacity associated with mmWave cells and the higher cost associated with mmWave indoor small cells.

Figure 16 presents the expected cost savings of deploying mmWave indoor small cells alongside 3.5 GHz small cells according to a range of share of devices connected to the indoor 5G network and of share of devices concurrently active, assuming 100% of standard communications equipment is on 5G.

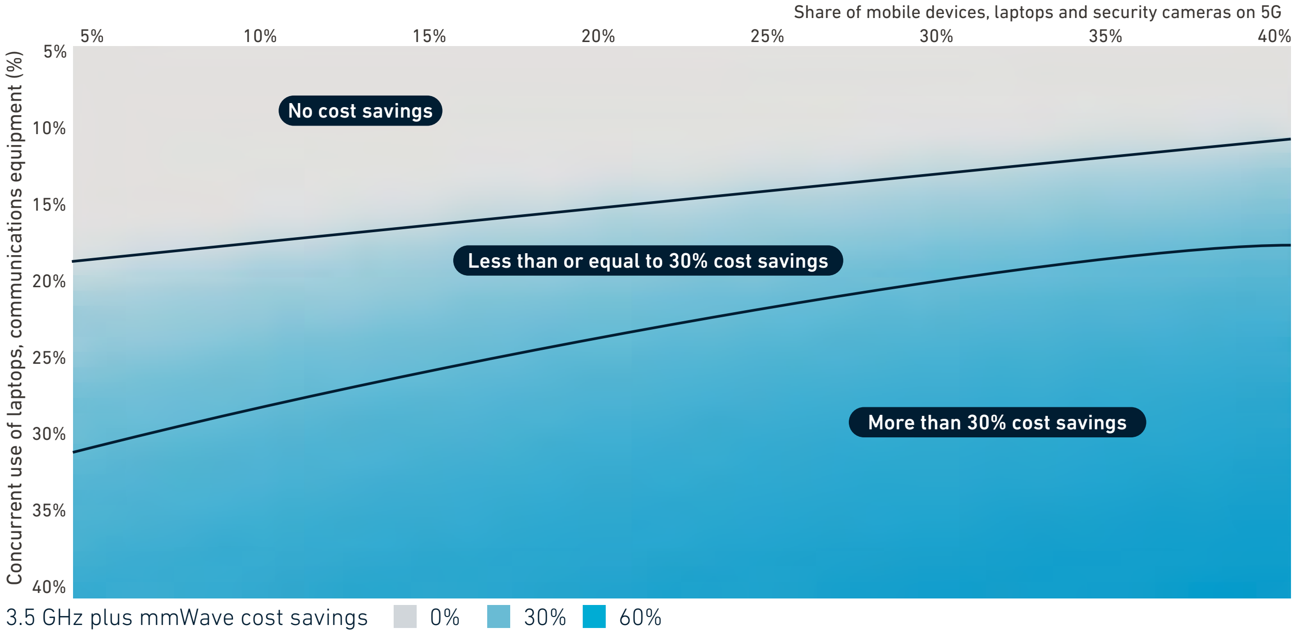
We find that when a significant share of data traffic from devices needs to be supported by indoor 5G services, a mmWave network could generate cost savings of up to 54%. The precise value in the range depends on the share of devices concurrently active and on whether and to what extent there is the need to provide connectivity to next-generation video communications equipment.

Depending on whether standard or advanced communications equipment is deployed,[20] mmWave indoor small cells alongside 3.5 GHz small cells could provide cost savings between 42% and 46%. In the case where standard communications equipment is deployed, the deployment of mmWave small cells to complement a 3.5 GHz network is cost effective when the share of mobile devices, laptops and security cameras exceeds 10% and the share of laptops and standard communications equipment is above 17%.

20 Also assuming 40% of mobile devices, laptops and security cameras are on 5G and 25% of both laptops and communications equipment are concurrently active.

Figure 16

Cost savings in an indoor office space scenario – standard communications equipment

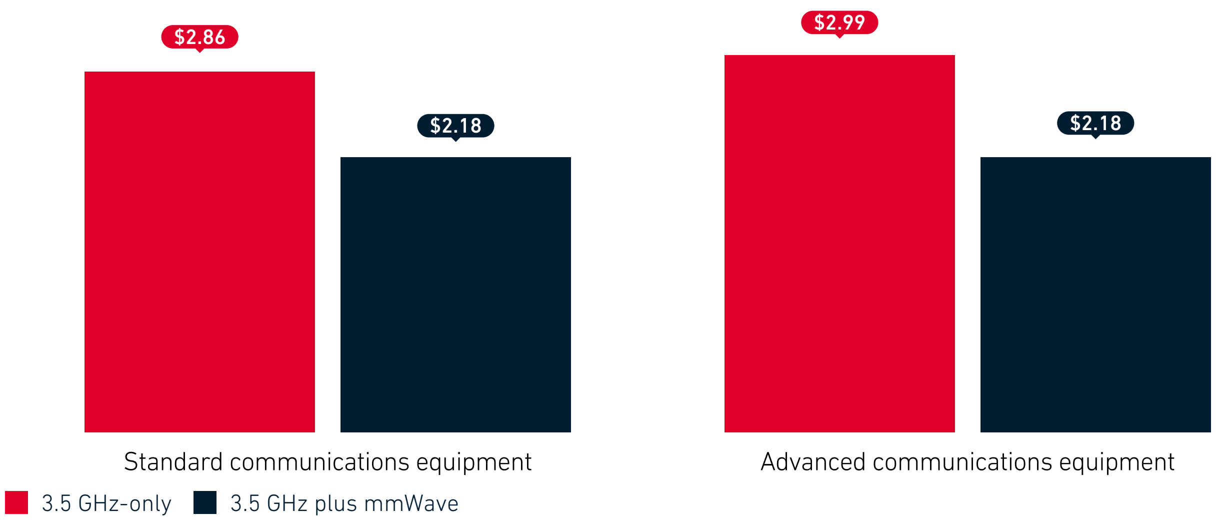


Source: GSMA Intelligence

Figure 17 presents the cost per square metre of a mid-band-only indoor 5G network versus a mmWave plus mid-band 5G network, assuming 10% of smartphones, laptops and security cameras are on 5G and 20% of both laptops and communications equipment are concurrently active,[21] according to whether advanced or standard communications equipment is deployed in conference rooms. We estimate that, if standard communications equipment is deployed, the yearly cost per square metre of a mid-band indoor network would amount to approximately $2.90,[22] while if advanced communications equipment is deployed, the cost per square metre of a mmWave plus mid-band network would amount to approximately $3.00.

Figure 17

Cost per square metre in an indoor office space scenario



Source: GSMA Intelligence

21 Plus assuming 10% of mobile devices and 100% of security cameras are concurrently active
22 Including capex and assuming five years' asset life and linear depreciation

4 Conclusion and recommendations

As the TCO analysis shows, despite its shorter range and higher equipment costs, the high throughput and capacity of mmWave could lead to targeted cost-effective 5G deployments in the period between now and 2025. These results have clear implications for mobile operators, device and equipment manufacturers, and governments:

- **Mobile operators should not underestimate the role of mmWave in the short term.** While it is clear that mmWave will be an enabler of future 5G use cases where high capacity and throughput are required, mmWave can also be a robust solution for areas where traffic demand is concentrated in the short term. As the analysis shows, adding a capacity layer with mmWave 5G solutions alongside 3.5 GHz networks can be cost effective. The results hold under a considerable range of scenarios in the period to 2025, including in the densest parts of some cities, in the provision of FWA 5G services or as an indoor solution to provide 5G connectivity. Operators that do not have access to this spectrum or that have not yet sufficiently tested these network solutions run the risk of finding themselves at a disadvantage to competitors when offering 5G services without mmWave solutions.

- **Governments and regulators should facilitate the timely availability of mmWave spectrum bands, in the right conditions.** Governments across the world are looking to capitalise on 5G as a catalyst of economic growth and further digitisation of their economies. As we show in our analysis, we estimate that 5G will generate an annual boost to global GDP of 0.6%, adding approximately $600 billion annually to the global economy, with mmWave solutions playing an increasingly important role in delivering these benefits. Without the timely assignment of sufficient (around 1 GHz per operator) mmWave spectrum in the right conditions, governments risk creating an artificial barrier to the development of 5G networks and their associated socioeconomic benefits. While mmWave spectrum is now becoming more widely available, many countries have still not developed clear plans for the assignment of the band to mobile services.
- **Market readiness has been achieved and a greater choice of equipment and devices is expected to accelerate adoption.** Despite momentum and market readiness across the mmWave ecosystem building up rapidly in the last couple of years, vendors need to continue to improve product readiness for mmWave 5G devices and equipment to reach full maturity. Many operators with 5G have pressed their device suppliers to bring 5G support to all new flagship smartphones – if not all new smartphones. Those operators with mmWave 5G can think about a similar strategy by making it clear to suppliers that mmWave smartphone support is a priority. Broader economic benefits are to be realised as mmWave 5G solutions achieve more scale. A wider choice of consumer devices and equipment is poised to further reduce deployment costs, increase the choice of affordable devices available and facilitate greater adoption.

Annex
Modelling the total cost of ownership of 5G networks between 2020 and 2025

A1 Dense urban scenarios

We evaluate the cost effectiveness of two alternative deployment strategies:

- **5G networks rely on 3.5 GHz mobile sites only:** We assume that a given operator would first provide a 5G 'coverage' layer of 3.5 GHz spectrum covering the whole area, and would subsequently densify the network with further 3.5 GHz sites (macro and small sites) wherever traffic demand exceeds throughput capacity.
- **5G networks rely on 3.5 GHz and mmWave mobile sites**: As with the first deployment strategy, we assume that a given operator would first provide a 5G 'coverage' layer of 3.5 GHz spectrum covering the whole area and would subsequently densify the network with mmWave sites (macro and small sites), instead of 3.5 GHz sites, wherever traffic demand exceeds throughput capacity.

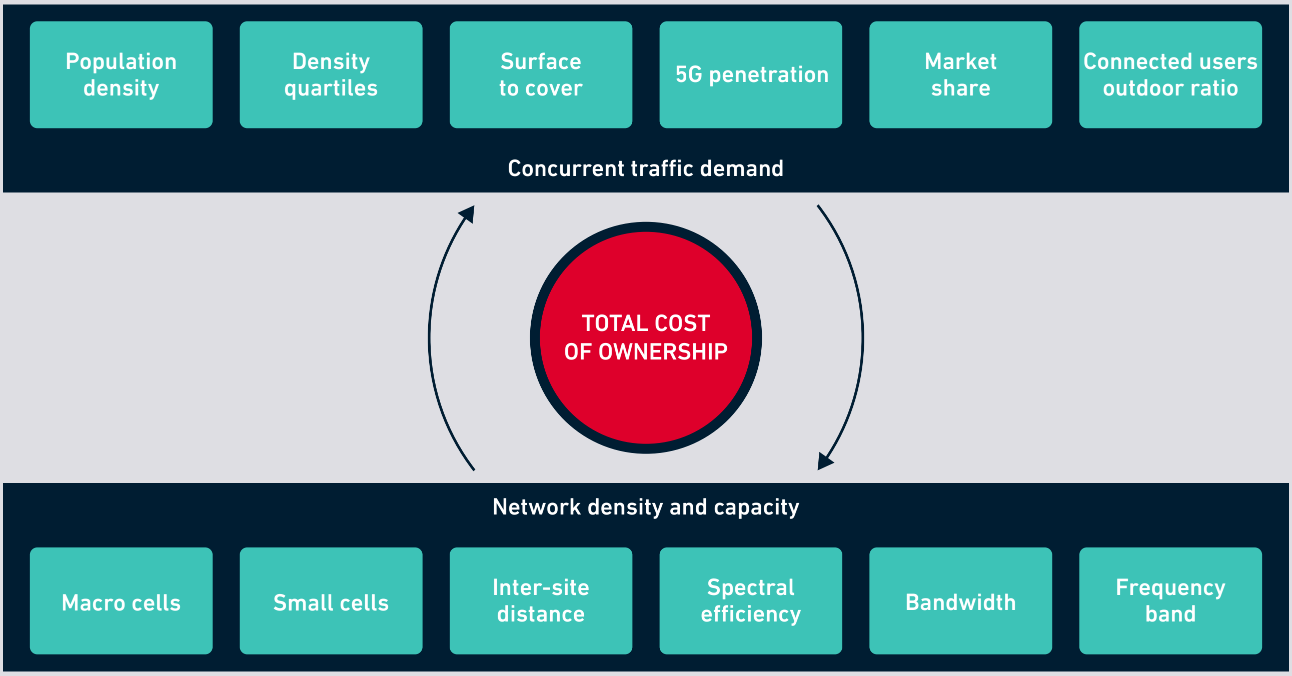
Our model relies on three modules to estimate the total cost of ownership associated with each of these two deployment strategies:

- traffic demand module
- supply module
- cost module.

Figure A1 presents the high-level methodology.

Figure A1

Dense urban model high-level methodology



Source: GSMA Intelligence

i Traffic demand

Traffic demand estimation relies on several factors:

- population density
- 5G adoption
- download speeds enabled by the network (the network performance scenarios)
- the share of users that are connected (the share of connected users)
- the share of connected users that are actively downloading data (the share of active users)
- the share of outdoor traffic on total traffic
- the market share of the operator.

Traffic demand = market share ⁎ population density ⁎ 5G connections penetration ⁎ download speed ⁎ share of connected users ⁎ share of active users ⁎ outdoor share

We assume traffic demand follows population density.[23] We identify the densest part of the cities retained in our study using satellite images coupled with granular population density data. For deployment, we only consider populated areas.

Tables A1 and A2 present the areas considered in Greater China and in Europe respectively.

Table A1

Areas considered in the dense urban scenario in Greater China

City	Area considered			Urban area		
	Population (million)	Area (km²)	Population density (thousands/km²)	Population (million)	Area (km²)	Population density (thousands/km²)
Hong Kong	5.4	342	15.8	7.5	11,151	6.5
Beijing	9.0	374	24.0	23.9	3,440	6.9
Shanghai	8.2	188	43.6	26	2,452	10.6
Average	7.5	301	25	19.1	2,348	8.1

Source: GSMA Intelligence

23 We assume population density grows by an annual rate of 1.78% in China and 0.3% in Europe.

Table A2

Areas considered in the dense urban scenario in Europe

City	Area considered			Urban area		
	Population (million)	Area (km²)	Population density (thousands/km²)	Population (million)	Area (km²)	Population density (thousands/km²)
Madrid	3.5	408	8.5	6.7	4,512	1.5
Paris	3.4	154	22.0	11.6	5,606	2.1
Athens	2.1	153	13.4	3.8	2,988	1.3
Average	3	238	12.4	7.4	4,369	1.7

Source: GSMA Intelligence

Tables A1 and A2 show that average population density in the hypothetical Greater China dense urban area is around 25,000 people per square kilometre and in the hypothetical European dense urban area is around 12,000 people per square kilometre. However, these averages include areas with higher population densities and areas with lower population densities. To reflect that a few localised areas experience the bulk of this traffic demand, we computed the share of population by area quartile and studied 5G deployment in each quartile. Table A3 presents the share of demand by population quartiles in the two dense urban areas. The top quartile in terms of population density features an average population density of around 65,000 people per square kilometre in Greater China and 21,000 people per square kilometre in Europe.

Table A3

Share of population by area quartile in the dense urban scenario in Greater China and in Europe

Region	Quartile	Share of demand	Population density (thousands/km²)
Greater China	25%	65%	65.3
Greater China	50%	19%	19.3
Greater China	75%	11%	11.3
Greater China	100%	4%	4.0
Europe	25%	43%	21.6
Europe	50%	30%	14.9
Europe	75%	18%	9.2
Europe	100%	8%	4.0

Source: GSMA Intelligence

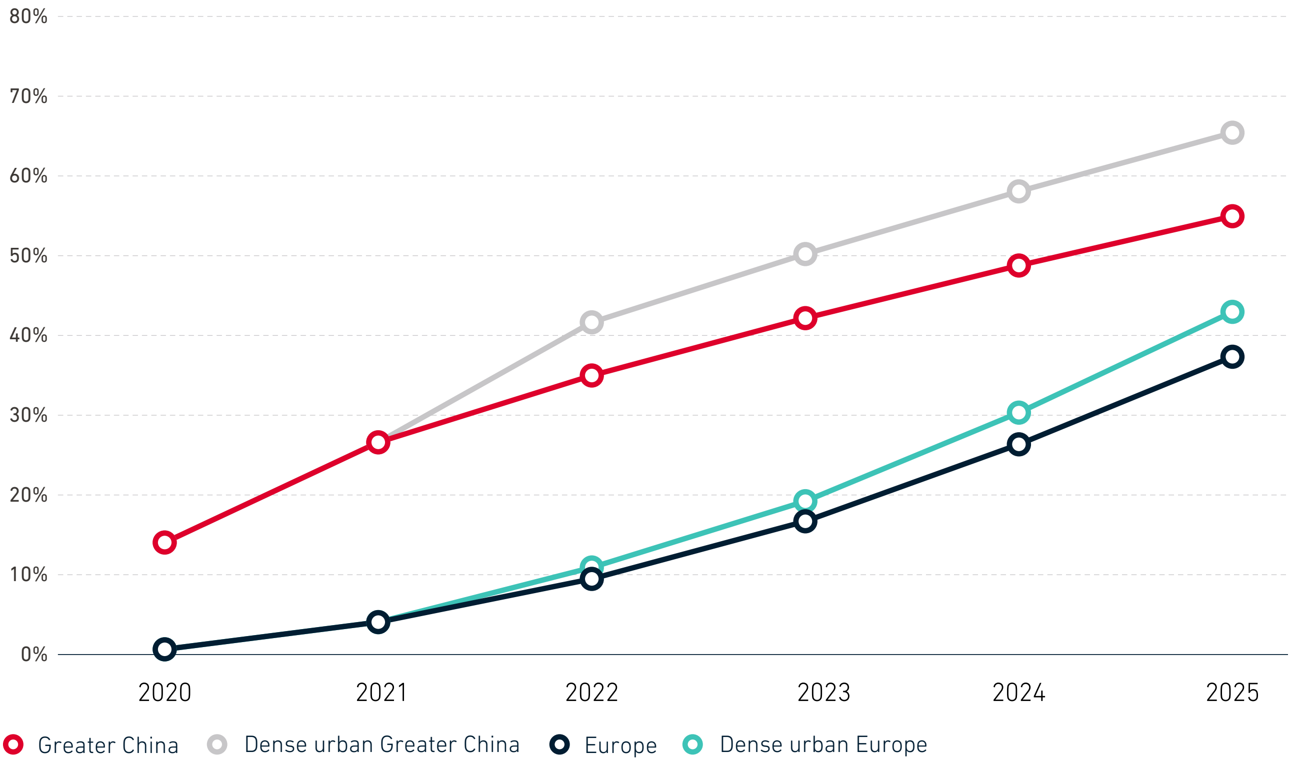
The intensity of traffic demand is adjusted based on the share of users that are connected, assuming 10% of connected users are actively downloading data.

5G adoption is proxied by 5G connections as a share of population. We rely on GSMA Intelligence forecasts in the period 2020–2025, adjusted to reflect that most 5G connections in the first years of 5G are expected to emerge in urban areas. Figure A2 presents the resulting 5G penetration forecast for the two regions in our study.

Figure A2

5G connections penetration forecasts, 2020–2025

% of population



Source: GSMA Intelligence

We only consider outdoor mobile data traffic and assume it represents 20% of total traffic demand. Finally, we adjust the traffic demand experienced by a given operator with a market share assumption throughout the period 2020–2025.

ii Supply module

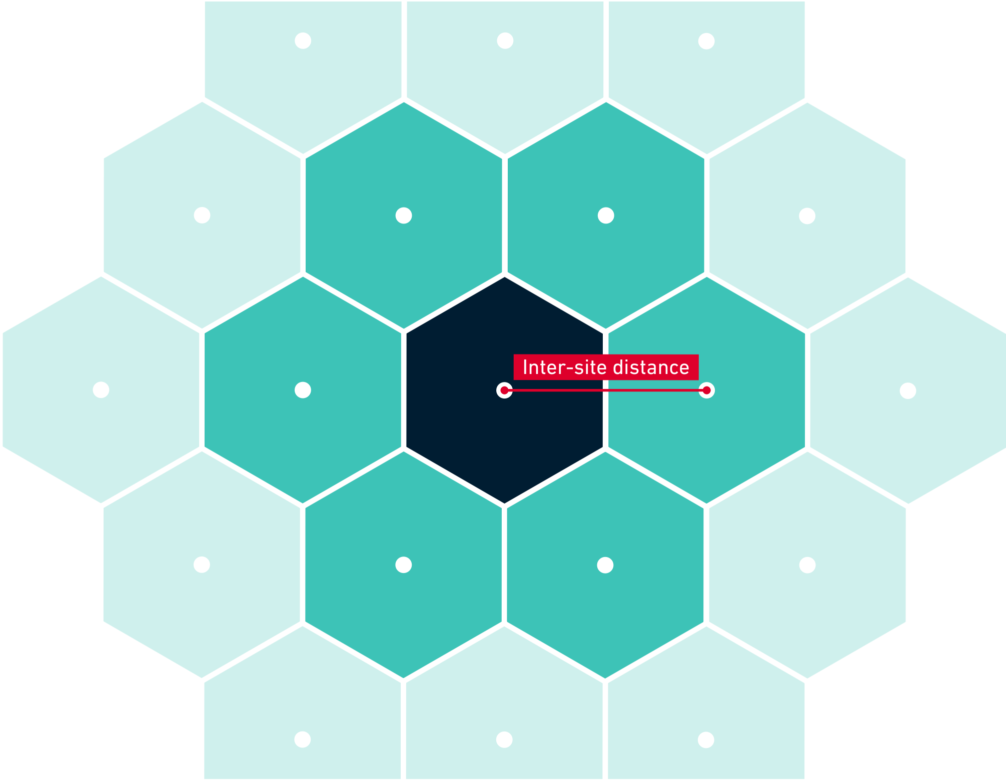
In order to determine the number of sites needed to cover a given area we assume the surface area to cover is made of regular hexagons and divide it by the surface area covered by a given site. The surface area covered by a given site is based on the average distance between macro sites (the inter-site distance, as shown in Figure A3). The surface area covered by a given macro site is determined by the following industry-standard equation:

$$\textit{Area covered by site} = 2.6 * \left(\frac{\textit{Inter-site distance}}{2}\right)^2$$

On central assumptions of a 100 Mbps downlink speed enabled for the edge users, we assume that inter-site distances of the initial 3.5 GHz coverage layer are approximately 1,000 metres.

Figure A3

Determining the number of sites to cover a given area



Source: GSMA Intelligence

We assume that 5G area coverage in the two dense urban areas we study would reach 100% by 2023.

Once the number of 3.5 GHz sites is determined, we consider that capacity gaps arising in the network would be filled either by additional 3.5 GHz sites (macro and small) or with additional mmWave sites (macro and small). We assume that mmWave sites can be placed anywhere outdoors.

Capacity gaps correspond to the difference between downlink throughput capacity[24] and downlink traffic demand. The number of 3.5 GHz or mmWave macro and small sites is determined by dividing the total capacity gaps by throughput capacity as determined by the following equation:

*Throughput capacity = # sectors * bandwidth * spectral efficiency*

Table A4 presents the technical assumptions used to determine throughput capacity.

Table A4

Technical assumptions

Region	Frequency band (GHz)	Macro/small cells	Number of sectors	DL spectral efficiency (bps/Hz/cell)	Bandwidth (Mhz)	Duplexing
Greater China	3.5	Macro	3	2.2	100	TDD
Greater China	3.5	Small cell	2	2.2	100	TDD
Greater China	28	Macro	3	3.5	800	TDD
Greater China	28	Small cell	2	3.5	400	TDD
Europe	3.5	Macro	3	2.2	80	TDD
Europe	3.5	Small cell	2	2.2	80	TDD
Europe	26	Macro	3	3.5	400	TDD
Europe	26	Small cell	2	3.5	200	TDD

Source: GSMA Intelligence

To reflect cost differences between brownfield and greenfield site deployment, we assume macro sites would either be placed in existing brownfield locations[25] or in greenfield locations, so that the model estimates the following quantities, for both 3.5 GHz and mmWave capacity layers:

- the number of brownfield macro site upgrades
- the number of greenfield macro sites
- the number of greenfield small cells.

To determine the number of small cells, we assume that in China they would represent 10% of total macro cells, while in Europe they would represent 50% of total macro cells.

24 We assume that 80% of site theoretical capacity can be utilised in practice before users start to experience reductions in their quality of experience.
25 To determine the number of possible brownfield sites that can be upgraded to 5G, we assume the existing 4G network features an average inter-site distance of 773 metres.

iii Cost module

Table A5 presents our estimates of capex and opex for each site type. Our estimates are calculated bottom-up by aggregating the different cost items associated with capex (equipment, backhaul, service and installation) and opex (energy costs, shelter lease, maintenance and optimisation). Estimates were informed through extensive interviews carried out by GSMA Intelligence with key industry players, as well as results from the GSMA Intelligence Network Economics model.

Table A5

Cost assumptions

Region	Item	Capex	Opex
Greater China	3.5 GHz upgrade of a brownfield macro site	$39,000	$13,000
Greater China	3.5 GHz new greenfield macro site	$88,000	$14,900
Greater China	3.5 GHz new small site	$20,700	$2,400
Greater China	mmWave upgrade of an existing brownfield macro site	$48,000	$12,800
Greater China	mmWave new greenfield macro site	$95,000	$14,700
Greater China	mmWave new small site	$24,700	$2,300
Europe	3.5 GHz upgrade of a brownfield macro site	$54,000	$15,200
Europe	3.5 GHz new greenfield macro site	$125,000	$23,000
Europe	3.5 GHz new small site	$33,000	$2,800
Europe	mmWave upgrade of an existing brownfield macro site	$73,000	$15,000
Europe	mmWave new greenfield macro site	$141,000	$22,800
Europe	mmWave new small site	$38,000	$2,700

Source: GSMA Intelligence

A2 Fixed wireless access scenarios

In the FWA scenarios, we consider two alternative deployment strategies:

- **Deploying a fixed wireless access network on 3.5 GHz spectrum:** We assume that a given operator would deploy a 'coverage' layer of 3.5 GHz FWA sites and would eventually deploy additional 3.5 GHz sites whenever traffic demand exceeds throughput capacity
- **Deploying a fixed wireless access network on mmWave spectrum:** We assume that a given operator would deploy a 'coverage' layer of mmWave FWA sites and would eventually deploy additional mmWave sites whenever traffic demand exceeds throughput capacity.

In both deployment strategies, we assume deployment would be done by first upgrading existing outdoor 5G infrastructure and eventually by deploying new greenfield sites.

We evaluate the TCO of these two alternative deployment strategies in three scenarios:

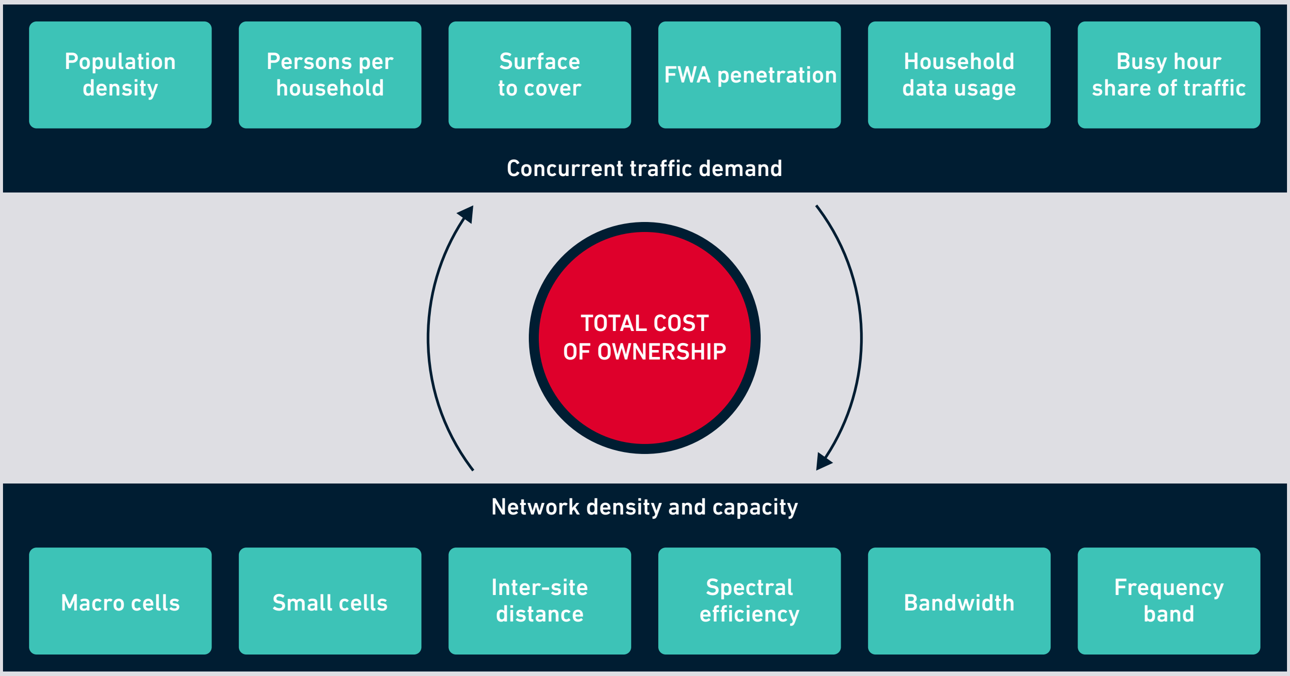
- a hypothetical urban area in China devised by averaging three real-world urban areas in China.
- a hypothetical suburban area in Europe devised by averaging three real-world suburban towns in Europe.
- a hypothetical rural town in the US devised by averaging three real-world rural areas in the US.

To estimate the TCO associated with each deployment strategy, our model relies on three modules:

- traffic demand module
- supply module
- cost module.

Figure A4

FWA model high-level methodology



Source: GSMA Intelligence

i Traffic demand

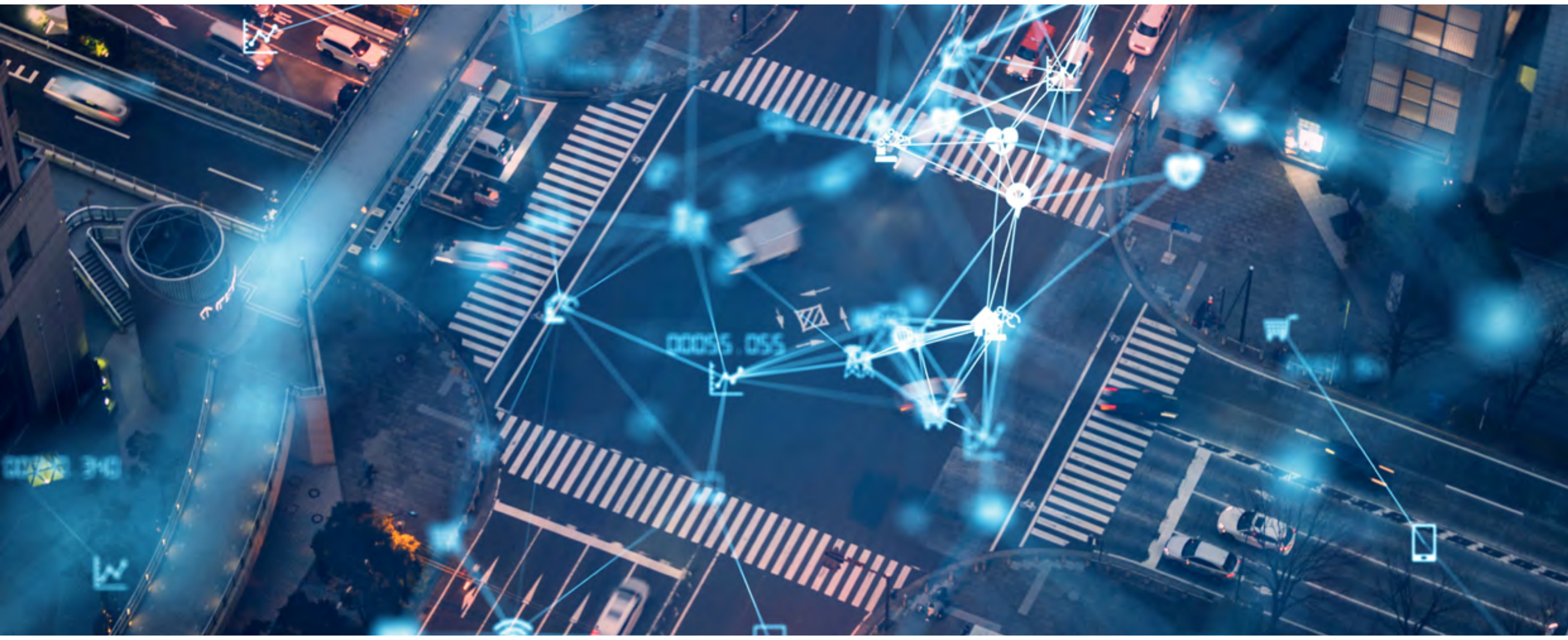
Our estimation of traffic demand distinguishes between uplink and downlink traffic and relies on five main factors:

- the number of households covered
- average household data consumption level and growth
- the busy hour share of traffic
- the share of households with an FWA subscription (FWA penetration)[26]
- downlink traffic as a share of total busy hour traffic.

$$\textit{DL traffic demand (Mbps)} = (\textit{households covered} * \textit{FWA penetration}) * \frac{\textit{data consumption}\left(\frac{GB}{Month}\right) * \textit{busy hour share} * \textit{downlink share of traffic} * 8 * 1024}{3600 * 30}$$

$$\textit{UL traffic demand (Mbps)} = (\textit{households covered} * \textit{FWA penetration}) * \frac{\textit{data consumption}\left(\frac{GB}{Month}\right) * \textit{busy hour share} * \textit{uplink share of traffic} * 8 * 1024}{3600 * 30}$$

Household density is based on population density and area devised by averaging three real-world areas for each region and geo-type and an assumption on the number of people per household.[27] We assume household density grows annually by 1.8% in the China scenario, by 0.3% in the Europe scenario and 0.6% in the US scenario.



26 This can also be interpreted as the market share of the FWA operator in the total home broadband market.
27 We assume 3.4 people per household in China, 2.3 people per household in Europe and 3 people per household in the US.

Tables A6, A7 and A8 present the areas retained in our study for each region as well as the underlying average population densities. In China we study FWA deployment in a hypothetical urban area of 112 square kilometres with an average population density of approximately 20,000 people per square kilometre.

In Europe, we consider a suburban area of approximately six square kilometres with an average population density of 5,000 people per square kilometre and in the US we consider a hypothetical rural area of 17 square kilometres with an average population density of approximately 1,100 people per square kilometre.

Table A6

Areas considered in an FWA scenario in urban China

City	Population (millions)	Area (km^2)	Population density (thousands/km^2)
Kunming	1.8	71	25.6
Harbin	2.3	102	22.9
Chongqing	2.7	163	16.4
Average	**2.3**	**112**	**20.3**

Source: GSMA Intelligence

Table A7

Areas considered in an FWA scenario in suburban Europe

City	Population (thousands)	Area (km^2)	Population density (thousands/km^2)
Ashford (UK)	24.1	5.2	4.6
Mechelen (Belgium)	37.4	6.6	5.6
Saint-Maur-des-Fossés (France)	13.6	4.8	2.8
Average	**25**	**5.6**	**5**

Source: GSMA Intelligence

Table A8

Areas considered in an FWA scenario in rural US

City	Population (thousands)	Area (km^2)	Population density (thousands/km^2)
Elmira, New York	35	25	1.4
Mitchell, Indiana	4	5	0.7
Shelbyville, Tennessee	17	21	0.8
Average	**19**	**17**	**1.1**

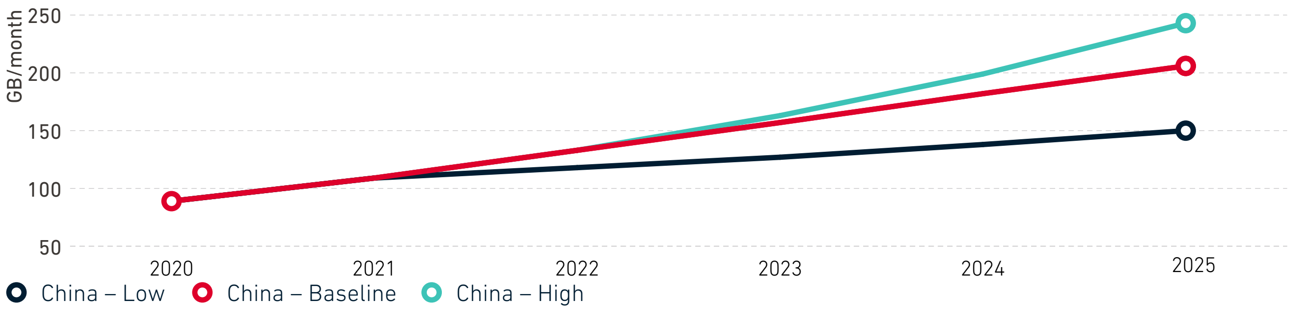
Source: GSMA Intelligence

Figures A5, A6 and A7 present our forecasts of household average data consumption for each scenario for the period to 2025. We produced three forecasts to evaluate the cost effectiveness of the two deployment strategies:

- Low case: data consumption growth slows down (compound annual growth rate (CAGR) between 6% and 11%, depending on the scenario).
- Baseline case: data consumption linearly grows over the period at a similar rate experienced in recent years (CAGR between 13% and 18%, depending on the scenario).
- High case: data consumption exponentially grows over the period (CAGR between 17% and 22%, depending on the scenario).

Figure A5

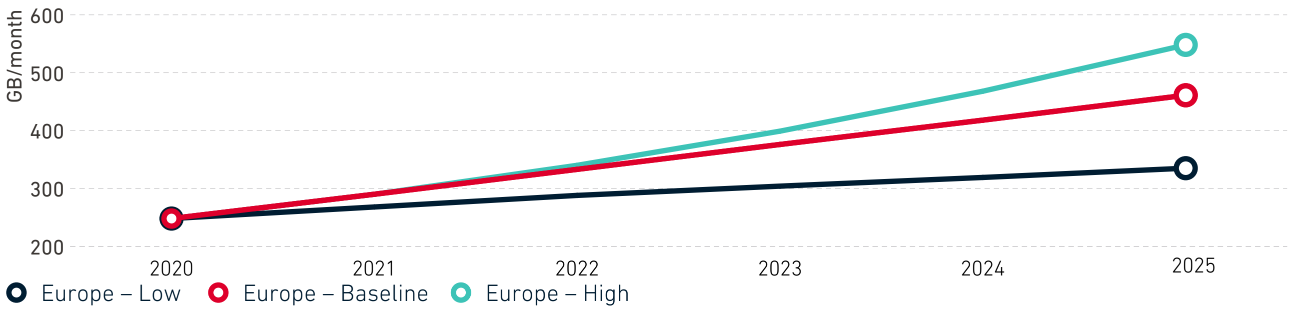
China: average household data consumption forecasts, 2020–2025



Source: GSMA Intelligence

Figure A6

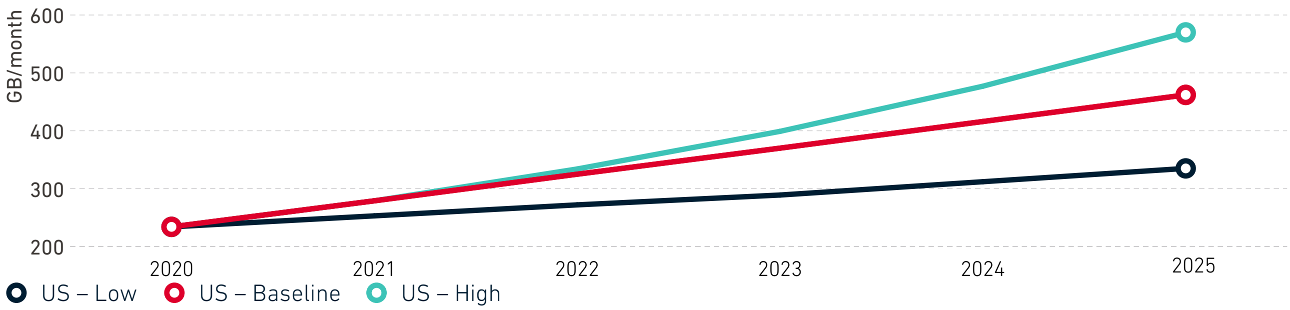
Europe: average household data consumption forecasts, 2020–2025



Source: GSMA Intelligence

Figure A7

US: average household data consumption forecasts 2020–2025



Source: GSMA Intelligence

We analyse the results based on several factors impacting the intensity and direction of traffic demand: the data consumption growth scenarios, the busy hour share of traffic, the subscription rate of households to the FWA service and the downlink share of total traffic.

ii Supply module

The supply module relies on two steps:

- First, we determine the number of macro sites needed to cover the area we study and to enable 100 Mbps download speeds and 50 Mbps upload speeds experienced by all households.
- Second, we determine whether this initial macro site network is capable of meeting uplink and downlink traffic demand. Wherever this initial macro network is not capable of meeting traffic demand, we further densify the network by calculating the number of macro and small sites needed to fill capacity gaps.

The initial number of macro sites needed to cover the area is based on assumptions on the inter-site distances required to cover a given area and enable the level of download speeds required, both for a mmWave-enabled network and a 3.5 GHz-enabled network. Given the uncertainty surrounding areas for deployment and the recent technological advances in mmWave propagation, we consider that more mmWave sites than 3.5 GHz sites would be needed to cover the area (Configuration 1 in Table A9), but we also explore the model sensitivity to a scenario where more 3.5 GHz sites than mmWave sites would be needed (Configuration 2 in Table A9). This could happen, for instance, when UEs are high-power rooftop-mounted CPEs and/or when the terrain presents few obstacles to propagation.

Table A9

Inter-site distances assumptions for 100 Mbps downlink and 50 Mbps uplink speeds

Region	Configuration 1		Configuration 2	
	3.5 GHz	mmWave	3.5 GHz	mmWave
China	800	600	770	960
Europe	900	700	760	920
US	2,500	2,200	1,480	2,950

Source: GSMA Intelligence

The number of macro and small sites needed to fill capacity gaps is based on downlink and uplink capacity per cell,[28] assuming a TDD DL/UL[29] ratio of 75%. In case there are any capacity gaps in downlink or uplink traffic, we assume the operator would fill these gaps with further site densification and, in practice, we take the maximum of the number of sites required to fill uplink and downlink gaps. To determine the number of small sites, we assume that they would represent 10% of macro cells in China, 50% in Europe and 0%[30] in the US.

28 In practice, we assume that each cell could satisfy traffic demand of up to 80% of its theoretical throughput capacity, before users start to experience reductions in their quality of experience.
29 Time division duplex downlink to uplink ratio
30 We do not expect small sites to be placed in rural locations in the US.

Table A10

Technical assumptions

Region	Frequency band (GHz)	Macro/ small cells	Number of sectors	UL/DL ratio	DL spectral efficiency (bps/Hz/cell)	UL spectral efficiency (bps/Hz/cell)	Duplexing
China	3.5	Macro	3	25%	3.2	1.6	TDD
China	3.5	Small cell	2	25%	3.2	1.6	TDD
China	28	Macro	3	25%	5.1	2.6	TDD
China	28	Small cell	2	25%	5.1	2.6	TDD
Europe	3.5	Macro	3	25%	3.2	1.6	TDD
Europe	3.5	Small cell	2	25%	3.2	1.6	TDD
Europe	26	Macro	3	25%	5.1	2.6	TDD
Europe	26	Small cell	2	25%	5.1	2.6	TDD
US	3.5	Macro	3	25%	3.2	1.6	TDD
US	3.5	Small cell	2.5	25%	3.2	1.6	TDD
US	28	Macro	3	25%	5.1	2.6	TDD
US	28	Small cell	2.5	25%	5.1	2.6	TDD

Source: GSMA Intelligence

Table A11

Bandwidth availability assumptions

Region	Frequency band (GHz)	2020	2021	2022	2023	2024	2025
China	3.5	100	100	100	100	100	100
China	28	0	0	0	800	800	800
Europe	3.5	80	80	80	80	80	80
Europe	26	400	400	400	400	400	400
US	3.5	25	25	50	80	80	80
US	28	400	400	400	400	400	400

Source: GSMA Intelligence

To reflect that in the period to 2025 outdoor 5G infrastructure will be deployed to serve mobile users and that FWA infrastructure will most likely be built in brownfield locations.[31]

Based on the assumptions above, the model estimates the following quantities, both for a mmWave-enabled network and a 3.5 GHz one:

- the number of brownfield macro sites upgrades
- the number of greenfield macro sites
- the number of greenfield small sites.

31 Inter-site distance of 316 meters in China, 716 meters in Europe and 1,418 meters in the US.

iii Cost module

Table A12 presents our estimation of the capex and opex associated with each type of site, as well as those associated with customer premises equipment. Our estimation relies on a bottom-up costing approach based on the different cost items associated with capex (equipment, backhaul, service and installation) and opex (energy costs, shelter lease, maintenance and optimisation). We also include capex and opex figures associated with customer premises equipment. Data sources include the GSMA Intelligence Network Economics model, internal interviews, and external interviews with vendors and operators.

Table A12

Cost assumptions

Region	Item	Capex	Opex
China	3.5 GHz upgrade of a brownfield macro site	$39,000	$13,000
China	3.5 GHz new greenfield macro site	$88,000	$14,900
China	3.5 GHz new small site	$20,700	$2,400
China	3.5 GHz CPE	$300	$14
China	mmWave upgrade of an existing brownfield macro site	$48,000	$12,800
China	mmWave new greenfield macro site	$95,000	$14,700
China	mmWave new small site	$24,700	$2,300
China	mmWave CPE	$300	$14
Europe	3.5 GHz upgrade of a brownfield macro site	$54,000	$15,200
Europe	3.5 GHz new greenfield macro site	$125,000	$23,000
Europe	3.5 GHz new small site	$33,000	$2,800
Europe	3.5 GHz CPE	$330	$15
Europe	mmWave upgrade of an existing brownfield macro site	$73,000	$15,000
Europe	mmWave new greenfield macro site	$141,000	$22,800
Europe	mmWave new small site	$38,000	$2,700
Europe	mmWave CPE	$330	$15
US	3.5 GHz upgrade of a brownfield macro site	$67,000	$15,600
US	3.5 GHz new greenfield macro site	$134,000	$21,800
US	3.5 GHz new small site	$36,000	$2,700
US	3.5 GHz CPE	$390	$21
US	mmWave upgrade of an existing brownfield macro site	$93,000	$15,500
US	mmWave new greenfield macro site	$157,000	$21,700
US	mmWave new small site	$43,000	$2,600
US	mmWave CPE	$390	$21

Source: GSMA Intelligence

A3 Indoor scenario

Our model relies on three modules to estimate the total cost of ownership associated with each of these two deployment strategies:

- traffic demand module
- supply module
- cost module.

i Traffic demand

Traffic demand estimation is based on three factors:

- the number of devices and the share of devices on 5G
- the download and upload speeds required for each type of device
- the share of devices concurrently downloading or uploading data.

Traffic demand (downlink or uplink) = $\sum$*(number of devices * speed requirement * share of devices concurrently active)*

Table A13 presents the number of devices assumed in the office and their download and upload speeds requirements.

Table A13

Number of devices and speed requirements assumptions

Device	Total number of devices	DL speed required (Mbps)	UL speed required (Mbps)
Mobile devices	1,800	50	10
Desk phones	1,875	0.1	0.1
Laptops	1,875	50	10
Security cameras	375	2	25
Standard communication devices in conference rooms	38	50	25
Advanced communication devices in conference rooms	38	100	50

Source: GSMA Intelligence

We let the share of laptops and communication devices concurrently active vary and we assume that 10% of mobile devices and 100% of security cameras are concurrently active. We assume that the office features communication devices in conference rooms and that this equipment could either be standard (e.g. HD video) or advanced (e.g. AR/VR or holographic communications).

ii Supply module

On the supply side, we assume that a fixed share of devices is on 5G, while the rest is either served by Wi-Fi or Ethernet. We also assume that 100% of communications equipment deployed in conference rooms is on 5G.

Regarding mobile network coverage from outdoor, we assume that this is limited and that only 10% of download traffic on 5G and 5% of upload traffic on 5G can be offloaded to an outdoor 5G network.

We estimate the number of 3.5 GHz and mmWave indoor small cells in two steps:

- First, we assume that 15 3.5 GHz small cells would be placed indoors to complete mobile coverage in the office.
- Second, we calculate the number of additional 3.5 GHz small cells or mmWave small cells that would be needed if traffic demand generated by the different device types cannot be met by the initial 3.5 GHz deployment.[32]

We calculate throughput capacity by multiplying downlink or uplink spectral efficiency with available bandwidth and with the TDD UL/DL ratio. Table A14 presents the technical assumptions used to determine throughput capacity.

Table A14

Technical assumptions

Technology	Frequency band (GHz)	TDD UL/DL ratio	DL spectral efficiency (bps/Hz/cell)	UL spectral efficiency (bps/Hz/cell)	Bandwidth (MHz)	Duplexing
3.5 GHz	3.5	50%	9	6.75	80	TDD
mmWave	28	50%	9	6.75	400	TDD

Source: GSMA Intelligence

32 The number of indoor sites needed to fill capacity gaps is calculated as:

$$\text{Number of sites needed for capacity} = \max\left(\frac{\text{downlink capacity of sites needed for coverage-downlink traffic demand}}{\text{downlink capacity of 3.5GHz or mmWave}}, \frac{\text{uplink capacity of sites needed for coverage-uplink traffic demand}}{\text{uplink capacity of 3.5GHz or mmWave}}\right)$$

iii Cost module

Table A15 presents our estimations of the capex and opex costs associated with either 3.5 GHz small cells or mmWave small cells. We also assume a centralised unit cost per project of $1,200. Our estimation relies on a bottom-up costing approach based on the different cost items associated with capex (equipment, backhaul, installation) and opex (energy costs, yearly software update, optimisation and maintenance). Data sources include the GSMA Intelligence Network Economics model, internal interviews, and external interviews with vendors and operators.

Table A15

Cost per cell assumptions

Frequency band	Capex	Opex
3.5 GHz	$4,700	$911
mmWave	$5,700	$934

Source: GSMA Intelligence

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