HEAVY READING

White Paper

Exploring the Potential of mmWave for 5G Mobile Access

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5G Vision & the Role of mmWave

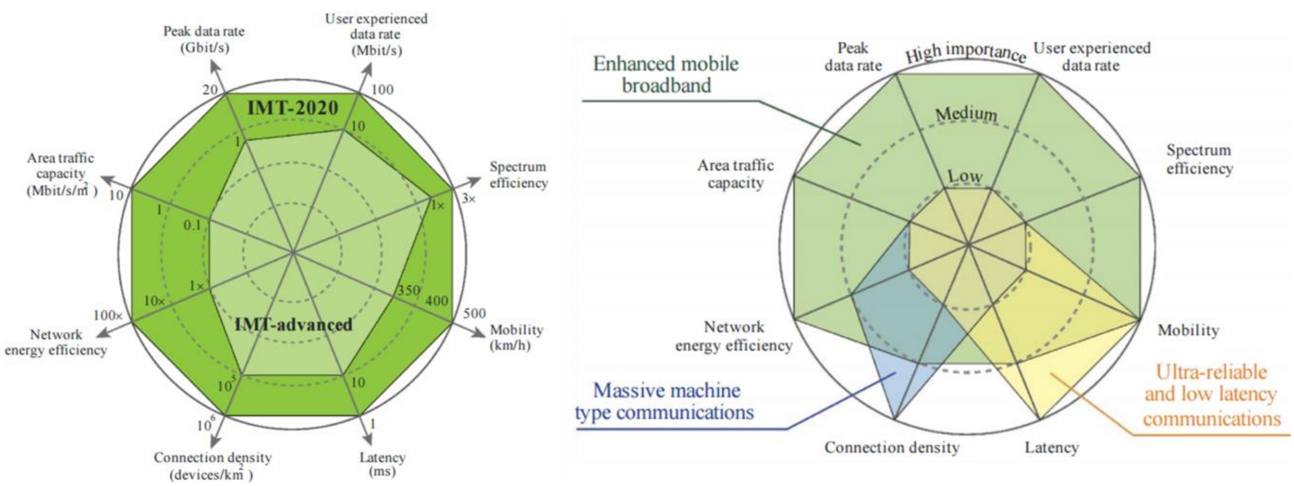
5G is a major advance in mobile communications that will impact every industry and every service provider worldwide. mmWave is emerging as an important – and probably critical – access technology that will enable 5G to meet challenging performance targets in areas of high-density demand.

This white paper discusses the role of mmWave in future 5G networks. It investigates why mmWave is attractive to operators, provides a status update on technology development, discusses field testing activity around the world, and investigates how to mobilize mmWave using advanced antenna processing technologies. In the final section, it examines proposed deployment options.

5G Use Cases & Performance Targets

High-level performance targets for 5G services have been developed by the International Telecommunications Union Radiocommunication Sector (ITU-R) through the IMT 2020 process. These are shown to the left of **Figure 1**, where the requirements are expressed either in absolute terms – for example, 20 Gbit/s peak rate or 100 Mbit/s user-experienced rate – or in terms relative to advanced LTE networks – for example, 3x spectrum efficiency or 100x energy efficiency. These diverse performance requirements are probably not achievable simultaneously in a single commercial implementation of 5G technology.

Figure 1: IMT 2020 Performance Targets



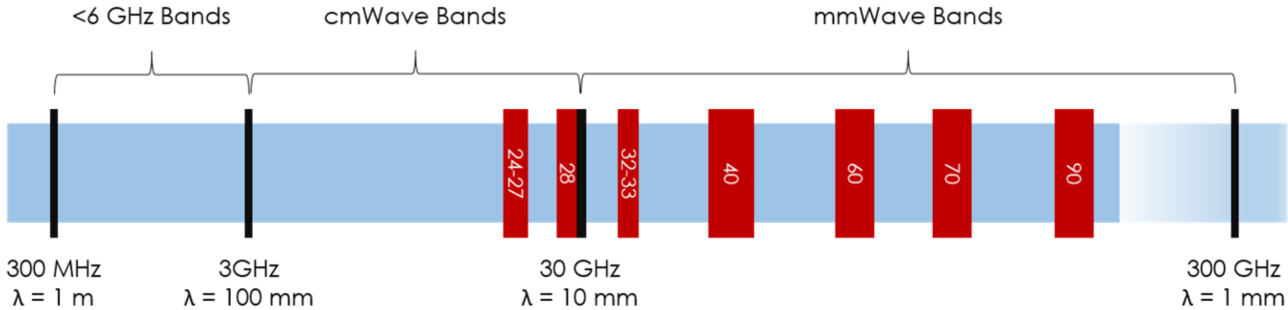
Source: ITU Recommendation ITU-R M.2083-0, September 2015

To the right of **Figure 1**, these high-level performance targets are mapped to three different classes of use case: (1) enhanced mobile broadband (eMBB); (2) massive machine-type communications (mMTC); and (3) ultra-reliable, low-latency communications (UR-LLC). Each use case incorporates a subset of the performance targets. For example, mMTC may not require 20 Gbit/s peak rate, but would need high connection density and low power. eMBB, however, does require high peak rates – hence the interest in mmWave, a technology that is able to support extremely high capacities with dense spatial reuse of spectrum.

Candidate mmWave Bands for 5G Access

Spectrum for 5G services is typically considered in two categories: sub-6 GHz frequencies, which include the traditional cellular bands; and above 6 GHz, which includes the mmWave bands. Both low-band and high-band frequencies will be combined into a common system architecture, with devices able to connect to both accesses simultaneously. **Figure 2** identifies some of the leading candidate bands for 5G mmWave. (Classically, mmWave refers to spectrum between 30 GHz and 300 GHz, but for this paper, we will also consider 24 GHz and 28 GHz.)

Figure 2: Candidate mmWave Bands for 5G



Source: Heavy Reading

The large amount of spectrum available in the higher bands is the primary reason operators are interested in mmWave. Whereas sub-6 GHz bands offer channel widths of up 20 MHz today, and may scale to 100 MHz in future, the mmWave bands under consideration offer much larger channel widths of 500 MHz, or perhaps even 1 GHz. For example, some 28 GHz license holders in the U.S. have up to 850 MHz of spectrum, and there is potential for even greater channel widths in other bands.

The World Radio Congress (WRC) will attempt to harmonize mmWave bands on a global basis, but actual allocation to "mobile primary" or flexible use is determined by national and regional regulators. Thus the 28 GHz band – which is not under consideration at the next WRC in 2019, but is the leading mmWave band for 5G – could be allocated independently by, for example, U.S. and South Korean regulators.

Harmonization is important in wireless systems to generate economies of scale. This may be particularly true in mmWave, because the technical implementation of an antenna array can vary significantly between bands that are several gigahertz apart. European countries, for example, are looking closely at 24.25 to 27.5 GHz and 31.8 to 33.4 GHz, and this may allow the same (or similar) terminal implementations used for 28 GHz in the U.S.

mmWave is also particularly well suited to spectrum-sharing schemes in which mobile users can coexist with other users, such as satellite operators or the military, due to the relatively tight beams and the opportunity for dense spatial reuse. This further extends the opportunity to exploit this spectrum commercially.

The Advance of mmWave Technology

Mobile systems, to date, are specified for sub-6 GHz operation, and in practice are only deployed at scale below 3 GHz. This is because higher frequencies suffer from greater path loss in the event of obstructions such as buildings, foliage, rain or even absorption by oxygen, and by convention are considered useful for short-range applications or for carefully engineered point-to-point links. This convention is now under challenge, and there is a real possibility that these frequencies could be used for mobile access to deliver gigabit speeds to end users.

A HUGE Advance in mmWave R&D

There are three primary factors driving the advance in mmWave: (1) a better academic understanding of mmWave propagation as relates to mobile access (there is now a large foundation of mmWave research on which to base future system development); (2) a radical improvement in computation capability embedded in silicon to enable the beam-forming, beam-steering and bream-tracking techniques needed to mobilize mmWave; and (3) the ability to integrate a large number of antenna elements and RF chains into cost-effective phased-array RFICs.

In addition, early operator field testing of the technology (e.g., by Docomo, KT and AT&T) indicate that the theoretical potential is realizable in real-world deployments. This reappraisal of mmWave, and excitement about 5G deployment, has been called a "Halley's Comet Moment" by esteemed radio engineers and academics, who refer to it as a once-in-a-lifetime opportunity to open up a vast new swath of spectrum for mobile use.

The miniaturization of phased-array antenna systems, which is required to develop low-power, cost-effective user devices, remains a challenge. However, advances in other high-frequency wireless systems provide input into the development and implementation of 5G mmWave devices. For example, there is good progress in 60 GHz WiGig (802.11ad) specified by the IEEE for short-range indoor applications, such as wireless media transfer. This is driving greater chipset integration, and 32-antenna array elements can already be integrated into commercial handsets.

Work on more advanced PHY, MAC and antenna processing will also make WiGig links more robust, and there are already proposals to repurpose the technology for more challenging scenarios. Facebook, for example, is using the 802.11ad physical layer in its Terragraph project to create a low-cost broadband access network architecture that is simple and fast to install.

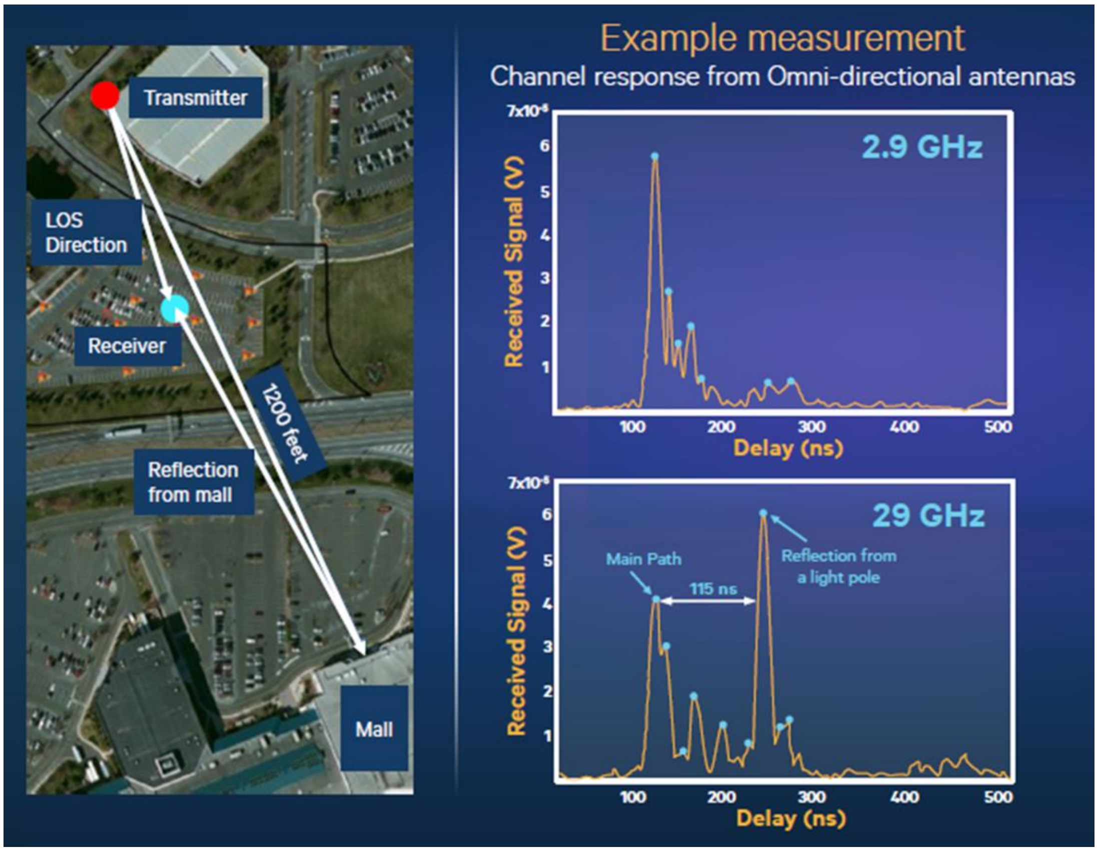
mmWave is also used in mobile backhaul, particularly in lightly licensed E-Band or unlicensed V-Band. Applications include macro-cell backhaul, small-cell aggregation and fiber extension. These are point-to-point applications, but provide a useful insight into how mmWave performs in demanding, outdoor conditions. For example, vendors have been able to compensate for "pole sway" and rain fade.

Massive MIMO & Reflected Signals

A major lesson learned from mmWave simulations, channel measurements and field testing to date is that, using advanced antenna processing, it is possible to capture reflected signals – in effect, non-line-of-sight (NLOS) signals – and use them to supplement the line-of-sight (LOS) signal to increase channel capacity. Because alternative paths in mmWave can produce a very large receive signal, this can make a major contribution to channel throughput and, in some cases, could make it practical to deploy mmWave on existing cell sites (particularly where inter-site distances are relatively small – say, up to approximately 150 meters).

A mmWave test bed operating outdoors at 29 GHz is shown in **Figure 3**. To the left, the transmitter and receiver are shown has having a LOS connection and a NLOS connection reflected from the mall building 1,200 feet away. To the right, the chart shows sample channel measurements for the 29 GHz band and, for reference, the 2.9 GHz band. This shows that the lower-frequency 2.9 GHz band receives a stronger LOS signal than the 29 GHz band (see the first peak on the graph); however, the second peak in the 29 GHz plot shows that the reflected signal in mmWave can be very strong, and may provide a superior receive signal that could be used where objects such as foliage or street furniture impact LOS.

Figure 3: Outdoor mmWave Propagation Using LOS & NLOS Paths



Source: Qualcomm

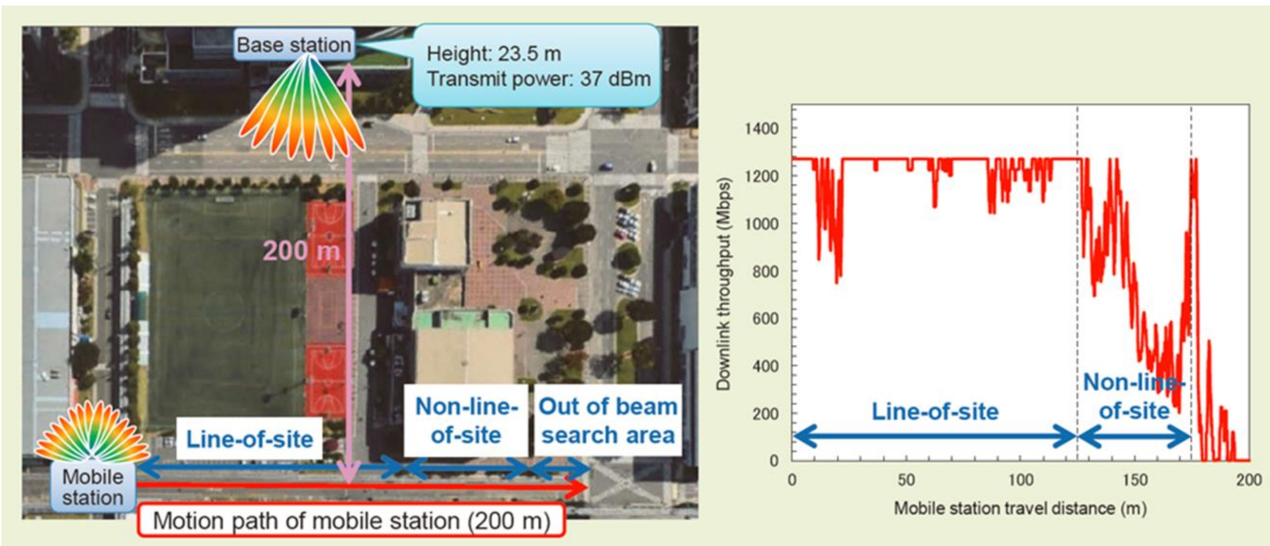
NLOS Operation

Taking this a stage further, there is the potential to use reflected signals to maintain a link to a mobile device even when it moves entirely out of LOS of the transmitter. If this proves to be practical in real-world deployments, it could radically expand the role of mmWave in 5G access.

Figure 4 shows a 28 GHz test bed operated by Japanese operator Docomo using an 800 MHz channel with 64 antennas at the transmitter and 4 antennas on the mobile device. The transmitter is mounted on a rooftop and the device, which is moving at 3 km/h, is located 200 meters away. The figure shows that where the device has LOS to the base station, downlink speeds of 1.2 Gbit/s are observed. This is impressive performance to a moving device (albeit at very low speed); however, it is also interesting that when the device moves out of direct LOS, the mmWave link continues to work, due to reflected signals. Whereas it was previously thought that mmWave was only practical for LOS applications, it may now be useful even in full NLOS conditions.

Performance in the NLOS area is substantially diminished, as shown in **Figure 4**. However, because mmWave channels are hundreds of megahertz wide – in this case, 800 MHz (32 times as wide as a standard LTE channel) – the usable data rate is still attractive – in this case, 300 Mbit/s. If a mmWave link is combined with additional lower-frequency links, the user-experienced data rate would be substantially higher.

Figure 4: NLOS Paths in Outdoor mmWave Transmission



Source: NTT Docomo Technical Journal, April 2016

Tests such as these offer an insight into the opportunities for mmWave to radically enhance mobile access network design and play a major role in 5G – it truly could herald a Halley's Comet Moment. However, it is still early days for the technology. Carefully controlled test beds using prototype equipment are a long way from commercially viable solutions that can be sold at mass-market scale.

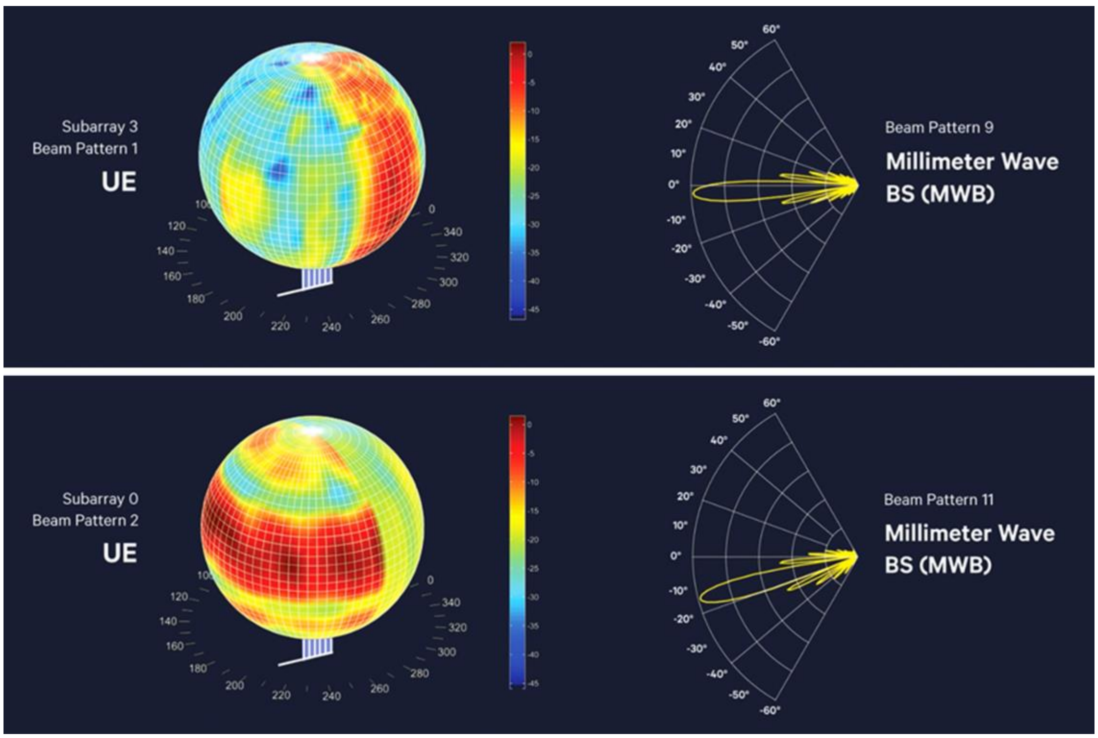
Mobilization With Beamforming, Beam-Steering & Beam-Tracking

One major challenge to using mmWave for 5G access is the ability to support mobile operation. Because mobility can result in rapidly changing channel conditions, the base station must adapt transmissions to maintain link performance. At mmWave frequencies, even small variations in the environment, such as the turn of the head, movement of the hand, or a passing car, can change the channel and impact performance. Addressing this is critical.

Beam-steering and beam-tracking techniques leverage massive MIMO antenna arrays to create highly directional "beams" that focus transmitted energy to improve performance in the uplink and downlink. **Figure 5** below shows this concept in action in a test bed network. In this example, the base station (shown right) has 128 antenna elements with 16 controllable RF channels, and the device or UE (the sphere shown at left) has four selectable subarrays, each a phased array with four controllable RF channels to give 16 antenna in total.

The device selects the best subarray on which to receive and transmit, depending on its position relative to the base station. The top image shows a beam pointing at a 0-degree angle to the device, with the red color on the "heat map" showing the beam-tracking and beam-steering activity by the selected subarray and the associated beam pattern. The bottom image shows the corresponding "heat map" for a beam at a 15-degree angle.

Figure 5: Mobile Beam-Tracking & Beam-Switching at 28 GHz



Source: Qualcomm

The phased array tracks the base station to create dynamic, directional beams, such that a change in the position of the device relative to the base station does not overly impact performance, and that a robust signal is maintained even as the device moves through the coverage area.

Developing beam-tracking and beam-switching techniques is critical to making mmWave suitable for 5G mobile access, and is expected to require continued investment in both the digital and analog domains to create products that are power-efficient and, from a consumer perspective, "just work."

5G System Architecture & mmWave

mmWave radio will be an important part of future 5G networks, but mmWave itself is not the entirety of 5G, nor is 5G synonymous with the technology. By common agreement, the new 5G radio will operate in multiple frequency bands. Moreover, the new network will support multiple radio access technologies (RATs) to incorporate 5G mmWave, sub-6 GHz 5G, evolved LTE, legacy LTE and non-3GPP access, such as WiFi.

mmWave in a Robust Multi-RAT Network

This concept of multi-RAT connectivity – with mmWave as one component – is inherent to 5G and has important implications for system design and for the user device. **Figure 6** shows how a device will connect to multiple air interfaces, both at different times, and simultaneously. This is obviously useful during the deployment phase when 5G coverage will be patchy, and will remain important over the longer term.

Even in a pure 5G environment, it is expected that devices will connect to sub-6 GHz radios at the same time as mmWave radios, in order to provide faster system acquisition; robustness to counter the fading that impacts high-frequency channels; and a reliable, "always available" wide-area 5G service. This model helps address many of the challenges with mmWave.

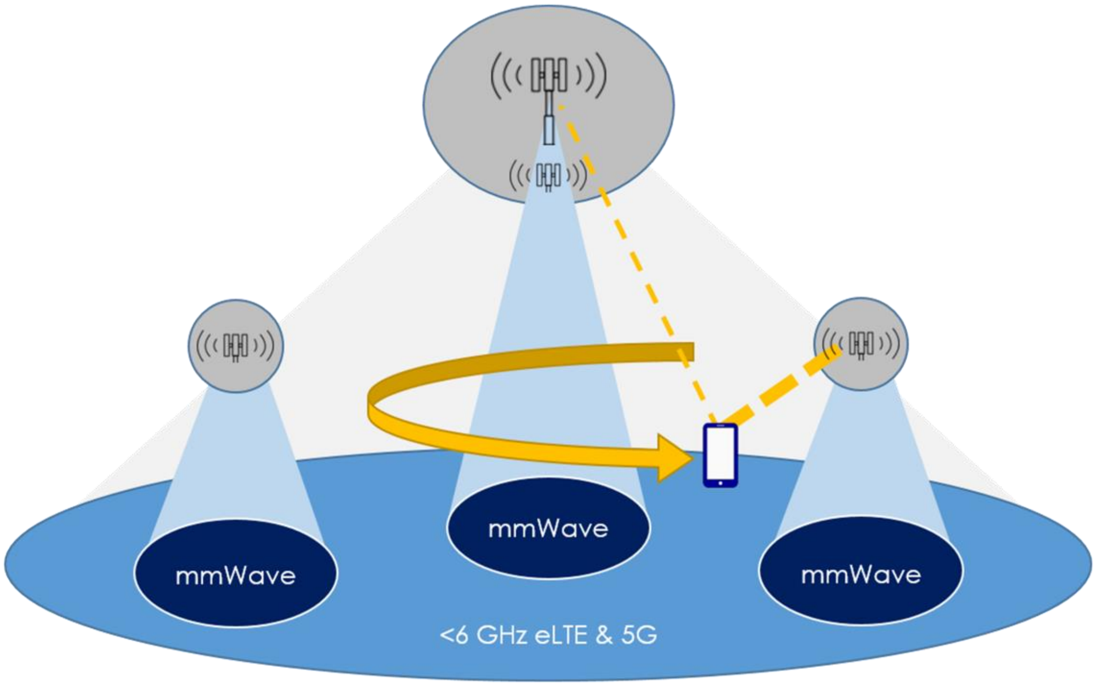
Figure 6: Role of mmWave in Multi-Connectivity Network

Source: Qualcomm

On the device side, multi-RAT connectivity places great emphasis on modem performance. The modem will aggregate multiple radio carriers at varied frequencies, with multiple antenna configurations, and provide MAC processing to interleave the data stream from different accesses. This complexity generates a high computational load, but also requires low power consumption to be effective in handheld devices. The device modem, therefore, is one of the critical components of 5G service, and one of the hardest to implement effectively.

On both the device and the network side, the proposal is to use dual-connectivity to support tight integration between mmWave and sub-6 GHz access. In this scenario, an anchor cell (typically a low-band macro cell) provides coverage and handles procedures for channel acquisition, paging and mobility, while a non-collocated booster cell (in this case, a mmWave small cell) provides localized, high-capacity user-plane services. **Figure 7** shows mmWave used as an underlay to a low-band macro network as part of a wider RAN architecture.

Figure 7: Multi-RAT Network With Dual Connectivity



Source: Heavy Reading

One extension of this concept in 5G is the "user-centric virtual cell." Rather than serve a device from one or two primary cells, the RAN will schedule resources across a range of access points, including mmWave, according to prevailing load and user demand. The first step is likely to be control- and user-plane separation, as employed in the dual-connectivity model, and then potentially to expand this capability to support more sophisticated "virtual cells" in future.

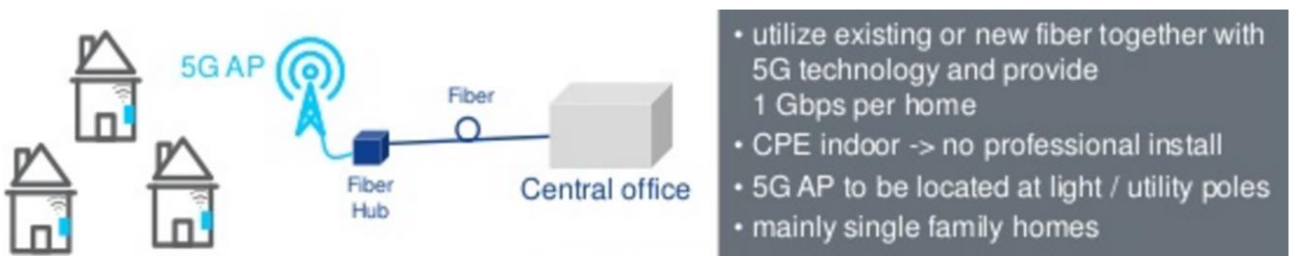
Deployment Options for 5G mmWave

There are several realistic deployment scenarios for mmWave as part of a 5G access network. Three of the leading candidates are discussed here.

Fixed Broadband Access

Fixed wireless access is fast emerging as the initial commercial use case for mmWave 5G radio. The idea is to use wireless links to extend street-level fiber deployments to serve residential users with gigabit speeds. By removing the need for civil works across individual homeowner properties, this should cost less than running fiber to each residence and, with wide channels, could provide gigabit per second performance. Given that foliage and construction materials can impair performance, there are questions about reliability; however, the hope is to compensate for this with features such as path diversity. The concept is shown in **Figure 8**.

Figure 8: 5G Fixed Access Concept



Source: Nokia

Several operators in the U.S. are trialing 5G for fixed wireless access. AT&T and Verizon are on record as planning to trial the technology in 2016 and 2017. Others, such as Google Fiber, are also understood to be evaluating the potential of mmWave for this use case.

Of course, there is some debate about whether this is really "true 5G," since there is no mobility component. There are also other wireless solutions available for this use case – typically based on some form of (modified) WiFi technology or using point-to-point and point-to-multipoint microwave technology. Nevertheless, this application provides an early opportunity to put mmWave into commercial use, and should generate experience of real-world operating conditions that can inform development of mobile systems.

Indoor & Outdoor Small Cell Access

The first mobile applications of 5G mmWave are likely to be in small-cell deployments, due to the relative limited range of the technology and the need for capacity in high-density environments. mmWave, with wide channels and smart antenna systems, is very well suited to this type of deployment.

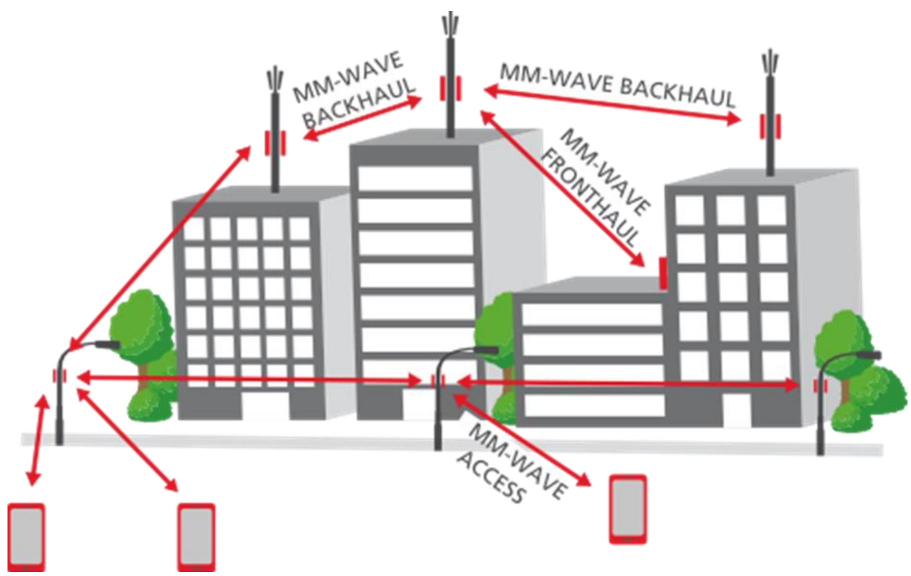
The leading examples are expected to be stadiums and public venues where there is demand for high-bit-rate services, such as HD or 4K video. These venues also provide operators with a high-profile opportunity to demonstrate their new 5G capability to a wider audience. The stadium use case for mmWave small cells was recently demonstrated by Sprint at the Copa America soccer tournament in the U.S., and is planned as part of the larger 5G demonstration network planned by South Korean operators at the 2018 Winter Olympics.

In many ways, mmWave faces the same deployment challenges as current small-cell systems: The operator still needs building-owner consent, base stations still need to be installed, maintained and backhauled, etc. – and technology alone is not a panacea. However, other factors, such as frequency planning and interference management are expected to be easier, and with miniaturization and self-back-hauling, there is potential, in principle, to reduce the overhead associated with passive infrastructure in the installation phase, and the cost of ongoing operation.

Integrated Access & Backhaul Small Cells

Outdoor mmWave small cells are also attractive, perhaps colocated with existing macro and micro cells or deployed as small-cell underlay in a HetNet. **Figure 9** shows how mmWave small cells can be deployed as part of an integrated access network incorporating access, fronthaul and backhaul.

Figure 9: Integrated mmWave 5G Access & Backhaul



Source: MiWeba

Self-backhaul is attractive because it can radically reduce the cost of installation and operation and offers a greater degree of freedom to deploy the small cell at the optimal location from a radio performance perspective. The wide channel widths available in mmWave bands mean it is feasible to allocate (dynamically) a portion of this bandwidth to backhaul/transport and another portion to access.

A number of research projects are pursuing integrated backhaul for mmWave access, and the associated requirement for a mesh networking architecture and protocols. As part of this, there may be an opportunity to share channel state information over the air where coordinated multipoint (CoMP) schemes are used to manage interference.

About Qualcomm

Qualcomm Incorporated (NASDAQ: QCOM) is a world leader in 3G, 4G and next-generation wireless technologies and chipsets. For more than 30 years, Qualcomm ideas and inventions have driven the evolution of digital communications, linking people everywhere more closely to information, entertainment and each other.

Qualcomm has been investing in 5G research and development for many years. At Mobile World Congress in February 2016, Qualcomm did a live demonstration of their 5G mmWave prototype, operating at 28 GHz. The demonstration showcased adaptive beamforming and beam-tracking techniques to enable robust and sustained broadband communications under line-of-sight (LOS) and non-line-of-sight (NLOS) RF channel conditions and device mobility.

In addition, Qualcomm has been able to use the technologies it has developed and is developing for Wi-Fi and 4G LTE as a starting point for its work in 5G. For example, the company has a 60 GHz Wi-Fi (802.11 ad) device chipset with a 32 antenna element array suitable for mobile form factors.