GSMA

5G mmWave Coverage Extension Solutions Whitepaper

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1. Contributors and Reviewers

2. Executive Summary

Mobile operators are deploying millimetre wave (mmWave) 5G networks in crowded locations, such as sports arenas, stadiums, airports, concerts, busy shopping streets and other large venues. Operating at frequencies of 24 GHz and higher, these 5G Frequency Range 2 (FR2) networks are able to deliver multi-gigabit data rates and very low latency [1]. The mmWave bands offer a 10-fold increase in available contiguous bandwidth compared to sub-6 GHz 5G Frequency Range 1 (FR1) bands. As a result, mmWave networks can handle a greater number of connections, while also boosting the peak data rates for individual devices.

This is the fourth document in GSMA 5G mmWave Accelerator series. It looks at mmWave coverage solutions to improve the performance of 5G mmWave networks in both indoor and outdoor scenarios.

The chapter on 5G mmWave deployment scenarios explores the various aspects of capacity, considering how high-density outdoor hotspots can add 5G mmWave capacity to reduce the need for additional site builds. 5G mmWave networks are also particularly well suited to meeting the demand for data connectivity inside public buildings. For businesses, private 5G mmWave networks can be designed to deliver specific capability, such as ultra-low latency or massive bandwidth, to support high levels of automation, for example.

The chapter on 5G mmWave coverage solutions looks at innovative ways of utilising mmWave as backhaul, fronthaul and air interface connectivity. For example, integrated access backhaul, which has different configurations and antenna deployment options, can reduce the number of base station sites that require fibre backhaul, allowing for faster deployments and lower costs.

The chapter on coverage cost analysis shows the benefits of 5G mmWave in three different scenarios; in dense urban environments, deploying mmWave in a 3.5GHz 5G network can lower total cost of ownership (TCO) by up to 35%. In suburban and rural fixed wireless access (FWA) deployments, 5G mmWave can provide a TCO reduction of up to 34%. Interestingly, when 5G mmWave is used indoors – and 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%.

Although there are technical benefits from network densification with mmWave solutions, the network planning and site acquisition required to achieve it presents challenges for operators. The final chapter of the report looks at how 5G mmWave solutions can actually assist in resolving planning challenges and open up new coverage opportunities.

3. 5G mmWave Deployment Scenarios

3.1 High Density Outdoor Hotspots

Deployment of 5G networks using mmWave spectrum, which offers an abundance of bandwidth, will significantly improve the user experience and network capacity, particularly in dense and heavy traffic areas.

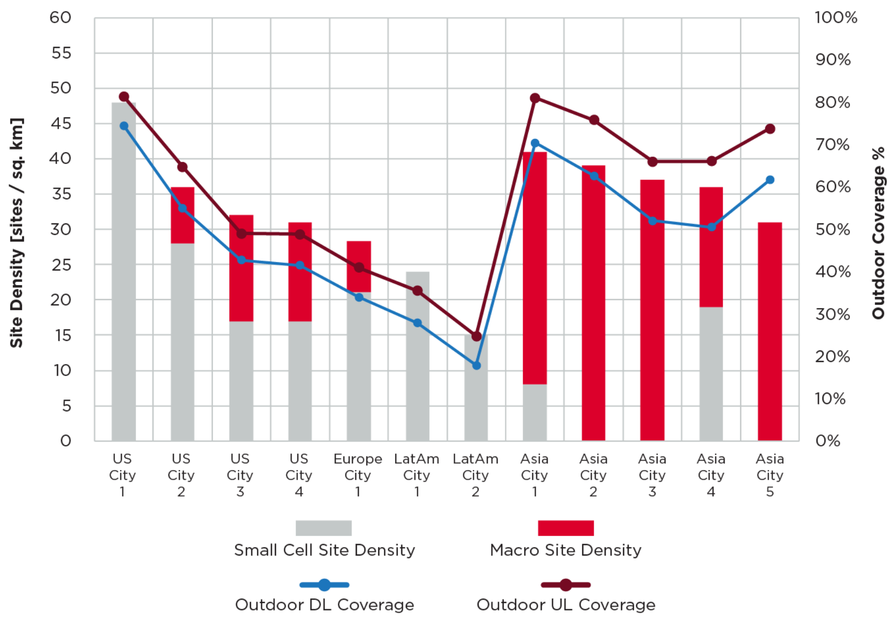
Operators planning 5G mmWave deployments in crowded outdoor areas may start by co-siting 5G sites with existing LTE sites. Any coverage gaps that will exist with co-siting could be fixed by deploying additional macro or small cells, depending on the space availability, local regulation and other factors.

Studies have shown that co-siting 5G mmWave with existing sites could provide significant mmWave coverage, particularly in dense clusters, which are the target of a 5G mmWave deployment.

Figure illustrates the coverage simulation results[1] of co-siting 5G 28 GHz sites with existing LTE sites in different cities. It shows site densities in terms of macro sites (transmit power higher than 60 dBm), as well as small cells (transmit power less than 54 dBm). With such co-siting, downlink (DL) coverage, as a percentage of the cluster, is typically higher than uplink (UL) coverage, owing to the link imbalance that is a common feature of in cellular systems.

The right vertical axis represents the mmWave coverage as a percentage of the cluster area. Note, higher existing site densities typically lead to higher mmWave coverage.

Figure 1: 5G mmWave coverage for different site densities worldwide

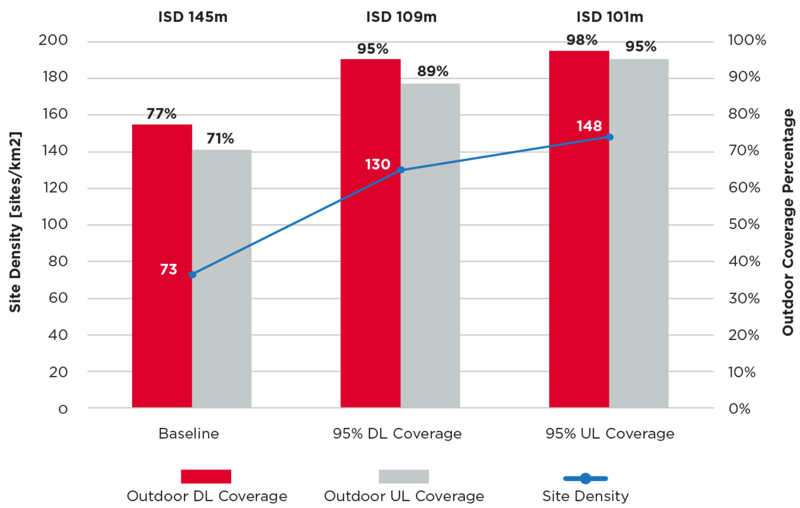


1 Assumptions: 3GPP 38.900 Umi/Uma propagation models, 256 x2 (V&H) antennas at gNodeB, 133 dB Maximum Allowable Path-Loss, 0.4 & 0.1 bps/Hz DL & UL spectral efficiency. Site and geo database used. Foliage and other losses considered.

To illustrate the additional step of improving the 5G mmWave coverage to meet a certain target - 95% coverage for downlink and uplink - we considered a 0.8 km2 cluster within a US city with 8 macro and 51 small cells, with a resulting site density of 73 sites per km2. The existing inter-site density (ISD) of 145 meters generated 77% downlink and 71% uplink outdoor 5G mmWave coverage.

Additional densification is needed to achieve the 95% downlink and uplink target coverage, as illustrated in **Error! Reference source not found.**. To achieve 95% downlink coverage, an additional 46 small cells are required, bringing the site density to 130 sites per km2 with ISD of 109 meters. To achieve 95% uplink coverage, an additional 61 small cells are needed, bringing the site density to 148 sites per km2 with an ISD of 101 meters.

Figure 2: 5G mmWave coverage improvement via densification



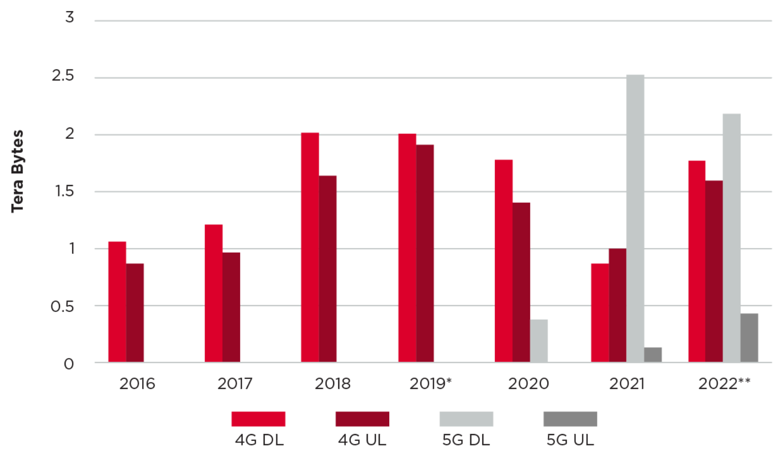
3.2 Inside Public Buildings

Public buildings with high user density will benefit from the extensive capacity that mmWave deployments bring.

Stadiums and Sports Venues

Stadiums generate heavy cellular data consumption, involving relatively high levels of uplink traffic, compared to typical macro network deployments. Figure illustrates the data volume trend[2] for a major operator during the US Super Bowl, one of the world's most prominent sports events. The year-over-year data consumption growth is evident[3], reaching about 6 TB in the 2022 game. A significant portion of the data is consumed in the uplink direction.

Figure 3: Super Bowl data volume trend between 2016 and 2022



5G mmWave networks can bring gigabit speeds to spectators, thus enabling data-hungry applications and enhanced personalised experiences exclusive to the venues. For example, the connectivity can be used to provide video streams of particular players or performers, personalised on-demand instant replays and the sensation of watching the game from almost any seat at the stadium. These personalised experiences are enabled by the vast amounts of capacity that mmWave spectrum brings to a sports venue.

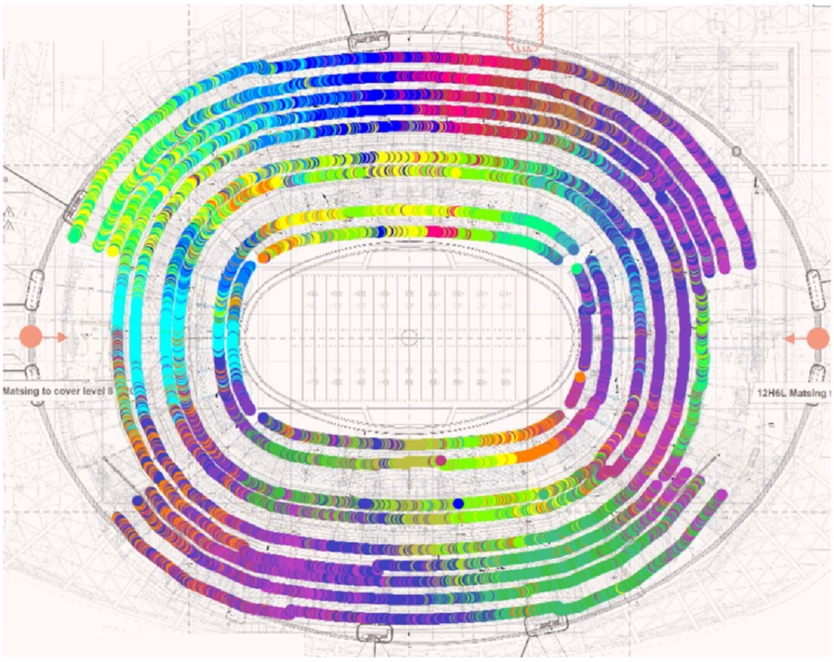
2 Data consumption within the stadium only for the game window, excluding parking lot

3 2021 game had lower attendance due to pandemic

In addition to the above benefits, 5G mmWave networks can be deployed in stadiums in a way that circumvents the potential range, signal propagation, and non-line-of-sight (NLOS) limitations. Coverage in the stadium seating area, where most cellular data is consumed, is typically achieved via LOS installed antennas, thus eliminating the penetration losses associated with high bands. Additionally, sports venues' architecture and structure mean their 5G mmWave deployments rarely suffer from foliage attenuation. Moreover, the coverage in the seating area is usually achieved via antennas installed within a relatively short range, thus eliminating the possibility of the signal decay associated with longer range mmWave macro deployments.

Owing to their massive capacity, the number of mmWave sectors needed to cover a sports venue is less than the number of low-band or mid-band sectors needed to cover the same venue. That reduces the number of antennas and hardware to be installed. Massive multiple-input/multiple-output (MIMO) techniques, superior antenna directivity and beamforming can further enhance the performance of mmWave deployments in stadiums. Figure illustrates the radio frequency (RF) scanner measurements, where different colours represent different best physical cell identifiers (PCIs), also known as Generation Node B (gNB), of a 5G mmWave deployment in a football stadium in North America. The well-defined sectorisation in the venue is achieved with minimal inter-sector interference.

Figure 4: Best PCI plot of a mmWave deployment in a stadium in North America



3.3 Private Networks

5G mmWave private networks can bring massive network capacity to factories, warehouses and offices. These networks also enable low latency applications within these enterprises, improving efficiency and transforming industries. Very wide bandwidth, combined with low transmission time intervals (TTI), make 5G mmWave networks ideal to serve such applications.

Table 1 outlines some common private network use cases that require high-speed throughput and/or very low latency, making them prime candidates to be served via mmWave deployments.

Table 1: Typical private network use cases with sensitivity and throughput requirements

Use Case	Latency sensitivity	Required DL throughput	Required UL throughput
Factory robot / AGV	20 ms	2-5 Mbps	2-5 Mbps
XR	10+ ms	30-100 Mbps	10-40 Mbps
Security guard body camera	50-100 ms	2 Mbps	25 Mbps (4K quality)
CCTV	50-100 ms	2 Mbps	25 Mbps (4k quality)
Smartphone or laptop	100s ms	50 Mbps	10 Mbps

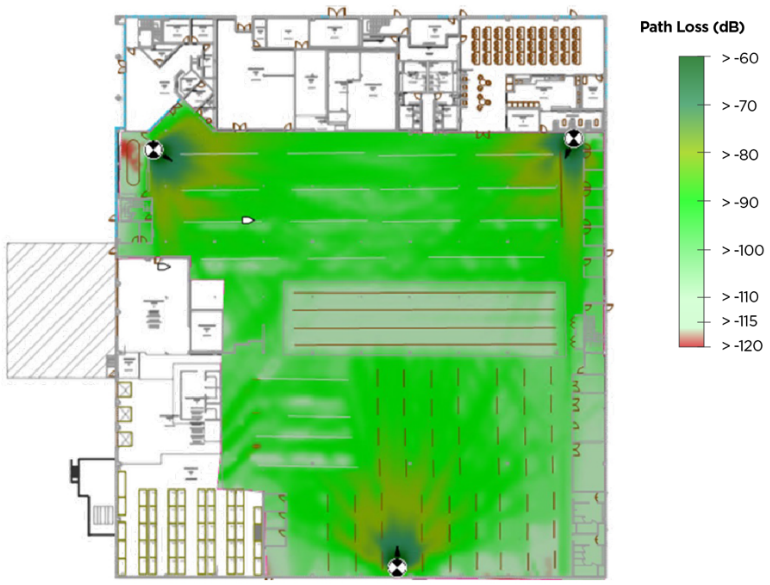
Simulations have shown that co-siting 5G mmWave antennas with existing Wi-Fi access points can provide excellent 5G mmWave coverage.

Figure shows simulation results for co-siting 5G NR mmWave gNodeB antennas with existing Wi-Fi access points in a 27,600 sq ft office environment[4]. Almost ubiquitous 5G mmWave coverage with gigabit speeds was achieved in such a scenario.

Figure 5: Co-siting 5G NR mmWave gNodeB antennas with existing Wi-Fi access points

In a similar manner, simulations have shown that ubiquitous 28 GHz coverage can be achieved in an open plan manufacturing environment using a small number of antenna elements. In Figure, a 5,000 sf ft manufacturing facility, with a challenging environment, could be covered using just three Generation node b (gNB) antenna locations, providing gigabit speeds to users.

Figure 6: 5G mmWave coverage in an industrial environment



4 Assumptions: 28 GHz; each gNB antenna: 128x2 elements and 16 horizontal beams; minimum 0.4/0.1 bps/Hz for downlink/uplink data and control; 800 MHz downlink bandwidth and 100 MHz uplink bandwidth with 7:1 DL:UL 40dBm EIRP [32 dual pole elements]TDD. gNB EIRP 40dBm [32 dual pole elements]

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3.4 FWA Deployment on Macro Site with Extended Range

The large unserved demand for broadband connectivity can be met most cost-efficiently with FWA when it is built on the large installed base and global reach of 3rd Generation Partnership Project mobile technologies (4G LTE and 5G NR). Mobile operators can deploy FWA together with mobile broadband in existing and new spectrum bands, thanks to the options for ensuring efficient spectrum sharing between the two services. Mid-bands using time division duplex (TDD) and low-bands using frequency division duplex (FDD) are sufficient in many FWA cases. High-end offerings in urban and suburban areas often require additional capacity. In these cases, “high-band” mmWave spectrum, such as 26GHz and 28GHz, can be added to the macro sites.

While mmWave spectrum is often associated with dense deployments, with each site covering only a few hundred meters, a new innovation, known as mmWave extended range [2][3], can expand the use of mmWave spectrum for FWA to sparser suburbs and semi-rural areas as well. The principle is illustrated in Figure 7, where a macro cell site serving a range of several kilometres has been equipped with 5G NR for both mid-band and mmWave radios. As all spectrum assets are available for FWA services in the entire sector, the system will automatically serve homes with mmWave coverage, primarily using mmWave spectrum (shown in orange), while other homes without mmWave coverage will be served by mid-band spectrum (shown in black).

Figure 7: mmWave extended range can be used to provide FWA across several km

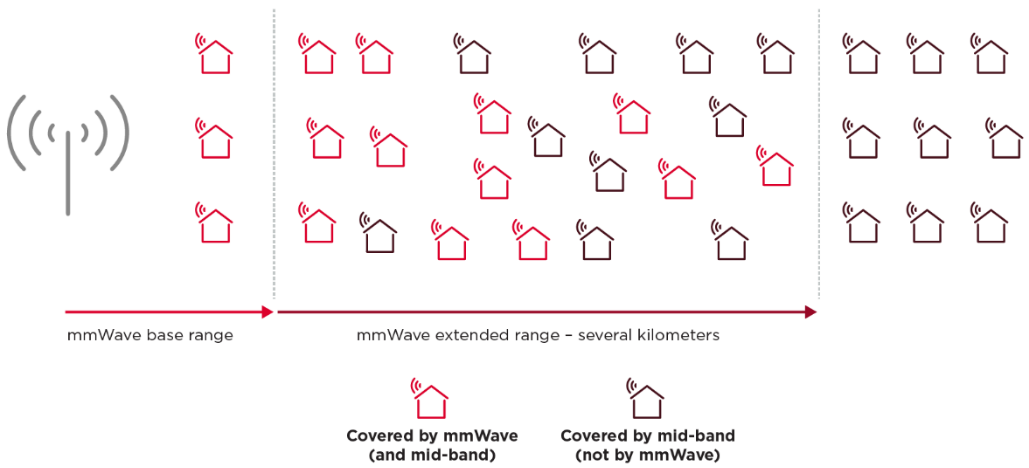


Figure 7 shows a macro-cell site equipped with 5G NR for both mid band and mmWave, in which well-located homes at a range of several kilometres can be served using mmWave extended range.

4. 5G mmWave Coverage Solutions

Key to customers' experiences of a mobile network, coverage is tightly related to the cost of hardware deployment. A full-function gNB can offer wide coverage and high capacity, but the ROI (return on investment) should also be considered. To address this concern, different network nodes with lightweight functionality were iteratively discussed in 3GPP NR Rel-16 and later versions.

The purpose of deploying these network nodes is to reduce the TCO (total cost of ownership) by lowering design complexity and reducing deployment cost. IAB (integrated access and backhaul) has reduced the backhaul deployment effort for wireless technology. Repeaters, which extend the original signal source to improve coverage, have long been used in Wi-Fi and 2G/3G/4G networks. New smart repeaters process side control information and utilise a phased array antenna to serve the user equipment (UE) more intelligently.

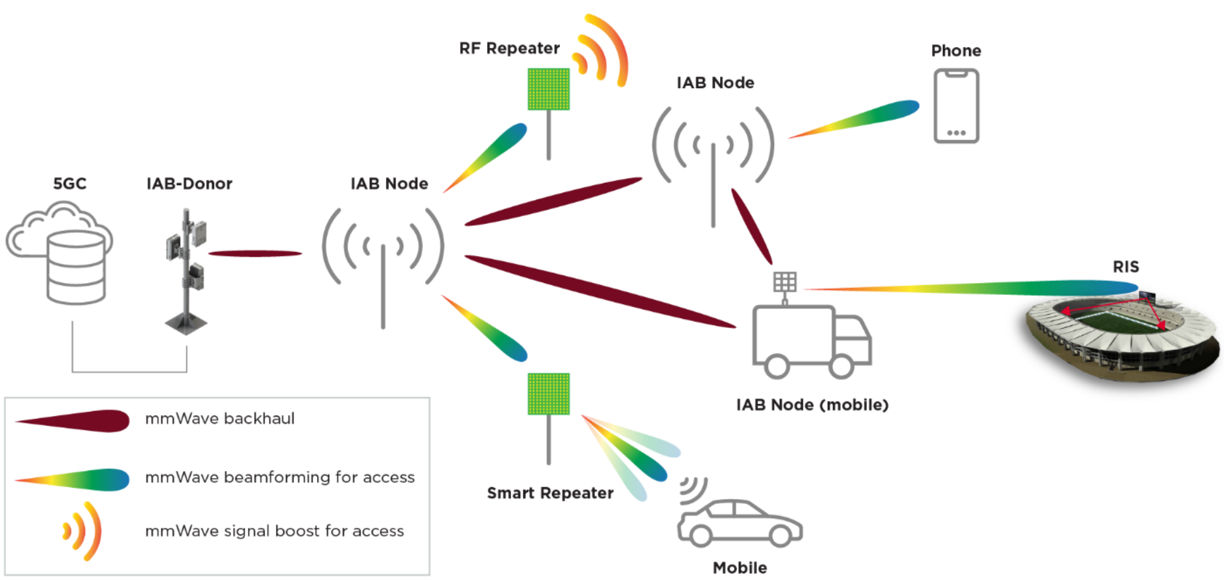
In this chapter, we will mainly talk about how antennas impact the cost, performance and coverage of a radio.

4.1 Integrated Access Backhaul

Architecture

Initially defined in Rel-16, integrated access backhaul (IAB) does not require wired backhaul and acts as a relay node to extend the network access. It lowers the deployment cost and operational effort by reducing the need for dedicated backhaul and complex construction of fibre wiring maintenance. A gNB with additional functionality acts as the IAB-donor and connects to the 5GC (5G core network) as a backhaul link (see Figure 8). An IAB-node can act as a relay to connect another IAB-node via an access link to the IAB-donor.

Figure 8: An overview of different network nodes - IAB and repeater topology



As shown in Figure 8, there are two complementary topologies. A ST (spanning tree) topology enables an IAB node to connect to an IAB-donor via other IAB nodes to support multi-hop connections for backhaul. A DAG (directed acyclic graph) topology creates multi-connections and multi-routes that are used for backhauling redundancy, concurrence for high availability back-up and load balancing purposes.

This means an IAB node is capable of multiple connections and multiple routing for both backhaul and access. This implies that there are multiple sets of antennas, and these antennas may be of specific types depending on the requirement, performance, and cost of the applications.

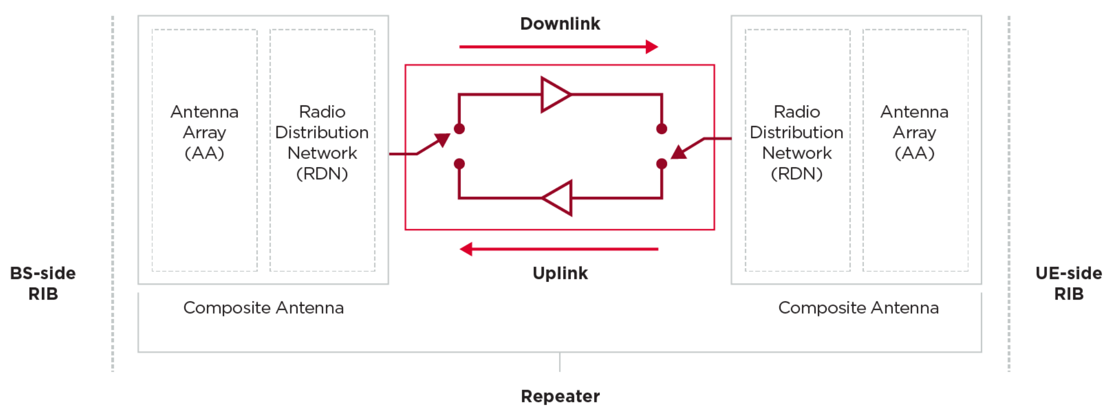
In-band and out-of-band

Since IAB is designed with multiple sets of radio for backhaul and access, the performance of the backhaul link should be considered when in duplex operation mode and the occupied bandwidth for throughput should also be considered. The full-duplex solution should be studied for an in-band scenario where backhaul and access operate in the same FR2-1 frequency band: 24,250 MHz – 52,600 MHz. However, it would be more efficient for out-of-band scenarios for backhaul and access to operate in different frequency bands. Although the access link has to operate in the same frequency band as the user equipment, the backhaul links have more flexibility (as the application requirements are fulfilled on the access side). As it is connected directly point-to-point, the backhaul link is normally static. Hence, higher frequency bands with wider bandwidths, such as FR2-2: 52,600 MHz – 71,000 MHz, can be employed.

4.2 Repeater

Whereas IAB is capable of supporting new cells, the RF repeater simply extends the signal coverage (as shown in Figure 8). When a repeater is connected to the IAB, it could also act as a gNB, to re-transmit the signal. Lightweight repeaters designed for coverage improvements can be cost-effective and easy to deploy.

Figure 9: Radiated reference points for repeater type 2-O



([4] 3GPP TS 38.106. NR Repeater Radio Transmission and Reception)

As with IAB, the repeater is designed with at least two sets of multiple antennas (see Figure 9) as stipulated in NR Rel-17. It connects with two sides; one is a base station (IAB or gNB) and another is the user equipment.

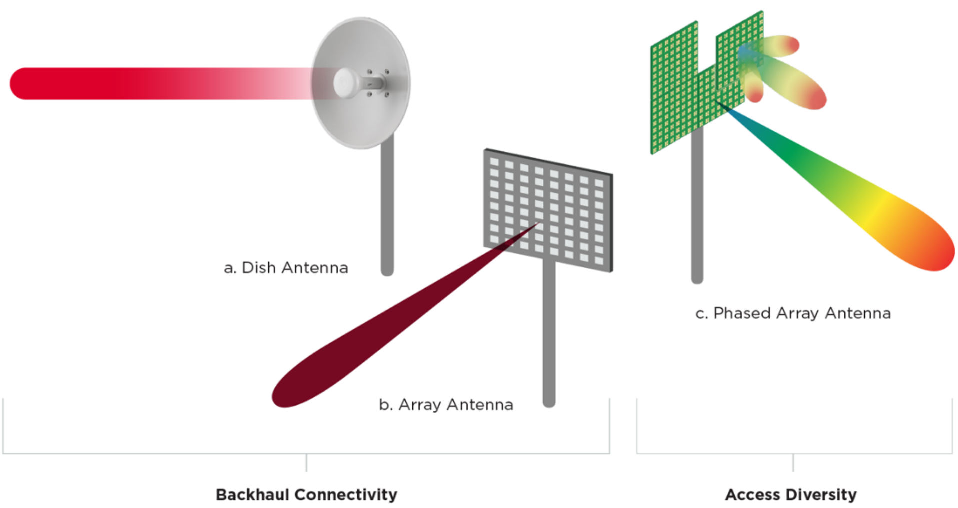
A **RF repeater** acts as a reply node and transparently amplifies-and-forwards traffic to both sides bidirectionally. It effectively boosts the signal to extend the link and coverage, but also potentially increases the noise level that contributes to the overall interference of the system. Thus, a simple RF repeater is unable to meet the performance demands, or support the beamforming and multi-beam operation features, which are functional requirements for NR, especially in the FR2 band.

A **smart repeater** is designed to leverage the advantages of RF repeaters and IAB. As well as processing the side control information, the smart repeater's antenna array is dramatically different to the antenna feature that is shown in Figure 9. To fulfil the various kinds of access requirements of user equipment, phased array antennas are essential. Through the network-controlled capability, multi-beam operation can be used to serve bandwidth-intensive applications (when using MIMO) and track the activities of multiple users through beam scan and steering.

4.3 Coverage Extension by Antenna Technology

As shown in Figure 8, the IAB and repeater are equipped with multiple sets of antennas to support multiple connections in different links, with a view to creating a wider network for extending the coverage. The multiple connections require many antennas sets or multiple beams for communication, while different links are dependent on network capacity and antenna capability. The most important consideration is how the antenna technologies can extend and increase the signal coverage, in a stable and cost-effective way.

Figure 10: Different antenna types for backhaul and access



As shown in Figure 10, there are different types of antennas for specific usages. High power and efficient antenna can reduce the number of network nodes required to achieve the required coverage range. As **backhaul connectivity** needs to supply sufficient bandwidth via a static point-to-point connection, high gain and directional antennas that operate in a high frequency band in FR2-2 are well suited to this purpose. The options include:

- A dish antenna, or parabolic reflector dish antenna (see Figure 10a) is a relatively simple antenna designed to serve one direction.
- An array antenna (see Figure 10b) can form a high directive beam, which would contribute higher gain with larger arrays.

The cost of dish and array antennas is lower than phased array antennas, and higher band (FR2-2) antennas are also smaller, thus reducing deployment and operational efforts.

Access diversity: The access link serves various kinds of user equipment (UE), which could be static or on the move, located near or far, small package or streaming applications. To achieve better coverage and a good user experience, beamforming technology is essential and this means adopting the phase array antenna shown in Figure 10c.

The features and benefits of phased array antenna for coverage improvement are:

1. **Beamforming**: an analog beamforming frontend forms a higher gain and higher directivity beam direct to UE.
2. **Beam tracking**: the beam can be steered to follow the movement of UE.
3. **Multi-beam**: a fully digital beamforming architecture is designed to support multiple radio paths that each connects to a phased array antenna.
4. **MU-MIMO**: each individual beam could aim to a different target UE simultaneously.
5. **Hybrid beamforming**: a mixed architecture of analog and digital beamforming. A beamforming algorithm further merges the multiple beams into one beam to reach a longer distance.
6. **Tile-base**: a flexible design for splicing multiple sets of phased array antennas, to achieve better coverage.

In summary, antenna are a crucial component to fulfil the coverage for different use cases and UE behaviours. In the mmWave band, phased array antenna performs the beamforming required to mitigate the propagation loss and can use their beam tracking capability to optimise the coverage area.

5. Coverage Improvements

In mmWave spectrum, propagation is limited by open space fading loss, signal blockage or reflection by leaves and buildings, and multi-path signal scattering from surrounding obstacles.

To strengthen penetration in a line of sight (LOS) scenario, an array antenna contributes to the high directive radiation gain. Furthermore, beamforming and multi-beam technology can be used to track mobile users.

It is more difficult to compensate for signal loss in non-line of sight (nLOS) scenarios. The most straightforward approach is to extend the signal at the discontinuous path by adopting techniques, such as IAB, repeaters or a distributed antenna system (DAS). Another approach is to refocus or reflect the signal by using a large electromagnetic surface (ES) or reconfigurable intelligent surface (RIS) to address the multipath characteristics of radio waves.

5.1 Deployment Investigation

To provide customers with a good experience, the network needs to meet the overall signal coverage and the bandwidth requirement of applications. At the same time, network providers need to reduce the TCO of the deployment by minimising the capital expense and the operating cost, while maximising the coverage.

Considering all of the technical and operational factors, completing the deployment investigation involves the following five steps:

1. **Identify Application & Scenario Requirements**

   To plan the hardware capability and software features, the network provider needs an overall understanding of the projected data usage, the mobility requirements and the use case.

2. **Field Investigation**

   Investigating the field conditions will help determine the optimum location of base stations for signal coverage, taking into account the latency between access and server for system performance. For example, extending coverage to rural highways could require building out fibre, with the related cost of cables and construction. In such a scenario, IAB may be an option.

   Given the propagation characteristics of mmWave, environmental factors need to be taken into account. Even in LOS deployments, there are many variables that need to be considered and planned for, including seasonal foliage on trees and meteorological conditions, such as fog and rain.

3. **Coverage Simulation & Network Planning**

   A simulation platform can process all the investigated information to generate a reference heat map of coverage. Based on the simulation result, different network nodes with diverse antenna capability could be deployed to reduce TCO.

Compared to radio access networks in the sub 6 GHz band, the deployment of 5G mmWave network nodes need careful analysis to address the non-LOS conditions for retransmitting or reflection. The precise installation location is very important to maximise coverage effectiveness and energy efficiency.

There are use cases that require the provision of temporary network capacity in a specific area, such as a stadium or another venue for sports fixtures, concerts and shows. In this case, wireless backhaul via IAB could offer flexibility of network planning by harnessing mobility. In such venues, there is typically a large LED display. Integrating a reconfigurable intelligent surface (RIS) into the LED panel is an ideal way to support IAB, fill the coverage gap and provide the high bandwidth enabled by 5G mmWave technology.

4. **Implement & Deployment**

   As the network is installed on-site, it should be tested for system compatibility and stability, and then the network availability should be validated.

5. **Evaluate Result & Continuous Optimisation**

   Set a test point to evaluate the entire network performance. The most effective way to optimise the network performance is to collect and feed the field operation results back into the simulation database from time-to-time to reflect the variability of the environment. The subsequent simulations may call for updates to both the hardware and software.

5.2 Network Controlled (optimised overall field coverage)

A modern 5G network is software based and can be configured in real-time to reflect consumption. That gives mobile operators the flexibility to adjust the real-time connection link, radio power and beam behaviours based on the overall network conditions of load and capacity, in order to sustain the network health and coverage.

Network-control functionality in **IAB** can be used to adjust the wireless backhaul link to sustain the availability of link and coverage, as well as maintain the entire network performance. IAB, which supports the ST and DAG topologies for flexible inter-connection, initially creates the topology using the network discovery protocol. An unexpected blockage, resulting from a physical or environmental change, or diverse traffic loads that cause an unbalanced data flow, may trigger adaptations to the topology. Based on the application's requirements, the multi-connection or multi-route could be adopted to boost availability and bandwidth via back-up redundancy, or data concurrence. The network controller can learn how the traffic flow changes over time to better prepare the redundancy link and dispatch the connections to extend the coverage range. It could even check the weather forecast to select the best path when there is both an in-band and out-band backhaul link.

The **network-controlled repeater (NCR)** is enabled by the NCR-MT (mobile terminal) protocol that communicates with the gNB for side control information; and the NCR-Fwd (forwarding) protocol that performs the RF signal transmit and receive between the gNB and UE [5]. The beam index in side control information can help to manage the behaviour of the access link. The coverage depends on the beam-based scan and measurement required to sustain the connection and maintain the performance. Further, **smart repeaters** may enhance the signal quality of amplify-and-forward channels to improve the coverage range, and also select only one-way paths to amplify the signal and reduce the total power consumption. Empowered by the network control system, a mesh network, with a group of smart repeaters, is automatically designed to optimise the overall area coverage, as well as consider the performance trade-off of multi-hops.

Conceptually for non-LOS scenarios, a **reconfigurable intelligent surface** (RIS) can be used to enhance performance and cost effectiveness. The RIS should be controllable to configure the angle of reflection. That enables the RIS to optimise the coverage by automatically changing the reflect angle based on changes in the activities of user equipment in the area.

5.3 Brownfield Integration

To cost-effectively meet the high demand for high-speed connectivity, mobile operators could integrate 5G mmWave into their existing 4G and/or 5G infrastructure.

> **Note:** In brownfield integration that works with legacy 4G networks and the present FR1 systems, the user equipment should support both the NSA and SA mode, and also be equipped with the DC-NR capability.

By integrating 5GmmWave into a brownfield deployment, an operator can extend/fill up the coverage and increase the network capacity. In this way, the mobile operator can improve the overall user experience, while limiting the TCO.

There is a typical integration scenario:

To Consummate the Public Network

> **Note:** By design, 5G telecom protocols provide higher reliability and mobility features than data communication via Wi-Fi and other technologies using licence-exempt spectrum. Private networks are mostly deployed in a specific area or inside a facility, where the high bandwidth and low latency benefits of mmWave technology tend to take priority over coverage.

In almost every public mobile network, there are blind zones without coverage. Deploying a dedicated gNB is usually not a cost-effective option to fill these gaps, particularly in cases involving complex network construction. 5G mmWave infrastructure can be used to provide seamless coverage that works well with existing infrastructure or even offer higher throughput. In-fill 5G mmWave coverage can be cost-effective to deploy and is compatible with the growing number of 5G mmWave devices that are heavily used in urban and indoor environments. For example, an IAB could be used to bridge the open space gNB signal into dense areas and indoor environments, while standalone small cells or repeaters are easy to set up.

6. Coverage Cost Analysis (TCO and $/sqm)

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, operators will need to employ 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.

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. To date, mobile operators' bids in auctions for mmWave bands have not been as high as for lower frequency bands. As a result, licencing mmWave bands is generally cheaper in $/MHz/pop terms.

To be sure, the utilisation of mmWave in mobile has had to overcome major technical challenges [6]. As discussed in previous chapters, mmWave signals travel relatively short distances compared to signals in lower frequency bands; and can be more susceptible to attenuation from trees, buildings and other obstacles. However, the continued growth of mobile data traffic plays to the strengths of mmWave bands, as mmWave can accommodate more capacity and bandwidth than lower frequency spectrum.

As of the end of Q3 2022, commercial 5G mmWave networks had already been launched in eight markets (Australia, US, Italy, Japan, Singapore, Taiwan, Thailand and South Africa)[5], And 5G mmWave solutions are poised to achieve more scale.

Two important signs of market readiness are:

- **mmWave spectrum is now becoming more widely available.** 219 operators in 63 markets are planning to bid in their local spectrum auctions. Some 75 countries have completed mmWave spectrum assignments for 5G, and a number of other countries are about to follow suit [7]. 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 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 to mobile operators. Consumer devices have recently seen remarkable growth, with the launch of the 5G mmWave-capable iPhone 12 series in 2020 giving a boost to the wider adoption of the technology. By the end of 2021, 854 5G mmWave products (SKUs) had been launched by 52 companies. These are predominately smartphones.

As 5G roll outs progress at pace, and the mmWave ecosystem matures, the main question that the mobile industry faces today is where and when mmWave solutions can be most cost effective. In this section, we focus on the critical question of its deployment costs.

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

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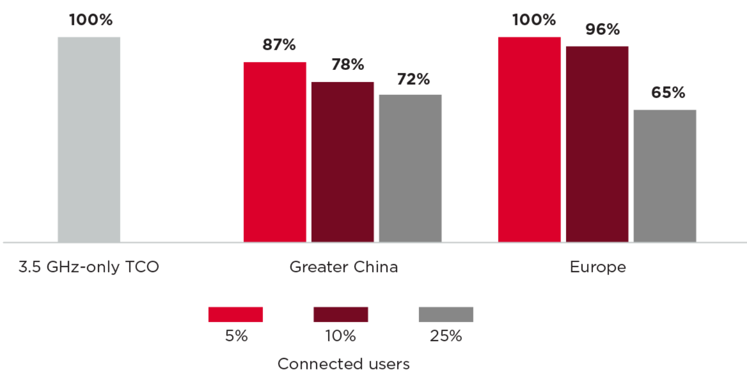
This chapter considers a range of scenarios where the high throughput and network capacity of 5G mmWave, both downlink and uplink, can lead to cost-effective targeted deployments in the period between now and 2025. It also explores and dissects the conditions under which these deployments could be cost effective, before evaluating the cost effectiveness of deploying 5G mmWave solutions in the six different scenarios:

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

The modelling exercise shows the following:

1. **Dense urban scenarios (Greater China and Europe):** A mixed 5G network, using both 3.5 GHz and mmWave spectrum, can be cost effective in delivering at least 100 Mbps download speeds for 5G services, 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, modelling shows that deploying mmWave solutions to deliver this additional capacity layer could bring cost efficiencies, compared to the use of only 3.5 GHz. This model assumes the proportion 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 (see Figure 11). In Europe, assuming that 400 MHz of mmWave and 80 MHz of 3.5 GHz spectrum are available per operator, a mixed 3.5 GHz and mmWave 5G solution could be cost effective if the proportion of connected users at peak times is 10% or above (see Figure 11).

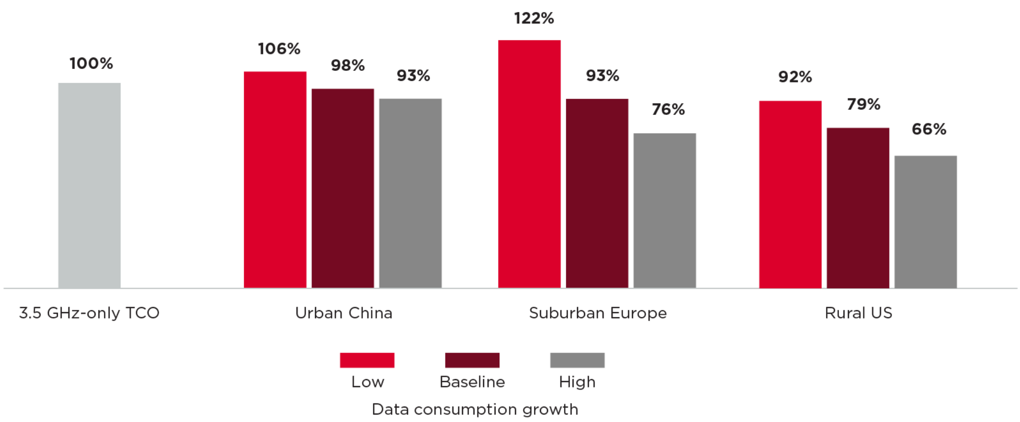
Figure 11: Net present value of TCO for a 3.5 GHz + mmWave 5G network



FWA scenarios: Deploying a 5G fixed wireless access (FWA) network using mmWave spectrum can also be cost effective when compared to a 3.5 GHz 5G FWA network. Under the central assumptions in the model, 5G mmWave FWA deployments in urban China, suburban Europe and a rural US town would be cost-effective, if 5G FWA is able to capture a good percentage of the residential broadband market demand (see Figure 12). 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. Employing mmWave 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. The validity of the assumptions underlying this sensitivity will vary for different cases though, as the results are dependent on capacity gaps emerging in a few localised spots in the area.

Hybrid network: Deploying some 5G mmWave gNB within a 5G network could save telecom TCO up to 71%, according to the GSMA intelligence whitepaper: *The Economics of mmWave 5G*. This saving is most apparent in areas that have high average data throughput and high peak data needs. In this use case, the mmWave gNB could handle higher data usage and be more responsive than legacy base stations, while also offering better power efficiency. Such scenarios could be V2X applications that require high data processing, but less frequent usage; and FWA for high-speed, last-mile connectivity.

Figure 12: The NPV for TCO for a 5G mmWave FWA network

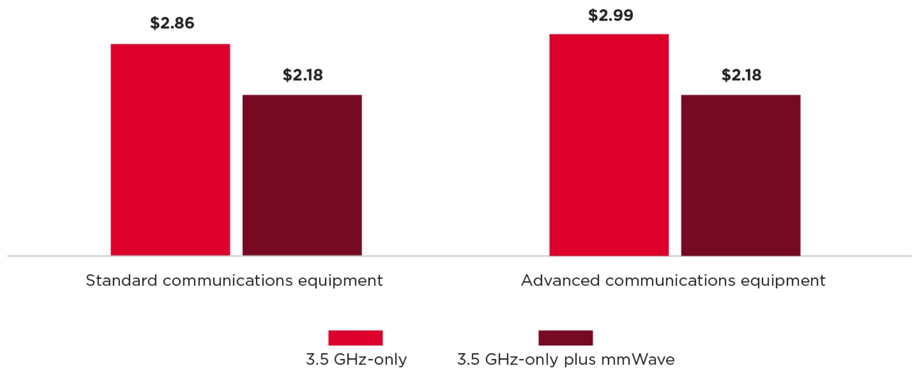


Indoor office scenario: On baseline assumptions, a 5G mmWave indoor network is cost effective and generates cost savings for operators between 5% and 20% compared to the TCO of a 3.5GHz-only network [7]. In cases where most of the data traffic from devices is carried by indoor 5G services, a mmWave network could generate cost savings of up to 54% [7]. The precise value depends on the share of devices concurrently active and to what extent there is the need to provide connectivity to advanced video communications (XR/VR/AR) equipment.

Public 5G networks cannot necessarily meet all the connectivity demands from vertical applications. However, the Open RAN/vRAN architecture and the release of new frequency bands in some markets are making it easier to deploy private 5G networks that offer the desired performance and reasonable TCO.

Integrating a 5G mmWave private network with the existing network could enable smooth and seamless connectivity. In parallel, the data privacy, network capacity and control latency will all be greatly improved. As well as benefitting enterprises and other end-user organisations, this kind of brownfield integration can meet the need of mobile operators and system integrators for a flexible network architecture.

Figure 13: Cost per square meter in an indoor office space scenario



While our TCO analysis looks at the period to 2025, we expect 5G mmWave 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% (equivalent to $600 billion), with 5G mmWave networks playing an increasingly important role in the delivery of these benefits [7].

7. Network Planning and Site Acquisition

Small cells, network repeaters and, in future, IABs are 5G mmWave solutions that can provide significant network capacity to a localised area. However, the limited coverage of these solutions means mobile operators need to consider that:

1. Sites will need to be deployed close to the intended customer
2. Many new sites will need to be deployed to cover an area

Therefore, these 5G mmWave solutions must be deployed in an efficient, cost-effective way, potentially utilising existing third-party structures close to the end customer.

Identifying the right locations for deploying network sites in a scalable way can be a challenging undertaking for mobile operators. Network planning for mmWave will be greatly aided through combining insights from multiple data sources. These sources may include highly granular network usage insights, crowdsourced data or other sources highlighting at a highly localised level where the user demand is.

The selection of the appropriate mmWave solution (small cell, repeater, RIS, etc.) will depend on the third-party structures available. Typical third-party structures include light poles, power poles, smart poles and building facades. Each has various constraints for the operator to consider including the available space and structural integrity of the infrastructure, the available transmission or wireless backhaul/donor signal, the availability of power, the electromagnetic energy (EME), visual amenity and heritage statuses. As mmWave solutions are highly flexible and typically have a much smaller form factor than previous technologies, mobile operators may be able to overcome historical obstacles and deploy mmWave coverage by matching the solution to the available third-party structure.

A summary of the pros and cons of each typical third-party structures is provided below:

Light poles are an appealing option as there are so many of them (meaning there are plenty to choose from) and often managed by a single group over a wide area. However, modern light poles are often not structurally capable of taking any additional electricity load. Surprisingly, there can also be power supply challenges during the daytime, which is obviously not conducive to the deployment of a mobile site requiring continuous power.

Power poles for overhead power lines are an appealing option as they generally have good structural integrity and, by their very nature, have available power to tap into. Some drawbacks can include strict EME constraints and minimal space available at sufficient height for mobile infrastructure. An additional challenge is that, in many busy urban areas, newer subdivisions or councils have often moved power infrastructure underground, meaning suitable poles can be missing where operators most want to deploy sites.

Smart poles[6] are now being deployed by councils and cities in place of traditional light posts in busy areas. Smart poles come in many variations, but can provide energy efficient LED lighting, cameras for security or traffic analysis, audio speakers, Wi-Fi access and space for operators to install small cell infrastructure, all within an aesthetically pleasing and discrete shroud. These are appealing for operators as they address many of the constraints around small cell deployments.

In areas where there are no suitable poles (light/power or smart), deploying a small cell on a **building facade** can be the best option and can usually be done discretely. However, negotiating leases with individual building owners will often require bespoke processes and lease agreements for each site acquired. This is often time-intensive and less efficient than the bulk approvals approach for utility poles.

Public transport shelters (i.e., train and bus stations/platforms) are locations where operators need to provide a particularly good customer experience. In these locations, large numbers of people spend time on their devices, and there may also be connected advertising screens. That makes public transport stations prime locations for the capacity mmWave provides. These structures, however, can be challenging as EME, structural capacity, power, fibre or a viable donor signal all likely to be constrained. The best option will likely be to utilise another third-party structure nearby to service the area.

Table 2 summarises these considerations and how they relate to each infrastructure type:

Table 2: Considerations for the deployment of 5G mmWave cells on third party structures

	Structural	Power	Available Space	Fibre/ Transmission	Donor Signal	EME	Visual Appeal	Lease Negotiation	Community sensitivity	Availability
Light Pole				Highly Varied	Highly Varied					
Power Pole				Highly Varied	Highly Varied					
Smart Pole					Highly Varied					
Public Transport Shelter				Highly Varied	Highly Varied					
Building Facade				Highly Varied	Highly Varied					

Typically highly constrained/unavailable	Can expect some constraints/availability	Typically not an issue/ readily available

6 A purpose built pole with space for MNO's and other service providers to locate their infrastructure.

The acquisition of new network sites is typically a time-intensive exercise requiring negotiation with multiple third parties, councils, and regulatory approvals. Given 5G mmWave networks will necessitate a large amount of site acquisition, it is important to pursue efficiencies in the process wherever possible. Operators can look to develop standard frameworks for engagements with councils and utilities and even bulk approvals for standardised solutions. Negotiating deployments on utility poles owned/managed by one group for a large region can create economies of scale and result in a win-win for all parties.

In summary, the deployment of 5G mmWave small cells, repeaters, IABs and other solutions will require the acquisition of many new sites. The highly localised coverage that 5G mmWave provides means it is important that operators develop the right processes and invest in the right tooling to identify where mmWave will be most utilised and acquire sites accordingly. There are several common third-party structure types available to deploy mmWave solutions, each with pros and cons. Operators can take advantage of the large number of flexible mmWave solutions to make use of these locations.

Site acquisition overheads can be minimised through bulk agreements and standardised solutions approved by utilities that enable efficient deployments at scale. Ultimately achieving a successful mmWave deployment will require having insights into where the user demand is, flexible mmWave solutions to take advantage of the available infrastructure close to the data traffic and the right site acquisition processes to achieve cost efficiencies at scale. Regulators, councils, utilities and operators should seek to collaborate around 5G mmWave deployments to ensure the right balance is achieved between planning approvals and bringing this new technology to market.

8. References

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9. Abbreviations and Definitions

Abbreviation	Meaning	Abbreviation	Meaning
AiP	Antenna-in-Package	**LNA**	Low-noise amplifier
BPL	Building penetration loss	**LOS/NLOS**	Line-of-sight/ none-line-of-sight
CA	Carrier aggregation	**LTCC**	Low temperature co-fired ceramics
CAPEX	Capital expenditure	**LTE**	Long-Term Evolution
CG	Configured grant	**MHz**	Mega Hertz
CPE	Consumer premises equipment	**MIMO**	Multiple-input/multiple-output
DAS	Distributed antenna system	**mmWave**	Millimetre wave
dB	Decibel	**NSA**	Non-standalone
DC	Dual connectivity	**OPEX**	Operational expenditure
DL/UL	Downlink/uplink	**PA**	Power amplifier
DRX	Discontinuous reception	**PAPR**	Peak-to-average ratio
DU	Donor unit	**PC1**	Power Class 1
EIRP	Effective isotropic radiated power	**PCI**	Physical Cell Identifiers
ES	Electromagnetic surface	**RACH**	Random access channel
FCC	Federal Communications Commission	**RAN**	Radio access network
FDD	Frequency Domain Duplex	**RF**	Radio frequency
FR1/FR2	Frequency Range 1/2	**RFFE**	Radio frequency front end
FWA	Fixed wireless access	**RIS**	Reconfigurable intelligent surface
GaAS	Gallium Arsenide	**RRC**	Radio resource control
GHz	Gigahertz	**RU**	Relay unit
gNB	NR node B	**SDT**	Small data transfer
HPUE	High power UE	**TCO**	Total cost of ownership
IAB	Integrated access and backhaul	**TDD**	Time Division Duplex
KM	Kilometres	**Tx**	Transmitter
IC	Integrated circuit	**UE**	User equipment
ITU	International Telecommunication Union		

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