5G mmWave Deployment Best Practices

November 2022

1. Executive Summary

Mobile operators are deploying millimeter wave (mmWave) 5G networks in crowded urban areas, such as sports arenas, stadiums, airports, concerts 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 [9]. 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 with greater peak individual data rates.

This document looks at the technical mitigation strategies to improve the performance of 5G mmWave networks in both indoor or outdoor scenarios.

1.1 Extending coverage

As mmWave operate in high frequency bands, its propagation characteristics are different from those in low-band and mid-band (FR1) spectrum. In particular, radio signals in the mmWave bands are subject to higher free space loss and higher building penetration loss, among other losses [23].

These losses can be mitigated by deploying antenna arrays. At mmWave frequencies, the wavelength is much smaller than traditional FR1 bands (thus the name millimeter wave). Due to the smaller wavelength, a larger number of antenna elements can fit into smaller antenna form factor and with the large number of antenna elements high gain and adjustable (narrow and wide) beamwidths can be achieved. The antenna arrays also allow for fast beam steering to improve radio link performance towards a particular area.

In any mobile network, devices must maintain an adequate link budget on both the Downlink (DL) and Uplink (UL) for both control signalling and user data. When there is a link imbalance between UL and DL, the usable coverage will be restricted by whichever link is more limiting.

In 4G and 5G networks, the DL coverage footprint of a cell is typically greater than its UL coverage footprint. The imbalance is particularly pronounced in mmWave networks because of the significant antenna array gain the base station has over the user equipment. To mitigate the DL-UL imbalance, several techniques can be adopted:

- Use of low-band spectrum for the UL: low-bands have better propagation characteristics
- Use of high power UE. Several commercial high power UE devices, particularly Consumer Premises Equipment (CPEs), are now available
- Uplink slot aggregation: UL transmission spanning several slots increases UL coverage and improves the cell edge user experience
- Utilisation of Discrete Fourier Transform spread Orthogonal Frequency Division Multiplexing (DFT-s-OFDM)
- Increasing the sensitivity of the base station by employing an antenna-in package subsystem.

For the mmWave mobility use case (power class 3 UE), the DL-UL link imbalance can be particularly large (up to 14dB depending on the assumptions). Use of low-band spectrum for the UL through implementation of the following network capabilities can help an operator overcome this challenge:

- Dual connectivity - either inter- or intra-RAT, i.e., E-UTRA-NR Dual Connectivity (EN-DC) or NR-NR Dual Connectivity (NR-DC) - involving two base stations, with a master node operating in FR1 and a secondary node in FR2
- NR carrier aggregation (NRCA) between FR1 and FR2.

Whilst good progress has been made on delivering DC-based support of FR2 (as demonstrated by the NR-DC live network demo by Telstra, Ericsson and Qualcomm and by TIM's FWA trial performed on EN-DC network), the industry is lagging in support of FR1+FR2 NR CA. Industry support for FR1+FR2 NR CA will help operators to speed up the expansion of their mmWave coverage footprint, thereby accelerating the development of a mmWave ecosystem in their respective markets.

Smart repeaters can also help to improve coverage cost-effectively. This technology can be used to amplify a 5G mmWave signal and then transmit the boosted signal in the required direction. Smart repeaters can be installed easily on streetlights, lampposts, walls and windows, reducing the high cost of a truck roll, complex zoning and trenching to support fibre connections. Smart repeaters promise to accelerate time to market and reduce the cost of deploying mmWave networks to meet the growing demand for capacity and new bandwidth-intensive applications.

1.1.1 How to overcome obstacles in dense urban environments and indoors

The mmWave propagation fading becomes more serious in urban environments due to building penetration loss, where Non-Line-Of-Sight (NLOS) conditions significantly increase the diffraction and reflection losses. Deployments in indoor environments are especially challenging, as there is no high spot from which to transmit signals, while the dense compartments seriously affect signal spread. There are several technologies that can be used to mitigate these issues:

- Integrated Access and Backhaul (IAB) architecture in which a wireless backhaul connection is integrated into the RAN node, removing the need to install a fibre connection to each node
- Reconfigurable Intelligent Surface (RIS): a meta-surface that can reflect the radio signal in a programmed direction. This approach could be used for NLOS deployments indoors, or in shopping malls and outdoor dense urban areas
- Electromagnetic Surface (ES) is a carefully-designed passive antenna pattern that can be printed on glass or wallpaper to steer a signal in a specific way. It is typically used indoors
- A smart Distributed Antenna System (DAS), that could be operated by hybrid beamforming
- Smart repeaters – as discussed above.

1.2 Fixed Wireless Access

Fixed Wireless Access (FWA) services provide primary broadband access through mobile network-enabled CPEs, which could be either indoor (desktop and window) or outdoor (rooftop and wall-mounted) devices. mmWave spectrum provides greater bandwidth to support lower latency FWA connectivity and higher (gigabit) speeds.

The GSMA estimates that between 150 MHz and 700 MHz of mmWave spectrum bandwidth will be necessary to satisfy 5G FWA demand in households located in dense urban areas, based on an FWA penetration of 30%. In areas characterised by a lower Fiber-To-The-Home (FTTH) penetration, including suburban areas and rural towns, more mmWave spectrum may be necessary to satisfy 5G FWA demand. Between 700 MHz and 1200 MHz will be required in a suburban area and between 50 MHz and 850 MHz in a rural town, based on an FWA penetration of 60%, according to GSMA Intelligence [15].

1.3 Reducing power consumption

Power consumption is one of the most critical barriers for application of mmWave technologies on smartphones. A major contributor to mmWave UE power consumption comes from the Radio Frequency Front-End (RFFE) and digital baseband processing, which mainly arises from the need to support a large number of antenna elements to enable beamforming, along with the relative inefficiency of RF components at high frequencies, the need to support a high number of MIMO layers, and large bandwidth for CA operation, among other factors.

High UE power consumption not only drains the UE battery quickly, but also causes over-heating problems that would further affect the UE performance and potentially reduce the life cycle of the battery. There are several enablers and technologies that can be used to mitigate this issue:

- Discontinuous reception (DRX) technology, so that the device isn't monitoring DL signals continually.
- Network topology optimisations – using repeaters and other techniques to reduce the transmission power used by the device
- RRC INACTIVE – a state in which the UE monitors paging only like in RRC-IDLE but with more efficient transition to RRC-CONNECTED
- Mobile-Originated Small Data Transmission (MO-SDT), which enables data and/or signalling transmission of the UE while remaining in the RRC INACTIVE state, i.e., without transitioning to RRC CONNECTED.

1.4 Device availability

There has been solid growth in the number of mmWave devices coming to the market in the past 24 months, with 854 devices from 52 companies. In the short-term, the key growth engine for mmWave CPE will be FWA. The Global mobile Suppliers Association (GSA) forecasts that in 2022, aggregate shipments of FWA CPE devices will grow 33%, resulting in 21.9 million units, higher than the 2020 volumes. The dip in 2021 coincided with the pandemic, which impacted the supply chain.

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Contributors and Reviewers

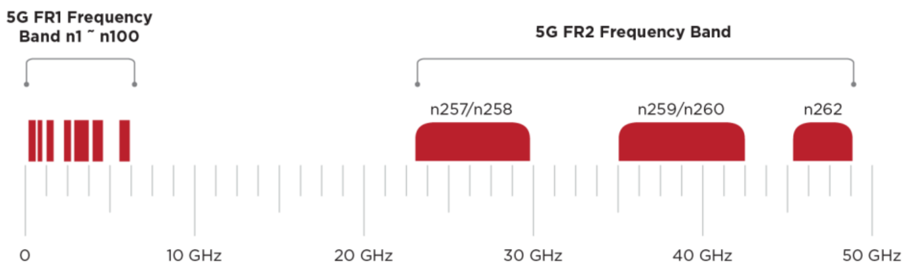
2. Introduction

The migration from 4G LTE to 5G is a transformative process for the mobile industry, involving tremendous performance improvements and enabling networks to keep pace with the growing traffic demand from mobile users. In particular, 5G Frequency Range 2 (FR2) [3] networks operating in the millimetre-wave (mmWave) frequencies (24 GHz and higher) are able to deliver multi-gigabit data rates and very low latency [9].

Standards body 3GPP has embraced the use of mmWave frequencies, extending mobile network operation in licensed spectrum up to 50 GHz to address the challenges facing network operators in dense urban environments, event venues, stadiums and private networks. The benefits of using mmWave technology are substantial due to the enormous amount of contiguous spectrum available. In the mmWave (FR2) frequency bands there is a 10-fold increase in available contiguous bandwidth compared to sub-6 GHz Frequency Range 1 (FR1) bands. Depending on the geography and network operator, this bandwidth increase could be even higher (see Figure 1), especially when comparing LTE to 5G. The difference in bandwidth between FR1 and FR2 will define the variations in performance of 5G networks as we move forward.

The 3GPP-defined bands provide a total of ~4.8GHz bandwidth for sub-6GHz bands (see 3GPP TS 38.101-1 [2]) and ~15GHz for mmWave bands (3GPP TS 38.101-2 [3]). The majority of the bands in the sub-6GHz range operate in Frequency-Division-Duplex (FDD) mode, which is inflexible for balancing the radio resource used for UL and DL to address traffic patterns. In contrast, mmWave bands only operate in Time-Division-Duplex (TDD) mode at present. Flexibility can be constrained by coexistence (see NGMN 5G TDD Uplink white paper [1]) and/or local regulation.

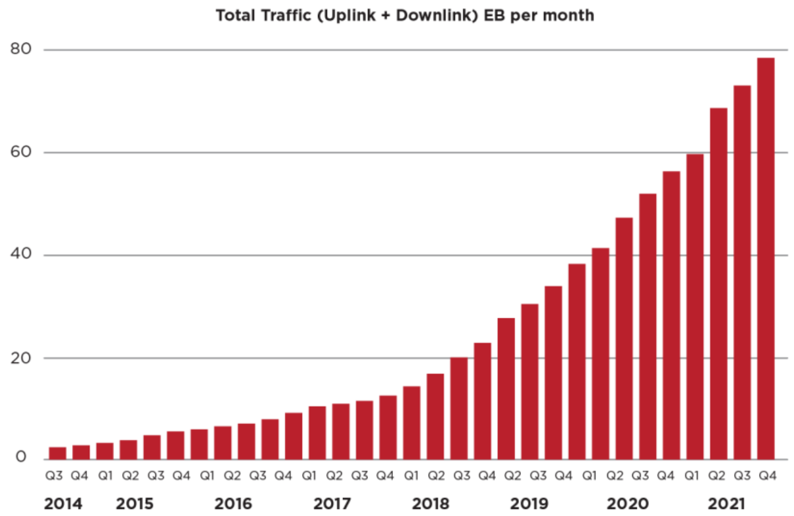
Figure 1: New mmWave Bands for High-Bandwidth 5G Use Cases



Today, 5G networks typically use low-band and mid-band spectrum in the 600 MHz to 6 GHz frequency range. While sub-6 GHz 5G is faster than 4G LTE, it doesn't offer the super-fast data rates or capacity that can be achieved with mmWave. In addition, both 4G LTE and sub-6 GHz speeds can slow down considerably when large numbers of devices are connecting to the network. As mmWave networks have much greater bandwidth than sub-6 GHz 5G and can handle a greater number of connections with a possible improvement to individual data rates, mobile operators are implementing mmWave 5G in crowded urban areas, such as sports arenas, stadiums, airports, concerts and other large venues.

The wide channel widths enabled by mmWave are required to support the immense amount of data generated by streaming 4K video, virtual and augmented reality, and other existing and emerging applications. A recent Ericsson Mobility report [10] shows that data usage has grown by 300X over the past 10 years (see Figure 2). These applications, combined with the growing number of users, are difficult to serve effectively using existing low-band and mid-band spectrum allocations.

Figure 2: Global Mobile Network Data Traffic



Source: Ericsson

As the industry progresses toward 5G Advanced (i.e., 3GPP Release 18 and beyond), more capacity can be unlocked using advanced technologies, such as carrier aggregation and discontinuous reception.

This document looks at the technical mitigation strategies to improve the performance of 5G mmWave networks in both indoor or outdoor scenarios.

3. Downlink and Uplink Performance

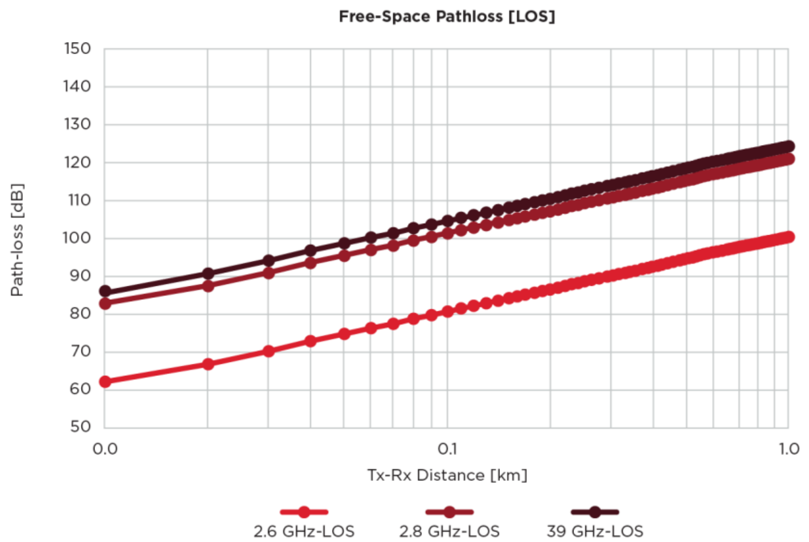
The following sections provide guidelines to get the best technical performance from the mmWave radio paths.

3.1 Propagation Characteristics

By virtue of operating in high frequency bands (24 GHz and above in 5G), mmWave propagation characteristics are different from those in low-band and mid-band spectrum. In particular, radio signals in the mmWave bands are subject to higher free space loss and higher building penetration loss, among other losses. Below is an outline of the typical 5G mmWave bands losses.

Line-Of-Sight (LOS) propagation. Compared to 2.6 GHz mid band spectrum, 28 GHz and 39 GHz bands are subject to 21 dB and 24 dB higher LOS loss consecutively, as shown in Figure 3. Frequency-dependent diffraction and reflection losses in Non-Line-Of-Sight (NLOS) conditions will add to these losses.

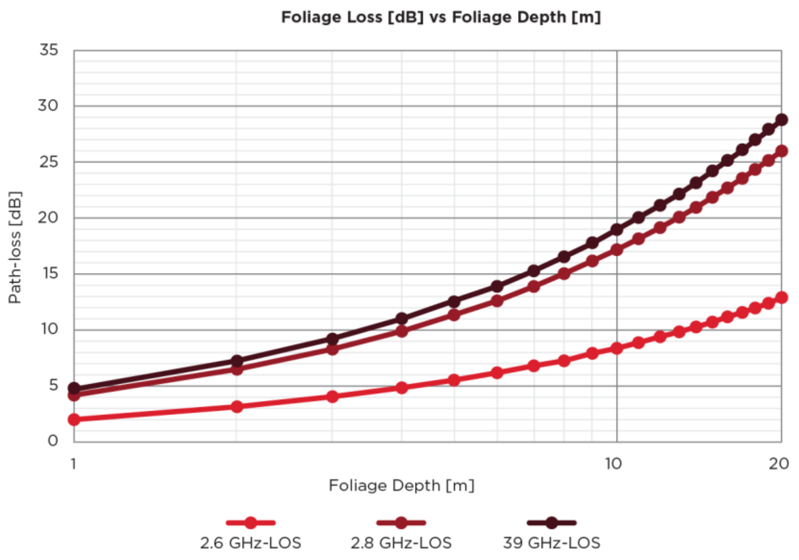
Figure 3: 1LOS Free Space Pathloss



Rain attenuation. Depending on the rainfall intensity (mm/h), rain attenuation can be significant for mmWave signals. Based on the FCC's Office of Engineering & Technology Bulletin on Millimeter Wave Propagation [4], rain attenuation ranges from 0.05 dB/km to 25 dB/km (@28 GHz) and 0.08 dB/km to 35 dB/km (@39 GHz). This translates to up to 2.5 dB (@28 GHz) and 3.5 dB (@39 GHz) of rain attenuation for every 100 meters with rainfall intensity of 150 mm/h.

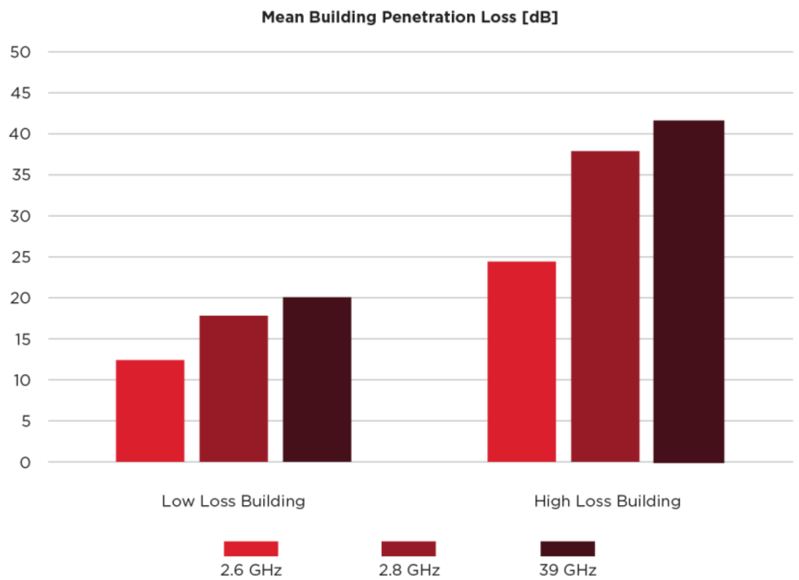
Foliage attenuation. Based on the FCC bulletin referenced above, foliage attenuation could be significant, depending on the depth of the foliage. At 10-meter foliage depth, 28 GHz band foliage attenuation is estimated to be 17 dB (11 dB higher than mid-band), whereas 39 GHz band suffers 2 dB additional attenuation at the same foliage depth.

Figure 4:2 Foliage Loss as a Function of Foliage Depth



Building penetration loss. Higher bands are subject to higher Building Penetration Loss (BPL). BPL is typically higher in commercial buildings than residential, due to the building materials used and window isolation techniques. Based on 3GPP TR 38.900 [13], the 28 GHz band is subject to 6 dB to 14 dB higher BPL over 2.6 GHz, whereas 39 GHz band is subject to 8 dB to 17 dB higher BPL, as shown in Figure 5.

Figure 5:3 Residential (Left) and Commercial (Right) BPL



Mitigation

The following techniques are available to mitigate mmWave losses:

Use of antenna arrays

As mmWave are high bands, and hence smaller wavelength, a larger number of antenna elements can fit into a smaller antenna form factor. The large number of antennas creates a radiation pattern with narrow beamwidth and high gain.

The Effective Isotropic Radiated Power (EIRP) of the antenna array is represented by the following equation:

EIRP (dBm) = P_out (dBm/element) + Individual_element_gain (dB) + 10*$\log_{10}$(N_elem) + 10*$\log_{10}$(N_elem)

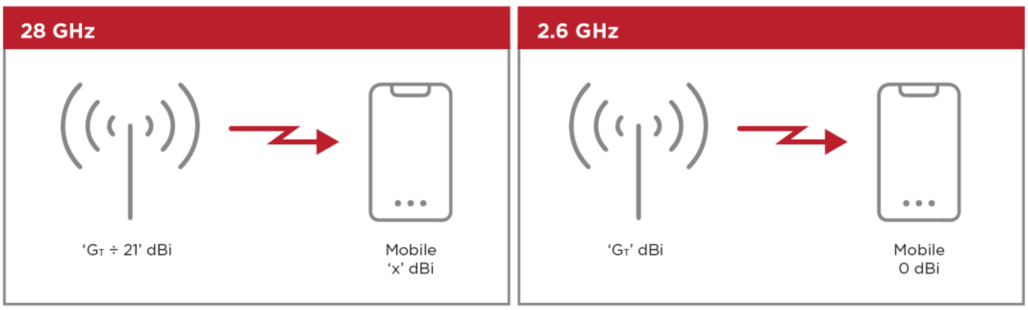
EIRP (dBm) = P_out (dBm/element) + 10*$\log_{10}$(N_elem) + Individual_element_gaingain_per_element (dB) + 10*$\log_{10}$(N_elem)

Where Individual_element_gain (dB) + 10*$\log_{10}$(N_elem) represents the antenna gain and 10*$\log_{10}$(N_elem) represents the beamforming gain.

Antenna gain. 5G mmWave bands enjoy a significant antenna gain advantage over typical mid-band antenna. Based on theoretical analysis and simulations, the base station and user equipment antenna gains in mmWave (over mid-band) are illustrated in Figure 6 and given below.[1]

- Base station: 21 dB (28 GHz) and 24 dB (39 GHz)
- User equipment: 11 dB (28 GHz) and 14 dB (39 GHz)

Figure 6: Antenna Gain Advantage of mmW vs. Mid-band



[1] Assumptions: gNB: 256 antenna elements per user. 29/32 dBi (28/39 GHz) vs. 18 dBi gain (2.6 GHz)
UE: 6/9 dBi (28/39 GHz) vs.0 dBi gain (2.6 GHz)

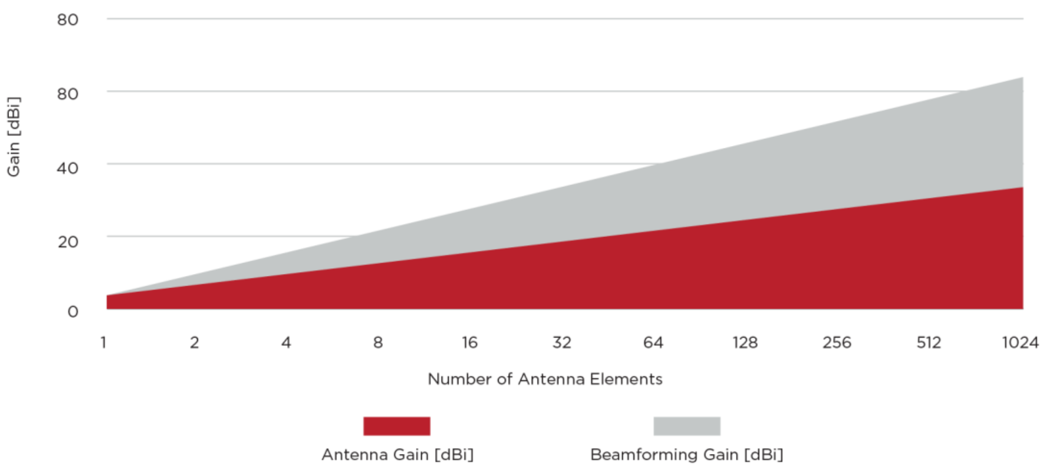
Beamforming gain. Beamforming can orient the beam in the direction of the user equipment without mechanical rotation. A larger number of antenna elements enables a sharper beam and, consequently, higher gain.

With 256 antenna elements on the base station, the theoretical beamforming gain is 24 dB. On the user equipment, with four antenna elements, the theoretical beamforming gain is 6 dB. In practice, the theoretical gain may not be realised due to beam shape loss and channel estimation errors, thus leading to a loss of about 2.5 dB. Therefore, the practical mmWave link budget advantage over 2.6 GHz due to beamforming gain is as follows:

- Base station transmit antenna gain: 24-2.5 = 21.5 dB advantage
- User equipment transmit antenna gain: 6-2.5 = 3.5 dB advantage

The mmWave theoretical antenna and beamforming gains (as shown in Figure 7), will offset the propagation and other losses discussed above.

Figure 7: mWave theoretical Antenna and Beamforming gains



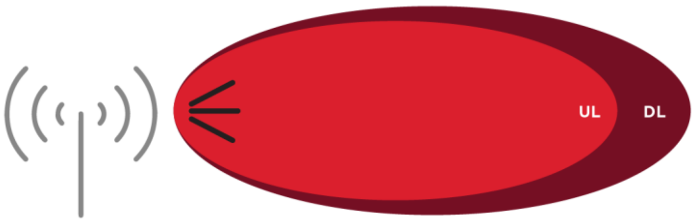
Recommended Action:
Raise industry awareness of the different gains that can be achieved to begin to balance the path loss at the mmWave frequencies.

3.2 DL / UL Imbalance

In a 5G system, as with LTE, the DL coverage footprint of a cell is typically greater than its UL coverage footprint. This is due to an imbalanced link budget between DL and UL, as shown in Figure 8 below. Several factors contribute to this imbalance, most notably the transmit power difference between the base station generation Node B (gNB) and the user equipment (UE) and the asymmetry in UL/DL timing, meaning that UL transmissions must occur in a fraction of time (e.g. UL/DL ratio of 1 in 4).

The imbalance is particularly pronounced in mmWave (FR2) networks compared to FR1 because of the significant antenna array gain the gNB has over the UE.

Figure 8: DL-UL Imbalance in a 5G Network



The magnitude of this DL-UL imbalance depends on several factors, including the deployment environment, transmit power of UE and gNB, antenna configurations and antenna gain, among others.

Mitigation

To mitigate the DL-UL imbalance, several techniques can be adopted.

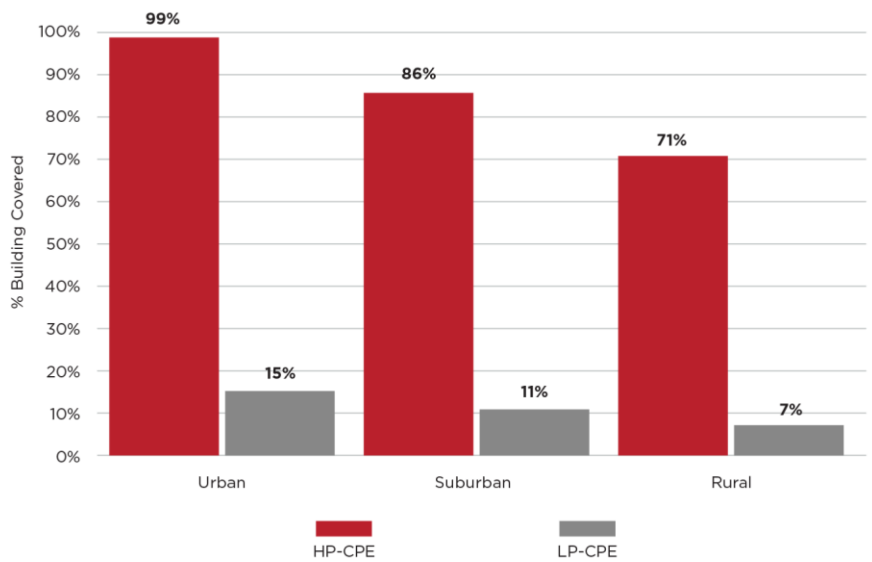
(1) Use of low-band for UL
As they have superior propagation characteristics, low-bands can be utilised to carry UL data and control. This should be implemented as a low-band/high-band CA pair, where both low- and high-bands are utilised for the DL, providing needed capacity and low-bands used for UL transmissions. This is further described in the *Maximising mm-Wave Coverage with FR1* section later in the document.

(2) Use of high power UE

High pPwer UE (HPUE), for example Power Class 1 (PC1), can be utilised, whenever it is supported. The higher transmit power of the UE will extend UL coverage, thus helping reduce or eliminate the DL-UL imbalance. Several commercial HPUE devices, particularly Consumer Premises Equipment (CPEs), are currently available.

Error! Reference source not found.~~Figure~~ 9 illustrates the simulation results of outdoor High Power (HP) CPE versus Low Power (LP) CPE in the 28 GHz band in three different morphologies[2]. The coverage advantage (shown in terms of the proportion of buildings covered), illustrates the benefits of a high power device, which helps close the loop for longer ranges.

Figure 9: Simulation of Outdoor 28GHz Coverage of HPCPE vs. LPCPE



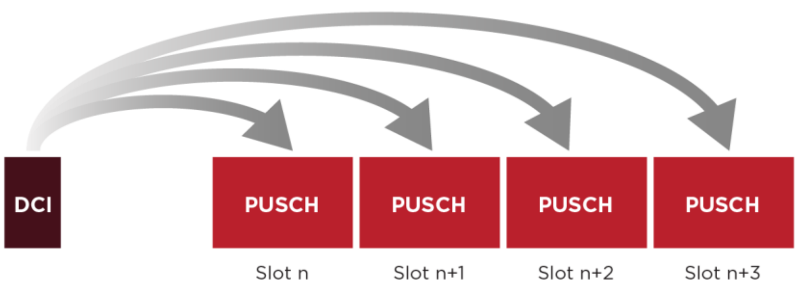
The use of HPUE for FWA applications in real world trials is discussed in the ‘FWA Best Practice Deployment~~FWA Best Practice Deployment~~’ section later in this document.

(3) UL slot aggregation

UL transmission spanning several slots over the Physical Uplink Shared CHannel (PUSCH), i.e., slot aggregation, increases UL coverage and improves the cell edge user experience. Slot aggregation, which is the same concept as VoLTE Transmission Time Interval (TTI) bundling, was adopted by 5G in order to improve the reliability of packet transmission.

3GPP Release 15 allows for UL repetitions over eight consecutive slots, whereas Release 17 allows UL repetitions over 32 consecutive slots. Figure 10 illustrates an aggregation factor of four being configured.

Figure 10: PUSCH Aggregation



[2] 28GHz; 4x100MHz BW; 3:1 DL:UL TDD

Note that UL slot aggregation, while improving reliability for the cell edge user, could increase packet transmission latency and may not be suitable for latency-sensitive applications. The level of slot aggregation, if any, can be limited by the deployed TDD frame structure, see [1].

(4) Utilisation of DFT-s-OFDM

3GPP has adopted the Discrete Fourier Transform spread Orthogonal Frequency Division Multiplexing (DFT-s-OFDM) for uplink transmission. It reduces the Peak-to-Average Power Ratio (PAPR), thus improving the Power Amplifier (PA) efficiency, and extends it range.

(5) Increasing the sensitivity of the gNB

Optimising the sensitivity level of gNB would benefit both:

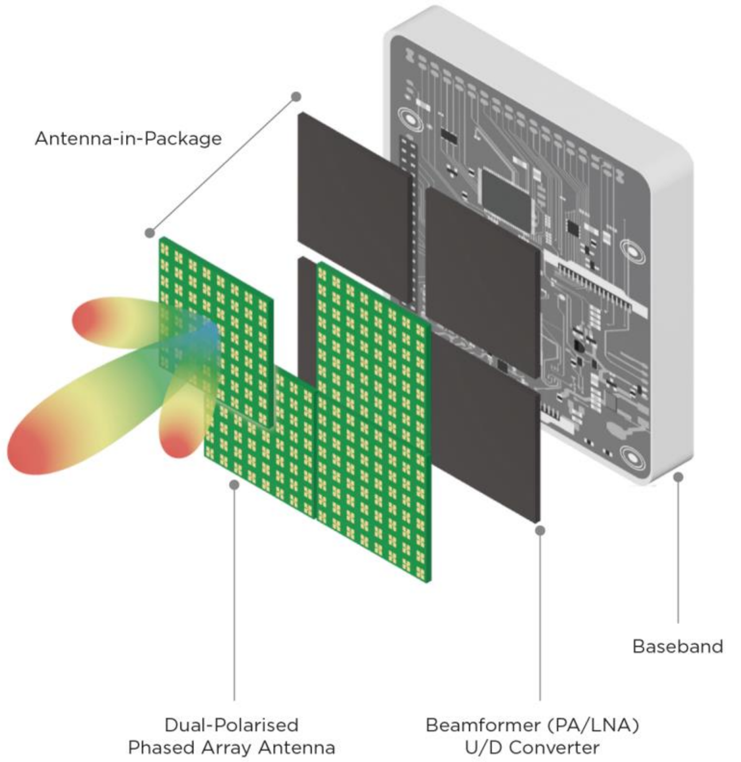
- high power UE for higher data rate to achieve higher throughput;
- legacy UE for increasing link budget to maintain the uplink connection.

An AiP (Antenna-in-Package) subsystem is designed for both gNB and UE to eliminate mmWave propagation loss as well as reduce the path loss from the antenna to the baseband to improve the receiving sensitivity.

Within each layer of AiP (as shown in Figure 11), there are several design approaches that can improve the receiving sensitivity:

- Phased array antenna - design for dual-polarisation and for a larger antenna element will increase the receiving capability, such as massive MIMO.
- Radio Frequency Front End (RFFE) – integrates the beamforming integrated circuit (IC), the frequency up and down convertor and other microwave components, such as power amplifiers, Low Noise Amplifiers (LNAs) and filters, into a compact design to minimise the transaction loss. Especially, to adopt Gallium Arsenide (GaAs) high performance LNA featuring high gain and low noise figure, that would effectively amplify the signal into a more useful level.
- Thermal – ICs or system heat contribute noise that affects the noise figure, gain and linearity of the LNA. Advanced processes and material science, such as Low Temperature Co-fired Ceramics (LTCC) technology, can be employed to design antenna and multilayer circuits from ceramic substrates.

Figure 11: The Antenna-in-Package System Architecture



Recommended action:
Raise awareness in the industry to improve the performance in the UL direction, and potentially within 3GPP to ensure the standardisation of the technical features identified in this section.

4. Deployment of Indoor & Outdoor Services Utilising FR2 spectrum

This section provides guidelines for different mmWave indoor and outdoor deployment scenarios, considering how FR1 and FR2 bands can have a different impact on performance.

There is a view that mmWave 5G is the true 5G because its high throughput and low latency can greatly improve the user experience. But mmWave propagation characteristics mean the performance in FR2 bands degrades significantly more than in FR1 bands at distances of more than 1km. As discussed earlier, the free space path loss is more than 20 dB compared to FR1 signals at the same distance, even in a LOS scenario (as shown in Figure 3).

The mmWave propagation fading becomes more serious in urban environments due to building penetration loss, where NLOS conditions significantly increase the diffraction and reflection losses. Deployments in indoor environments are especially challenging, as there is no high spot from which to transmit signals, while the dense compartments seriously affect signal spread. For a large building, a Distributed Antenna System (DAS) is a popular mean to distribute the network with good signal quality.

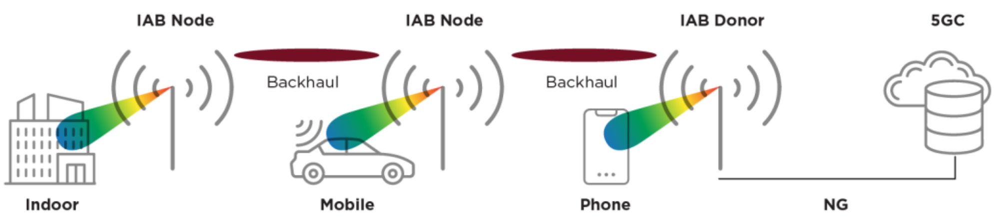
Beamforming can compensate for the propagation loss by aggregating the antenna array gain toward a direction, but it's only effective in LOS environments.

Different deployment strategies are needed for various different scenarios, which include outdoor-to-indoor transmissions in rural, urban and dense urban areas, in LOS and NLOS cases.

Mitigation

Integrated Access and Backhaul (IAB) is a new architecture that 3GPP standardised in Release 16 [7]. It's a RAN node that integrates a wireless backhaul connection, as well as providing connectivity for user equipment to access. The technology, which normally employs LOS connectivity, can be used to extend both outdoors and indoor coverage. The deployment of IAB equipment can lower the capital cost of infrastructure, speeding up deployment and satisfying user expectations of high throughput. In remote rural areas that are difficult to connect with fixed lines, this high-speed wireless backhaul technology could provide an easier and faster deployment architecture, without compromising on performance.

Figure 12: Reference IAB Diagram System and Application Architecture (refer to 3GPP TR 38.874)



Reference deployment scenarios:

- Sparsely populated areas with high network deployment costs
- Wireless network deployment on islands
- Wireless network deployments in historic buildings, such as castles, which can't be wired easily
- High tower to high tower, building top to building top for high-speed wireless backhaul

Reconfigurable Intelligent Surface (RIS): a meta-surface that can reflect the radio signal in a programmed direction. This approach could be used for NLOS deployments indoors, or in shopping malls and outdoor dense urban areas.

In an outdoor dense urban environment, the RIS could be used to disseminate the signal in a similar way to sun rays reflecting off a mirror. The RIS could be integrated within a large-scale outdoor advertising panel or building's exterior glass to minimise the deployment cost: no extra wiring and power would be required.

Figure 13: The RIS deployment scenario in a dense urban area

An outdoor NLOS deployment scenario is shown in Figure 13. The signal from the gNB is blocked by tall buildings. By integrating an RIS within the advertising display, the street, park area and walkway could be well covered through the signal redirection. The same deployment scenario could also be applied to stadiums and public squares that are equipped with a large display, and also for office buildings in which a RIS can be integrated into the glass exterior.

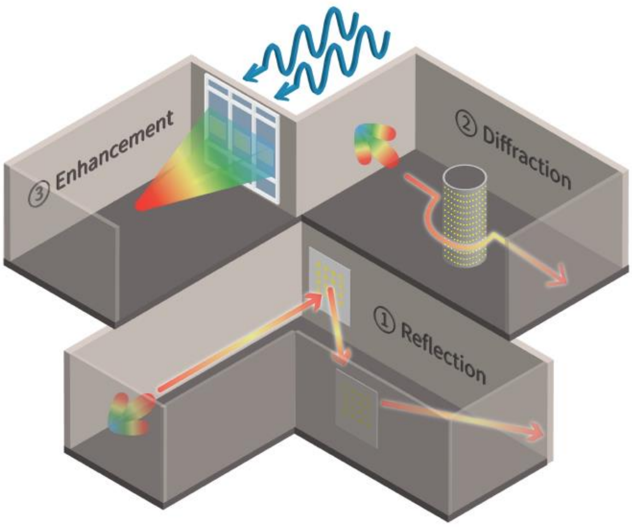
However, RIS deployments would need to overcome challenges related to RF performance, the capability of redirection and reflection loss, and how to identify the perfect spot to locate the reflector for best signal diffusion.

For indoor deployments, there is an alternative low-cost solution – the Electromagnetic Surface (**ES).** ES is a carefully designed passive antenna pattern that can be printed on glass or even wallpaper to steer a signal in a specific way. In additional to simply expanding the coverage, ES can be used to:

- customise signal distribution for specific space
- cover the dead zone at reasonable cost and with the required performance
- Intentionally create “a cold zone” that can act as secure area

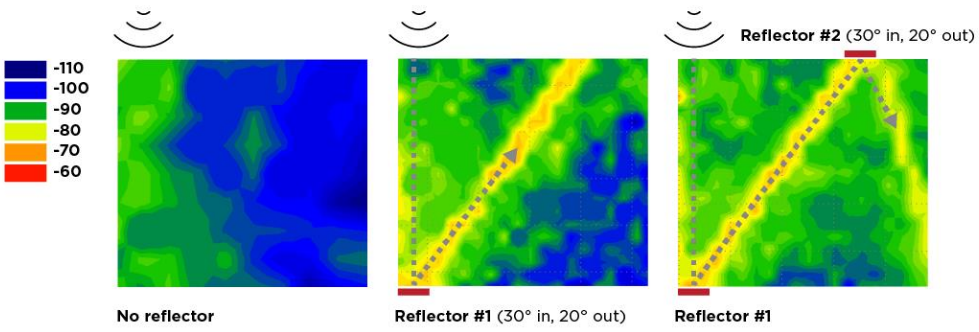
Figure 14 shows different ES deployment approaches: reflection, diffraction and enhancement. These three approaches are discussed further below.

Figure 14: ES deployment approach for indoor usage



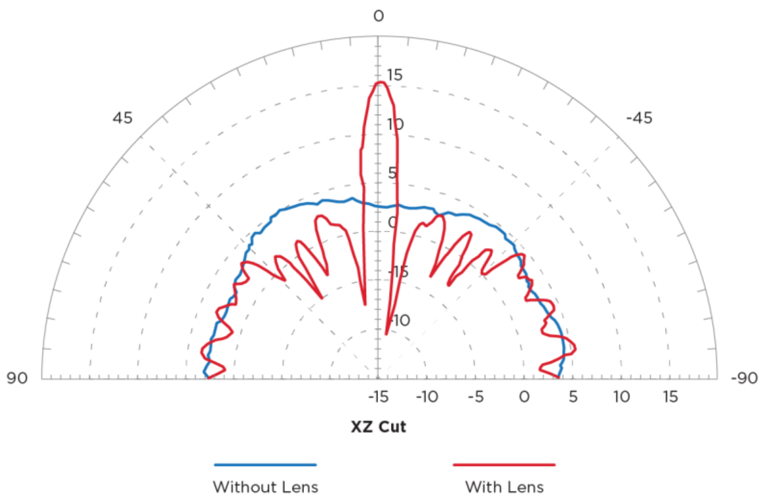
Reflection to redirect the signal to expand coverage in a specific area, or create a cold zone elsewhere. This approach is well suited to deployments in office buildings that have installed cubicles and home space. In Figure 15, the reflectors are at an angle to redirect the signal to a specific location, increasing the signal strength by more than 20 dB across office cubicles or multi-room conditions. That would allow the density of small cells to be significantly reduced.

Figure 15: Use case of Reflection deployment



- **Enhancement** – A design antenna pattern is used as an enhancement “lens” to refocus the signal to a certain direction. Ideally, the lens would be installed on the door or windows, which would then boost an incoming signal into the entire room. The signal strength could increase more than 10 dB, as shown by the radiation pattern after applying the lens in Figure 16.

Figure 16: Radiation pattern before and after applied Enhancement lens



- **Diffraction** - to guide the signal past an obstacle. There are situations when indoor building pillars can block the propagating signal. A diffraction surface can be applied onto the pillars to guide the signal around the pillar block to continue transmitting. The result could greatly improve the signal strength behind the blocking area.

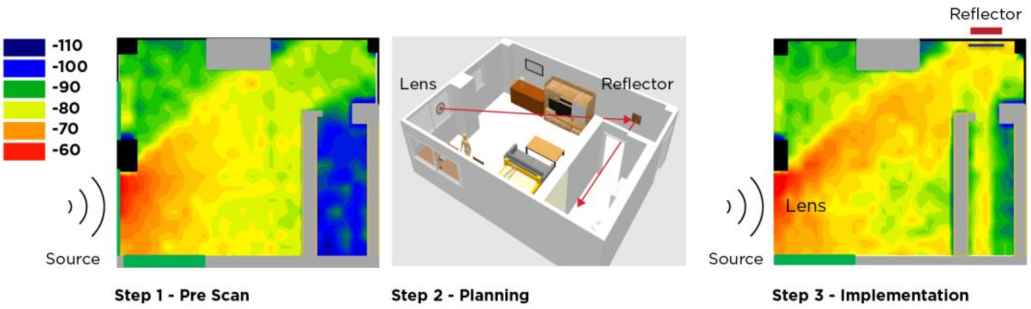
To optimise indoor coverage, the signal propagation pattern and the location of ES installation need to be carefully researched following the three steps shown in Figure 17:

Step 1 Pre scan: use scanning and profiling to create a model of the environment and find the blind spot. In Figure 17, it is the bathroom (blue space).

Step 2 Planning: put the model into an Artificial Intelligence (AI) simulation system that can design a solution. In Figure 17, it is an enhancement lens with a reflector to direct the signal into the bathroom.

Step 3 Implementation: after implementing the solution, measure the results and fine-tune the signal diffusion pattern. In Figure 17, the bathroom now has a very good signal level.

Figure 17: ES indoor deployment planning



A Distributed Antenna System (DAS) is normally applied for both outdoor and indoor FR1 deployments. A similar architecture could also be applied to a mmWave FR2 network. The major challenge is the capability of remote radio units, as the legacy sub-6 GHz antenna would not work for mmWave that requires a highly directional type. An active array antenna for beamforming and a beam steering mechanism to compensate for pathloss need to be adopted. To further optimise the whole network performance and efficiency, a smart DAS could be developed. This could be operated by hybrid beamforming, following system planning. It would be network-controlled.

Smart repeater - 3GPP initially defined a RF repeater without adaptive beamforming, then proposed a smart repeater with a network-controller, which could greatly extend coverage. Such a smart repeater could be easy to deploy, efficient and reduce the total cost of ownership. The '*Smart Repeater'* section of this document explains this concept further.

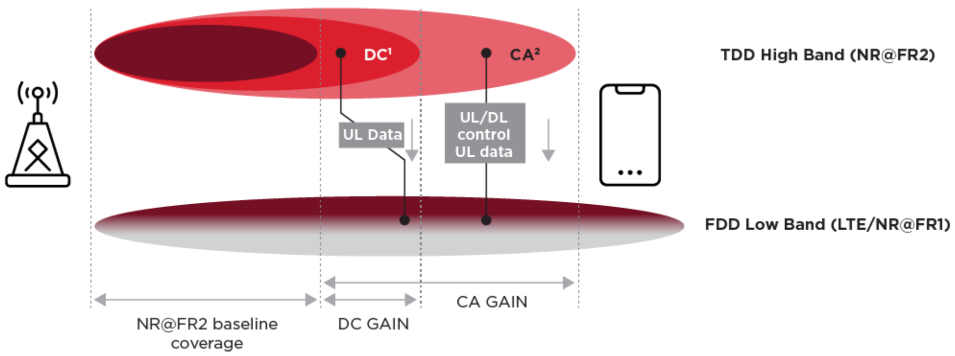
5. Maximising mmWave coverage with FR1 spectrum

In any mobile network, devices must maintain an adequate link budget on both the DL and UL for both control signalling and user data. When there is a link imbalance between UL and DL (as described in (1)) the usable coverage will be restricted by whichever link is more limiting, in this case the uplink. This challenge is particularly pronounced for the mmWave mobility use case (PC3 UE) since the link imbalance is so large (up to 14 dB depending on the assumptions). FR1 bands can be used to overcome this link imbalance through the implementation of dual connectivity (either inter- or intra-RAT, i.e., E-UTRA-NR Dual Connectivity (EN-DC) or NR-NR Dual Connectivity (NR-DC)); and NR carrier aggregation (NR CA) between FR1 and FR2.

In a dual connectivity (EN-/NR-DC) 5G network implementation (involving two base stations, with a master node operating in FR1 and a secondary node in FR2), some minor mmWave coverage extension is achieved through offloading data plane traffic to the FR1 connection. However, the continued reliance on the FR2 UL means this improvement is minor. Fundamentally, mmWave DL coverage remains significantly restricted due to its reliance on the FR2 UL. To maximise the DL coverage of mmWave all FR2 layer 2 signalling must be shifted to FR1. This can be achieved with NR CA between FR1 and FR2.

FR1+FR2 NR CA allows the mmWave UL (and DL) layer 2 signalling to be achieved via the FR1 connection. Since FR1 has better propagation characteristics the required layer 2 signalling can be maintained on FR1 allowing the FR2 to be utilised beyond the limits of its UL. This concept is illustrated in Figure 18.

Figure 18: Illustrative mmWave coverage extension gains through DC and NR CA



Note 1: DC can be either EN-DC (between LTE FDD Low band and NR@FR2) or NR-DC (between NR@FR1 FDD Low band – a dedicated NR FR1 band or share/re-farmed LTE band – and NR@FR2)

Note 2: CA is intra-NR only, i.e., FR1+FR2 NR CA

The use of FR1+FR2 NR CA will result in extended mmWave DL coverage, better utilisation of the mmWave spectrum, particularly for mobility UE, and a reduction in the number of new site deployments required to offer mmWave services across an area.

NR-DC does offer better peak speed performance on both the DL and UL when within good UL mmWave coverage. This has been demonstrated through a number of published network trials, such as that by Telstra, Ericsson and Qualcomm, which achieved near 1Gbps single user UL throughput on Telstra’s live network (Ericsson, 2021). Therefore, an optimal deployment is one where the benefits of both NR-DC and FR1+FR2 NR CA can be realised by switching between the two capabilities in different areas of the coverage.

The implementation of NR CA does have some strict latency requirements between the NR basebands to enable the coordinated scheduling. This is most easily achieved through co-locating basebands physically in a centralised RAN (C-RAN) architecture, but can also be achieved with low latency layer 2 links in a distributed RAN architecture. In summary, implementing FR1+FR2 NR CA does add additional considerations to network planning that must be considered in the context of the operator’s network architecture.

Recommended action
The further development of the mmWave ecosystem relies upon operators being able to deploy meaningful coverage. Given the propagation challenges of mmWave, any technical capability to extend the coverage footprint of early mmWave deployments is critical to this endeavour. Whilst good progress has been made on delivering DC-based support of FR2 the industry is lagging in support of FR1+FR2 NR CA. Industry support for FR1+FR2 NR CA will help operators to speed up the expansion of their mmWave coverage footprint, thereby accelerating the mmWave ecosystem in their respective markets.

6. Smart Repeaters

Providing full 5G network coverage with mmWave technology presents challenges that have been raised throughout this paper. These challenges could ultimately be addressed using a number of different methods. Mobile operators could, for example, deploy significantly more base stations of various sizes – ranging from higher power macro gNBs to relatively small "macrocell" on towers buildings and many other structures.

However, this is an expensive proposition and ultimately may not fully deliver robust coverage. Some industry analysts estimate that simply adding more base stations to achieve full coverage by 2030 would require spending hundreds of billions of dollars — and this is just the cost of providing coverage in the most densely populated areas [16].

Another approach is to build larger and more powerful gNB macro base stations and locate them on traditional cell towers. However, it is not possible to build a base station for 5G FR2 that could cover the same cell size as a low-band base station. This approach would fail due to limitations of power consumption, regulatory limits (in particular for indoor installations where safe exposure levels are required) and the physical propagation characteristics.

Another alternative - deploying hundreds of thousands of small cells almost everywhere – would also be economically impractical as it would take many years for carriers to amortise the costs involved, which are well beyond the reach of players with fewer financial resources. It is here that the traditional approaches to support new network frequencies start to fall short.

To achieve ubiquitous coverage at an affordable cost, non-traditional approaches are required – one such approach is using smart repeaters, which amplify the 5G signal and then transmit the boosted signal in the required direction.

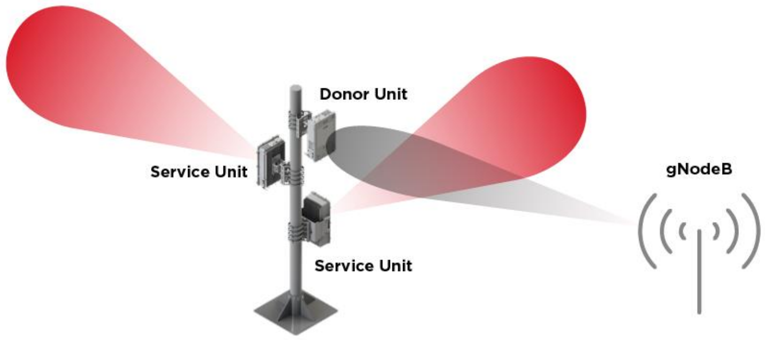
As they offer a balance between performance and cost, and can accelerate deployments, smart repeaters have become an integral part of the industry's mmWave deployment strategy and must continue to evolve to support larger scale 5G use cases and coverage requirements. Smart repeaters are designed to unlock the promise of high-speed mmWave connectivity and accelerate the entire 5G ecosystem.

Highly scalable, smart repeaters are low-cost, small, lightweight, easy and quick to install and provide an efficient way to extend the range and coverage of small cells. Smart repeaters can be installed easily on streetlights, lampposts, walls and windows, reducing the high cost of a truck roll, complex zoning and trenching to support fibre connections.

Unlike traditional DAS and passive RIS devices, smart repeaters can do more than just extend coverage of the gNB. Smart repeaters provide significant end-to-end gain and configurability that is not possible with these traditional approaches. This effectively makes the area of coverage and range of coverage of an indoor or outdoor cell site much larger. Smart repeaters are closely synchronized to the network gNB equipment. The main difference this achieves is that smart repeaters can add significant gain to the system, on the order of 100 dB or more. As opposed to other simple repeaters or passive devices which reduce the signal quality and reduce the overall range and signal quality.

Some of the systems currently being deployed by major network operators have demonstrated that smart repeaters can solve coverage and range challenges. Network repeaters have been deployed to support range extension, blind spot coverage enhancement, and expanding the signal to cover multiple users simultaneously (see Figure 19). Delivering more than 110 dB of end-to-end gain, while eliminating the need for fibre optic backhaul connections, they can overcome the physical limitations of the mmWave band.

Figure 19 : Network smart repeater extending range and coverage



Source: FRTek i

As it doesn't require a fibre backhaul connection and has low inherent power consumption, a smart repeater can be integrated into a device that can be powered by a standard power connector that is available on 360 million LED lamp posts today. Due to their small size, integrated power metering, and sleek profile (see Figure 20) repeaters can be deployed in a matter of minutes.

Figure 20: Streetlight smart repeater

Source: Ubicquiai

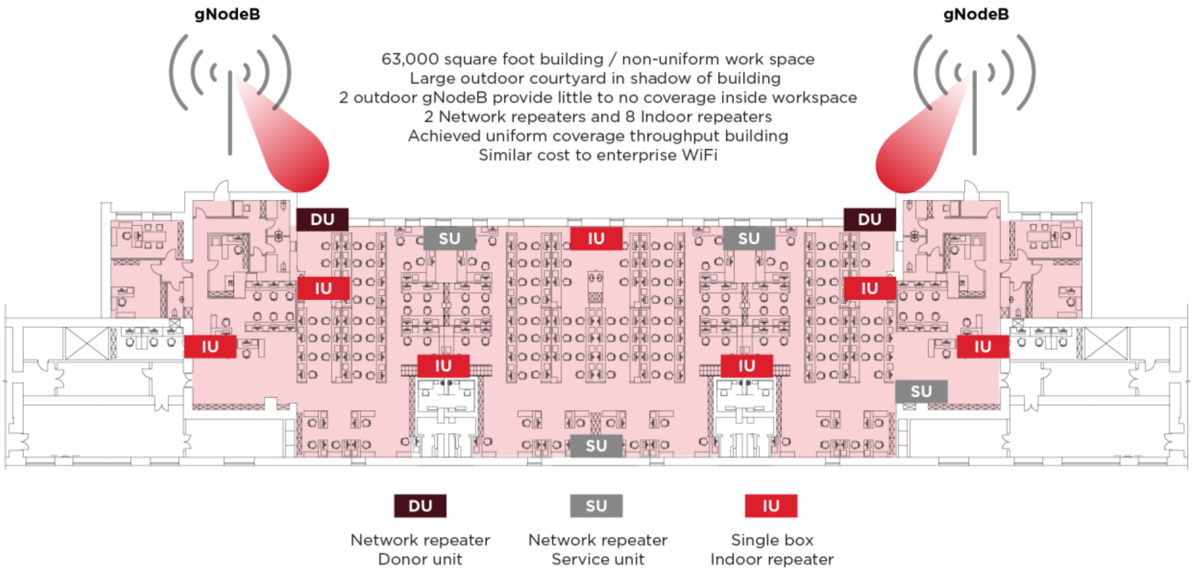
Very low power and compact indoor repeaters can be used to provide seamless and uniform coverage in enterprises, factories, and event venues. These single-box units have been used with ceiling mount brackets or window mounting systems (Figure 21) to provide uniform coverage within a conference room or event venue. As well as being flexible enough to address the challenges of different environments, smart repeaters have extremely low latency that make them completely transparent to the UE.

Figure 21: Single-box indoor smart repeater

Source: Movandi / WNC

An example of how indoor and network smart repeater can be combined to provide uniform coverage is shown in Figure 22. In this deployment, the two gNBs that were located outside the building provided coverage just 2 to 3 feet inside the window, with the UL and DL throughput rapidly deteriorating indoor. Two network repeaters and eight indoor repeaters were combined to provide uniform coverage over a 63,000 square foot area. The area itself was far from uniform – various office furniture, hidden offices, and odd shaped hallways all presented unique challenges. In addition, the building itself created a shadow that blocked coverage for an outdoor courtyard. When deployed, the users in the building were able to achieve gigabit per second throughput both indoor and in the courtyard areas.

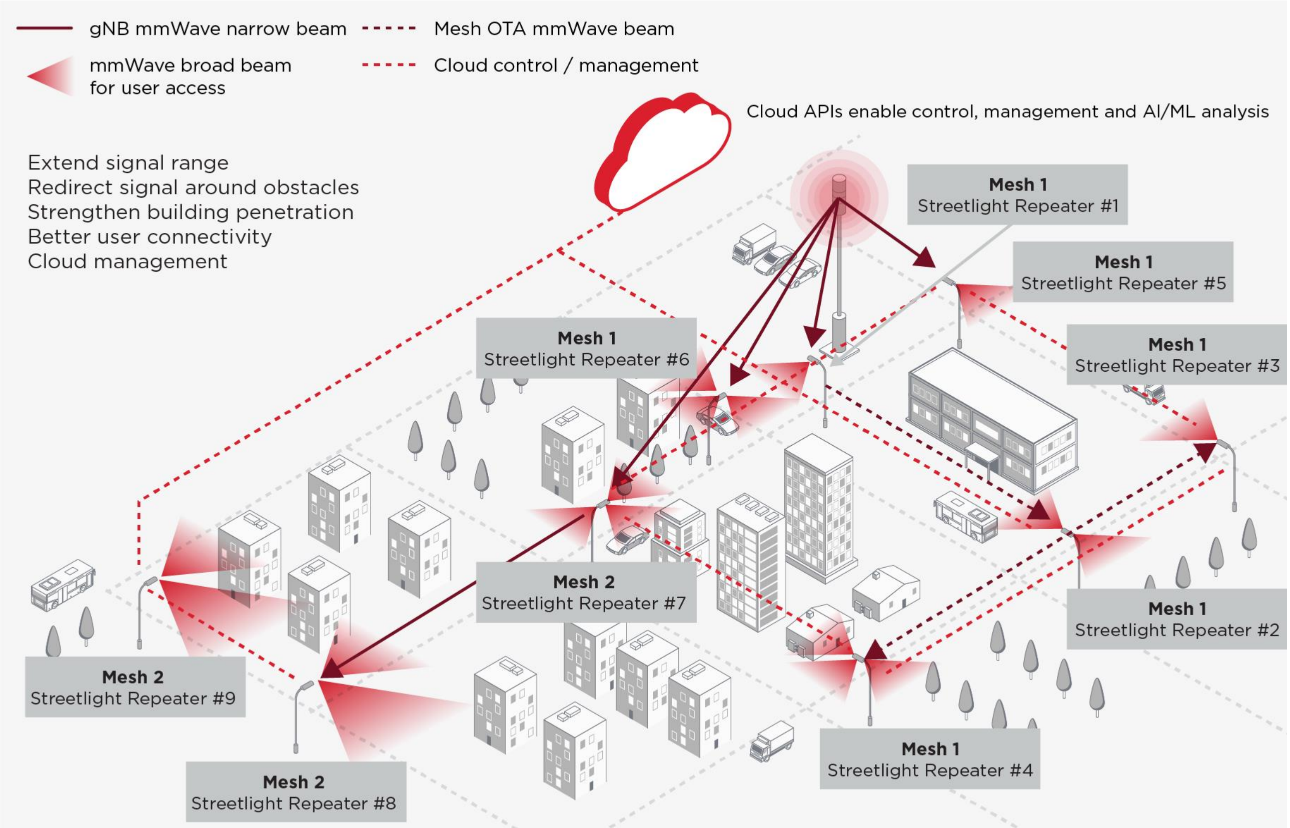
Figure 22: Enterprise and Outdoor Coverage Enabled by Smart Repeaters



Smart repeaters can improve point-to-point and LOS connections by leveraging active phased-array antennas. They help make coverage more uniform and seamless in high-demand areas with dense clusters of users, eliminating the “lumpy” coverage found in 5G networks based on traditional fibre-connected high power gNBs. Smart repeaters can also dynamically scan for the best 5G source and optimise performance based on the changing conditions in the environment. In addition, they further amplify very weak signals at the cell edge, extend the range and boost penetration into buildings. Smart repeaters can also redirect and reshape the signal from the base station. In essence, they can steer the signals to go around buildings or walls (see Figure 23) and ensure coverage everywhere beyond the blockage.

Unlike traditional network devices, smart repeaters do not add latency to the signal path and can be daisy-chained for further range extension at lower cost. More importantly, they can be cascaded in a mesh networking fashion and managed on the cloud to optimise performance and react to changes in network and environmental conditions.

Figure 23: How smart repeaters enhance coverage

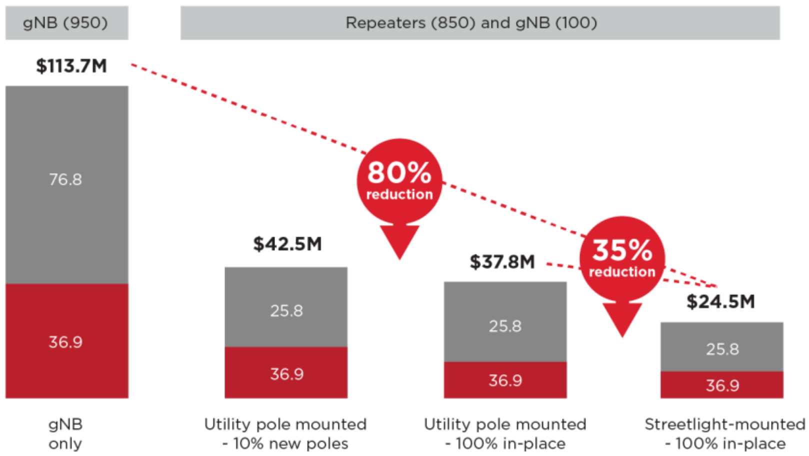


To perform efficiently and avoid creating more problems than they solve, smart repeaters must operate in a coordinated fashion with the rest of the network and the gNBs. Simple repeaters, for example, can create problems in the network by injecting noise, adversely impacting devices and reducing network capacity, rather than improving it. It is important for these devices to include a combination of advanced signal processing algorithms to perform network synchronisation, active beamformed phased-array antennas to handle beamforming and scan, and optimised MIMO performance.

As they can be built in specific configurations for different applications, smart repeaters can support almost all applications from extending an outdoor mobile network to support FWA, private networks and more. For example, single-box indoor repeaters are ideal for indoor applications, businesses, enterprises, venues and malls, and can be cascaded to cover large areas. For other applications, split Donor Unit (DU) and Relay Unit (RU) repeaters are ideal for outdoor environments mounted on utility poles or for outdoor-to-indoor extensions. And vendors are now demonstrating streetlight mount repeaters for outdoor use.

Many trials and tests conducted over the past two years by leading operators and equipment vendors in different locations with live networks have proven the feasibility of smart repeaters and highlighted the potential to significantly reduce the cost of mmWave deployments. In fact, field tests have shown that smart repeaters can reduce both the Capital Expenditures (CapEx) and Operational Expenditures (OpEx) of mmWave deployments by 50 percent [18] [19], and streetlight mounted smart repeaters can achieve Total Cost of Ownership reductions of 80 percent [17] (see Figure 24).

Figure 24: Total Cost of Ownership for a city over 10 years

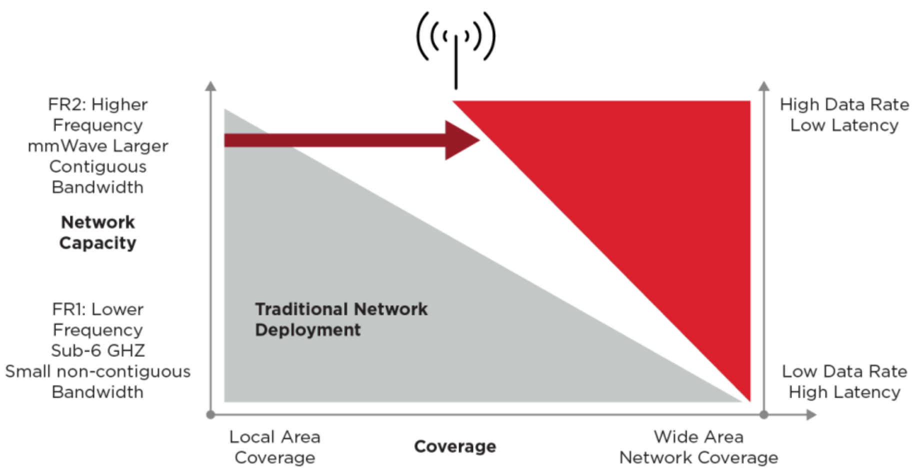


Source: Mobile Experts, Inc.

In the US, the Phoenix Suns basketball team has used Verizon 5G UltraWideband (mmWave) connectivity in its Verizon 5G performance centre to transform its team training tools and technologies into a unified system that has helped to drive a remarkable turnaround – the team reached the NBA finals in 2021. Phoenix Suns has smart repeaters strategically placed in its Footprint Center arena to provide coverage in areas where fans were previously not able to get connected. Verizon says the deployment demonstrates how 5G mmWave can deliver immersive experiences to fans.

In summary, smart repeaters will help accelerate time to market and reduce the cost of deploying mmWave networks to meet the growing demand for coverage and capacity (see Figure 25) and new bandwidth-intensive applications.

Figure 25: How smart repeater expands the coverage of high-performance networks



7. FWA Best Practice Deployment

FWA services provide primary broadband access through mobile network-enabled CPEs [8]. This includes various form factors of CPE, such as indoor (desktop and window) and outdoor (rooftop and wall-mounted), but it doesn't include portable battery-based Wi-Fi routers or dongles. FWA is one of the main 5G use cases and a key solution for meeting fixed broadband connectivity objectives. mmWave spectrum provides greater bandwidth to support lower latency connectivity and higher (gigabit) speeds.

When deploying mmWave for FWA to provide data services to a home, office or business park there are three main considerations; spectrum, CPE antenna location and coverage.

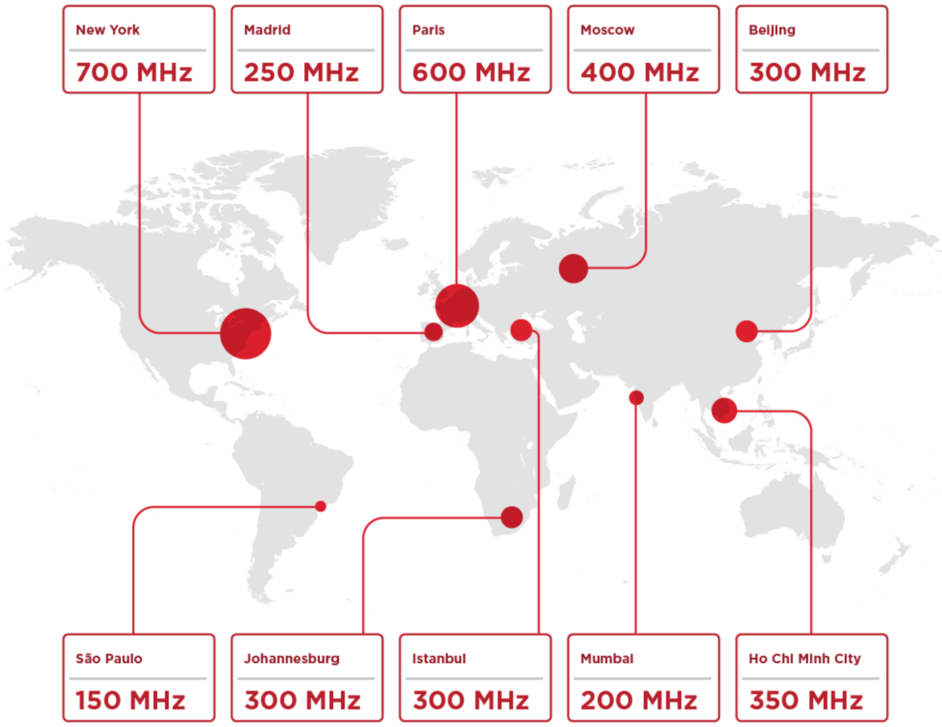
7.1 Spectrum

In those locations where mmWave spectrum is available, 5G FWA technology will allow fibre-like connectivity in areas where high deployment costs have curbed FTTH penetration.

The GSMA estimates that between 150 MHz and 700 MHz of mmWave spectrum will be necessary to satisfy 5G FWA demand in households located in dense urban areas, based on an FWA penetration of 30% [20]. In the 10 cities analysed by the GSMA, an average of 350 MHz will be required (as shown in Figure 26). Even in cities with relatively high FTTH penetration, FWA may need significant spectrum capacity to serve large numbers of households, given the likely increase in data consumption between now and 2030.

In areas characterised by a lower FTTH penetration, including suburban areas and rural towns, more mmWave spectrum may be necessary to satisfy 5G FWA demand from households located in these areas. Between 700 MHz and 1200 MHz will be required in a suburban area and between 50 MHz and 850 MHz in a rural town, based on an FWA penetration of 60%, according to GSMA Intelligence.

Figure 26: 5G mmWave spectrum needs in cities, suburban areas and rural towns



5G FWA mmWave spectrum needs, suburban areas

Source: GSMA Intelligence

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

5G FWA mmWave spectrum needs, rural towns

Source: GSMA Intelligence

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

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

In suburban areas, which will require additional capacity to meet the demand for data from households, mmWave is ideally placed to provide a layer of additional capacity while also allowing higher speeds and lower latency.

A recent series of GSMA studies has shown the cost-effectiveness of this technology in providing fibre-like connectivity in regions not covered by FTTH. Some of these studies have shown how under some conditions, deployment of a mmWave FWA network can be cheaper than an FTTH alternative [21].

The GSMA found 5G FWA can be both more economical and faster to deploy than fibre to bring 100 Mbps connectivity to households and businesses located in rural areas. The use of 5G FWA mmWave in small rural towns, for example, should provide substantial cost savings compared with FTTH deployment. While 5G FWA networks in rural areas will be mostly deployed on mid-bands, as data consumption grows or as the number of subscribers increases, operators are likely to add capacity using mmWave spectrum.

7.2 Customer Premise Equipment (CPE) Antenna Location

Different base station antenna configurations and techniques, MIMO, active phased arrays and beamforming antennas can have an effect on the customer deployment options of the FWA CPE.

There are three traditional methods for CPE positioning in a home or office scenarios.

1. External mounted antenna, omni-directional or more common direction patch antennas: professional installations will provide the best performance, where an active or passive directional high gain antenna is mounted on the roof top or side of the building with the strongest signal strength. There is an element of upfront cost for the customer or FWA operator, but reduced customer service expense in the future.

2. Patch or transparent window antennas, with customer premise solutions that are either passive as conduits or reflectors to improve the coverage penetration for portable CPEs in a room. Alternatively, passive or active antennas can connect to the CPEs or, as described in the '*Smart Repeater'* section, a window mount can act as a reflector of coverage in to "not spots" or coverage holes. Positioning or configuration of these antennas may need to be done by a professional, although Do-It-Yourself (DIY) installations can be performed with the aid of smartphone applications.

3. Internal CPE antenna provides the best customer self-install option. Smartphone applications can find the best position in the home, usually near a window on the best coverage side of the house. However, there may be aesthetic considerations for the position or location of the CPE.

7.3 Coverage

To economically provide FR2 FWA services, operators will wish to reuse existing cell sites wherever possible. However existing sites are designed for macro coverage, with the inter-site distance typically greater than 1 km in rural areas. The challenge for FR2-specific FWA deployments is to maximize the cell extension up to a few kilometres, especially in suburban and rural areas, to ensure reliable connectivity service in those areas with limited/absent fixed broadband infrastructure. As discussed in the '*Downlink and Uplink Performance'* section, mmWave propagation is heavily attenuated by vegetation, buildings and even heavy rainfall, as well as the UL/DL imbalance limiting DL coverage. Overcoming these limitations will be important for FWA operators.

As discussed earlier, one method of overcoming these challenges is the use of PC1 user equipment, also known as high power UE. PC1 CPE can be used to both a) overcome the DL/UL link imbalance and b) extend the useable DL & UL far beyond what a mobility UE could achieve.

Several field trials have been conducted to assess the achievable performance of FWA over FR2. For example, Ericsson [12] reported that in a US outdoor trial – over a 5G commercial EN-DC network, aka 5G non-standalone (NSA) – a distance of 7 km has been reached, with average DL speeds of ~1 Gbps, average UL speeds of ~55 Mbps and instantaneous peak DL speeds recorded at greater than 2 Gbps, by using a high-power CPE.

TIM demonstrated the feasibility of reusing macro cells for FWA applications by providing a DL speed of 1 Gbps at 6.5 km distance, very close to the performance reported by Ericsson. The adopted network configuration was also based on EN-DC, (i.e., 5G NSA with anchor LTE at 1.8GHz), with externally mounted CPEs power classes PC1 and PC3, and LoS conditions [22].

Recommended actions
The GSMA report, *The Economics of mmWave 5G [6],* indicated increasing the FR2 mmWave FWA deployment ratio with respect to FR1 could reduce the Total Cost of Ownership by up to 70% for telecom operators. There is now a need for field experiments to test the best practices and optimise the technical approaches for a FR2 deployment scenario.
Network infrastructure deployment to support FWA services may begin to address the connectivity gap between rural and urban areas. That would give 5G ecosystem vendors the opportunity to trial the newer deployment approaches and speed up technology development, to improve the user experiences and accelerate the rollout of new advanced applications.

8. UE Power Consumption

Power consumption is one of the most critical barriers for application of mmWave technologies on smartphones. A major contributor to mmWave UE power consumption comes from the RFFE and digital baseband processing, which mainly arises from the need to support a large number of antenna elements to enable beamforming, along with the relative inefficiency of RF components at high frequencies, demands to support a high number of MIMO layers, large bandwidth for CA operation, and so on.

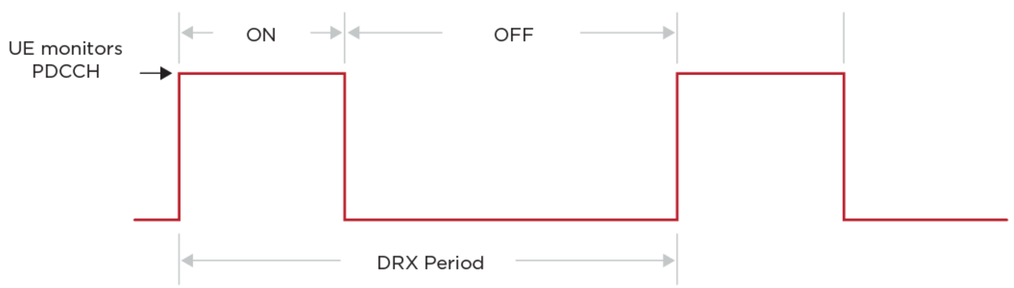
High UE power consumption not only drains the UE battery quickly, but also causes over-heating problems that would further affect the UE performance and potentially reduce the life cycle of the battery.

Mitigation

Discontinuous Reception (DRX)

One of the most efficient ways to reduce UE power consumption is to employ DRX technology. DRX consists of two states, the ON state and the OFF state, as illustrated in Figure 27.

Figure 27: DRX



During the ON period, the UE monitors DL signals and channels, such as the Physical Downlink Control CHannel (PDCCH), and performs corresponding data reception. During the OFF period, the UE turns off the transceiver unit and does not monitor DL signals, thereby reducing the UE power consumption. The DRX parameters (e.g., the ON/OFF time period, etc.) can also be dynamically configured to fit different types of services.

Network topology optimisations

One of the major contributors to UE power consumption is the transmitter (Tx), which is responsible for sending out the electromagnetic signals from the device. Due to the weaker penetration capability and higher path loss of mmWave spectrum, compared with lower bands, higher UE transmit power is needed in order to reach satisfactory UL coverage. Hence, various network topologies, such as repeaters and RIS, could be deployed to reduce the physical distance between the UE and network node(s), which will reduce the UE transmit power required for the desired UL performance.

RRC INACTIVE

A RRC INACTIVE state is similar to the RRC IDLE state where UE monitors paging only, but with the following key advantages:

1. The UE can transition from RRC INACTIVE to RRC CONNECTED state with fewer signalling exchanges than required for the transition from RRC IDLE to RRC CONNECTED
2. For DL traffic, the UE can be reached quickly because the network knows precisely which cell to page the UE
3. Reduces network signalling load compared to the complete transition from RRC IDLE to RRC CONNECTED.

The above key differences make RRC INACTIVE suitable for handling bursts of traffic, resulting in lower UE power consumption while being network friendly.

Mobile Originated Small Data Transmission (MO-SDT)

For Release 17, 3GPP introduced support for Mobile Originated Small Data Transmission (MO-SDT), a procedure that enables data and/or signalling transmission while remaining in the RRC INACTIVE state, i.e., without transitioning to RRC CONNECTED state [12]. The UE initiates MO-SDT for the UL transmission only if the following conditions are met:

- less than a configured amount of UL data awaits transmission across all radio bearers for which MO-SDT is enabled,
- the DL Reference Signal Received Power (RSRP) is above a configured threshold,
- and a valid MO-SDT resource is available.

The MO-SDT procedure is initiated with either a transmission over the Random Access CHannel (RACH) configured via system information or over Configured Grant (CG) Type 1 resources configured via dedicated signalling within the *RRC Release* message being used for the UE's RRC CONNECTED to RRC IDLE transition.

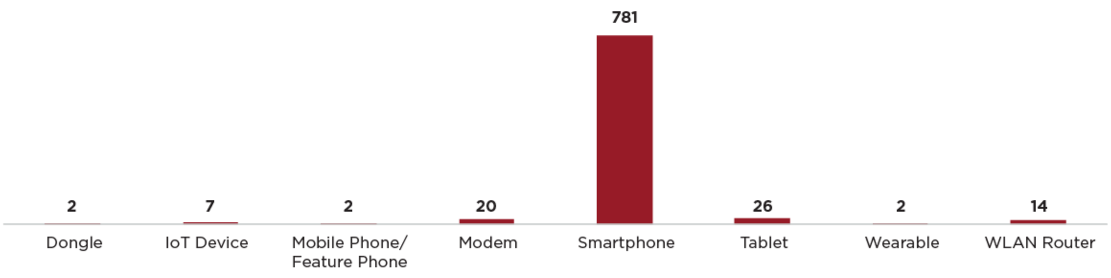
3GPP plans to enhance the MO-SDT procedure in Release 18 by also allowing DL-triggered small data to be sent from the network towards the RRC INACTIVE UEs [12], hence reducing signalling overhead and UE power consumption (by not transitioning UEs to RRC CONNECTED), while also reducing the latency by allowing fast transmission of (small and infrequent) packets, e.g., for positioning.

Recommended actions
Encourage network and UE vendors to support the standardised power saving features described in this section
Facilitate more collaboration between MNOs infrastructure and UE vendors.

9. UE CPE Availability

There has been solid growth in the number of mmWave devices coming to the market in the past 24 months, with 854 SKUs from 52 companies. At this point in time, the network coverage lags the supply of devices.

Figure 28: Available mmWave devices



As previously discussed, as mmWave networks adopt advanced techniques, such as FR2 support, DTX, dual carrier, carrier aggregation, performance will improve and will drive device penetration.

In the short-term, the key growth engine for mmWave CPE will be FWA. The GSA forecasts that in 2022, aggregate shipments of FWA CPE devices will grow 33%, resulting in 21.9 million units, higher than the 2020 volumes (see GSA survey July 2022 [11]). The dip in 2021 was caused by the pandemic, which impacted the supply chain causing a shortage of chipsets.

The GSA forecasts that battery-operated pocket routers will grow 23% in 2022, reaching 7.7 million units, but still significantly below the level of 2020. Figure 29 shows a summary of shipments of FWA devices by type from 2020 to 2022, and Figure 30 (see GSA survey July 2022 [11]) presents FWA device shipments by technology.

Figure 29: Summary of FWA device shipments by type (millions of units, and year-on-year growth)

	2020	2021	2022 (forecast)	2021 YoY growth	2022 YoY growth (forecast)
Battery-operated hot spots	9.8	6.3	7.7	-36%	23%
Indoor CPE	17.6	14.6	19.6	-17%	34%
Outdoor CPE	2.8	1.8	2.2	-37%	26%
Total device shipments	30.2	22.7	29.5	-25%	30%
FWA CPE (indoor and outdoor)	20.4	16.4	21.9	-20%	33%

Figure 30: Summary of 4G/5G FWA device shipments, (millions of units, for 2020, 2021 & 2022 (forecast) and year-on-year growth for 2021 & 2022 (forecast))

	2020	2021	2022 (forecast)	2021 YoY growth	2022 YoY growth (forecast)
Total device shipments	30.2	22.7	29.5	-25%	30%
4G-only shipments	28.8	19.1	21.8	-34%	14%
5G devices	1.4	3.6	7.6	162%	114%
Millimetre-wave-capable devices	0.13	0.16	N/A	27%	N/A

Although shipments of 5G FWA devices (devices supporting 4G and 5G) doubled in 2021 to 3.6 million units, 4G-only shipments made up 84% (19.1 million units) of all FWA shipments in 2021. Of the 5G FWA shipments, 160,000 were mmWave-based devices, jumping from 130,000 in the previous year. The GSA forecasts shipments of 5G FWA devices will double again to 7.6 million units in 2022 (see Figure 31), representing more than a quarter of volumes, while 4G-only devices are expected to have a modest gain (~14%). Furthermore, in the GSA survey, 88% of respondents indicated that they have, or plan to introduce, mmWave 5G products in the next few years (see Figure 32).

Figure 31: Shipments of 5G FWA Devices (millions of units, and as a percentage of total shipments) (Sample: 2021 FWA Survey, 25 respondents; GSA 2022 FWA Survey 26, respondents)

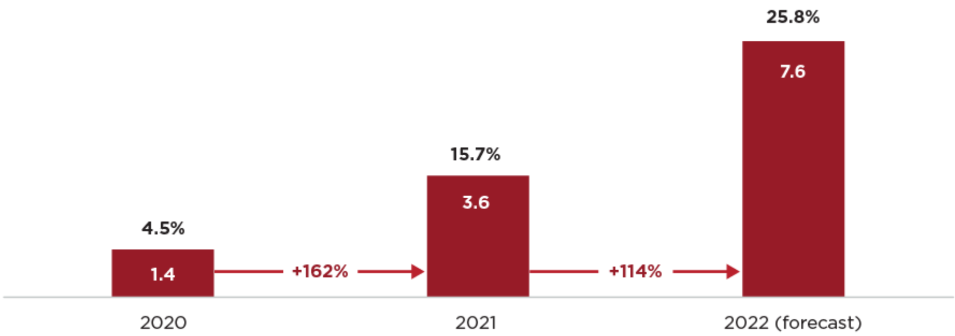
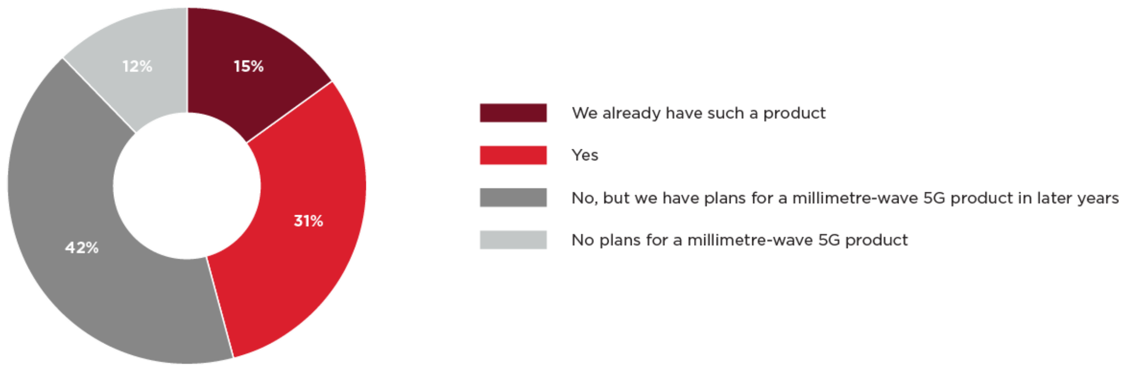
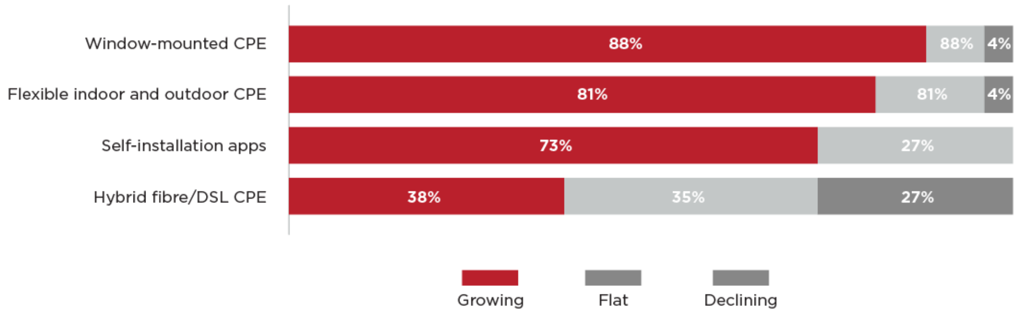


Figure 32: mmWave 5G product roadmaps. (sample: GSA 2022 FWA Survey, 26 respondents)



The GSA asked respondents how they thought the market will change in 2022 for various form factors. Responses show a clear expectation that the market for window-mounted solutions, flexible indoor and outdoor CPE and self-installation apps will grow (see Figure 33).

Figure 33: Vendors' views of prospects of device form factors and capability trends (sample: GSA 2022 FWA Survey, 26 respondents)

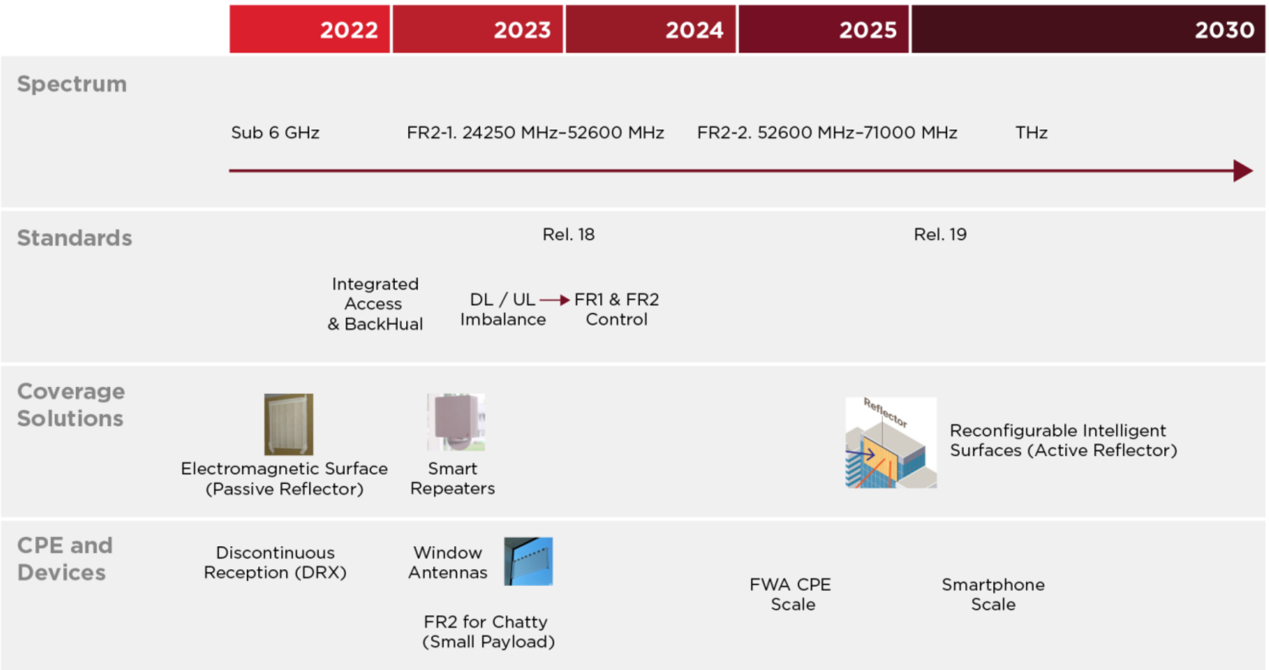


Recommended action:
Whilst there is growth in 5G mmWave FWA CPE, the lack of ubiquitous coverage reduces the demand for mmWave capable smartphone devices. Further deployment of 5G mmWave networks either for FWA, private networks or capacity solutions will inevitability drive adoption.

10. Consolidated Requirements

Section	Mitigation	Recommended Action
Propagation Characteristics	Antenna Gains >20dB Beamforming UL Gain 3.5dB	Industry Awareness
DL/UL Imbalance	Carrier Aggregation for use of Low Band Uplink Use of High Power UE / CPE UL Slot Aggregation gNB Sensitivity increases	Industry Awareness Industry Adoption Standardisation Support for Features
Deployment of Indoor & Outdoor Services Utilising FR2 spectrum	Integrated Access & Backhaul Reconfigurable Intelligent Surface (Active) Electromagnetic Surface (Passive) Distributed Antenna Systems Smart Repeater	Industry Adoption
Maximising mm-Wave coverage with FR1 spectrum	FR1 + FR2 NR Carrier Aggregation NR Dual Connectivity	Industry Adoption Standardisation Support for Features
Smart Repeater	Outdoor, Street Furniture and Indoor Repeaters	Industry Awareness
FWA Best Deployment Practices	mmWave Spectrum Allocation CPE Antenna Location	WRC-23 Lobby Industry Awareness
UE Power Consumption	Discontinuous Reception RRC-INACTIVE Small Data Transfer	Industry Awareness Standardisation Support for Features OEM Adoption
UE CPE Availability	FWA Device Demand Smartphone Device Demand	Industry Adoption OME Adoption

11. 5G mmWave Roadmap



12. Further Enhancements

3GPP continues to make enhancements to 5G in Release 18 [12] and some of these enhancements are also beneficial for mmWave deployments.

- In Release 17 MO-SDT was introduced to reduce UE power consumption and signalling load. Release 18 3GPP is introducing similar enhancements for traffic initiated by the network, i.e., when paging required to reach the UE. The enhancement is called Mobile Terminated Small Data Transmission (MT-SDT) and it will provide similar benefits (i.e., reduced power consumption through reduced number of transactions with the network to deliver small data to UE) as MO-SDT[14].
- Several MIMO enhancements to improve performance of:
    - High/medium speed UEs by introducing faster measurements
    - Coverage and throughput for non-smartphone devices, such as FWA, CPE, vehicle mounted UEs.
- UL coverage enhancements for:
    - Physical Random Access CHannel (PRACH)
    - Support for faster switching between two different uplink waveforms (DFT-s-OFDM - power efficient waveform and Cyclic Prefix Orthogonal Frequency Division Multiplexing (CP-OFDM) – provides high throughput). Currently the switching between the two waveforms is controlled via RRC signalling and this is a slow process.
- NR RF requirements enhancement for frequency range 2 (FR2) aims to improve uplink performance for high modulation (256QAM) during random access and RRC INACTIVE states. This will improve the UL performance for small data transmission.
- Release 18 3GPP is actively working to create smarter mmWave repeaters that are tightly coupled with the the beamforming control from the gNB. Defining requirements for smart mmWave repeaters whose beamforming can be controlled by the gNB

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Abbreviation	Meaning	Abbreviation	Meaning
AiP	Antenna-in-Package	**KM**	Kilometers
BPL	Building Penetration Loss	**LNA**	low-noise amplifier
CA	Carrier Aggregation	**LOS/NLOS**	Line-of-Sight/ None-Line-of-Sight
CAPEX	Capital expenditure	**LTCC**	Low Temperature Co-fired Ceramics
CG	Configured Grant	**LTE**	Long-Term Evolution
CPE	Consumer Premises Equipment	**MHz**	Mega Hertz
DAS	Distributed Antenna System	**MIMO**	Multiple-Input/Multiple-Output
dB	Decibel	**mmWave**	Millimeter Wave
DC	Dual Connectivity	**NSA**	Non-Standalone
DL/UL	Downlink/Uplink	**OPEX**	Operational Expenditure
DRX	Discontinuous Reception	**PA**	Power Amplifier
DU	Donor Unit	**PAPR**	Peak-to-Average Ratio
EIRP	Effective Isotropic Radiated Power	**PC1**	Power Class 1
ES	Electromagnetic Surface	**RACH**	Random Access Channel
FCC	Federal Communications Commission	**RAN**	Radio Access Network
FDD	Frequency Domanin 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	Generation Node B	**SDT**	Small Data Transfer
HPUE	High Power UE	**TCO**	Total Cost of Ownership
IAB	Integrated Access and Backhaul	**Tx**	Transmitter
IC	Integrated Circuit	**UE**	User Equipment
ITU	International Telecommunication Union		

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