mmWave 5G
It’s crucial role in the 5G commercial journey

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Foreword

The past 12 months have not been an ordinary year, but have seen the beginning of 5G's large-scale commercial journey. Every periodic update of the mobile industry promotes the development of the world and social progress. The technology has proved its value and strengthened its mission in the process of fighting against this pandemic. The pace of 5G will not stop, and it should be more firm and powerful after the pandemic.

There is wide recognition that 5G is the general enabling technology in the era of Industry 4.0. It will bring revolutionary improvement of user experience and digital transformation of thousands of industries. It will inject new vitality and energy into digital entertainment, healthcare, energy, manufacturing, transportation and other industries. To this end, 5G needs to give full play to its maximum potential, continuously develop and improve according to business and user needs, and constantly strive for higher, faster and stronger.

mmWave 5G uses higher frequencies, achieves faster speed, has larger system capacity and stronger business capability, and can help 5G truly realise all the initial commitments and achieve the original vision of the technology. As a result, mmWave has become the key technology of 5G deployment. In some regions the advantages of mmWave 5G have not been understood or promoted as well as they could, for example, relative to the benefits of low- and medium-frequency 5G.

The GSMA has long been committed to promoting the opening of more spectrum for mobile communication, helping operators to launch better networks and better serve users. In June and August 2020, GSMA organised two mmWave 5G special forums to discuss the demand, application scenarios and technical characteristics of mmWave, and launched a series of nine mmWave 5G lectures. At the same time, the opinions of operators, equipment manufacturers, chip suppliers, terminal manufacturers, test service providers, universities and scientific research institutes were widely solicited. This mmWave 5G Technology white paper aims to summarise the technical advantages of mmWave 5G, elaborate the innovative solutions of mmWave 5G bands, explain the product realisation and test schemes, describe the application scenarios, share successful use cases, promote the industry to form a consensus on the technology, and promote the technical progress and industrial development. A report* published by the GSMA, predicts that $565 billion in global GDP and $152 billion in tax revenue will come from mmWave 5G services. That equals 25 per cent of the value created by 5G. A follow-up report* demonstrates the benefits on mmWave 5G will be felt across industries and explores exciting new 5G use cases, including healthcare, industrial automation, education and connectivity across multiple geographies such as Sub-Saharan Africa, South and South East Asia and the Pacific Islands, Latin America and the Caribbean, and the RCC region.

5G provides a platform for all aspects of life, and mmWave 5G can further enhance the height and breadth, and increase the value of this platform. It is hoped all parties in the industry can make joint efforts to promote the application of various 5G technologies, including mmWave 5G, and give full play to the full potential of next-generation networks.

* See https://www.gsma.com/spectrum/resources/mmwave-5g-benefits/

1

Introduction to mmWave 5G technology

Introduction to mmWave 5G technology

mmWave is widely used in many fields including communications, radar, remote sensing and astronomy.

As implied by the name, mmWaves are millimetre electromagnetic waves typically defined to lie within the frequency range of 30GHz to 300GHz, sometimes also including 24GHz frequency or above. 5G is needed to support higher speed and lower latency, and enable a wide variety of new applications which were previously unattainable. Compared with 4G, one key improvement in 5G is to use more spectrum resources to meet various types of business requirements, including tapping mmWave frequency band resources to achieve ultra-high bandwidth and ultra-low latency.

mmWave 5G will bring tremendous socio-economic benefits.

As one of core enabling technologies in high-speed access, industrial automation, healthcare, intelligent transportation and virtual reality (VR), mmWave 5G is expected to drive an increase of $565 billion in the global GDP by 2035, producing 25 per cent of the value created by 5G before 2035.

[1] https://www.qualcomm.com/news/onq/2020/06/01/mmwave-5g-devices-powered-qualcomm-snapdragon-can-deliver-4x-faster-5g

mmWave 5G is an inevitable direction in the evolution of communications technology.

As the business demand for bandwidth is incessantly growing and communications bands are continuously extending to higher frequencies, mmWave 5G with rich frequency resources is an inevitable direction in the evolution of mobile communications technology. Results of Speedtest® by Ookla® show average download speeds on the mmWave 5Gband in live networks are four-times faster than on the sub-6GHz band (6GHz and below) and nearly 20-times faster than on LTE [1]. 5G commercialisation at scale started in 2020, and the industry has begun to look at key technologies for the next phase of 5G deployment. Among these mmWave boasts high bandwidth, low latency and other impressive advantages, and can unlock the full potential of 5G and thus realise revolutionary improvement on business experiences and digital transformation in all industries. mmWave 5G can truly deliver on the vision that 5G will change society, and has therefore attracted much attention and become a focus in the industry. mmWave 5G and sub-6GHz low/medium frequency have their own different performance advantages and pairing with and supplementing each other is key to the most complete and best use experience enabled by 5G.

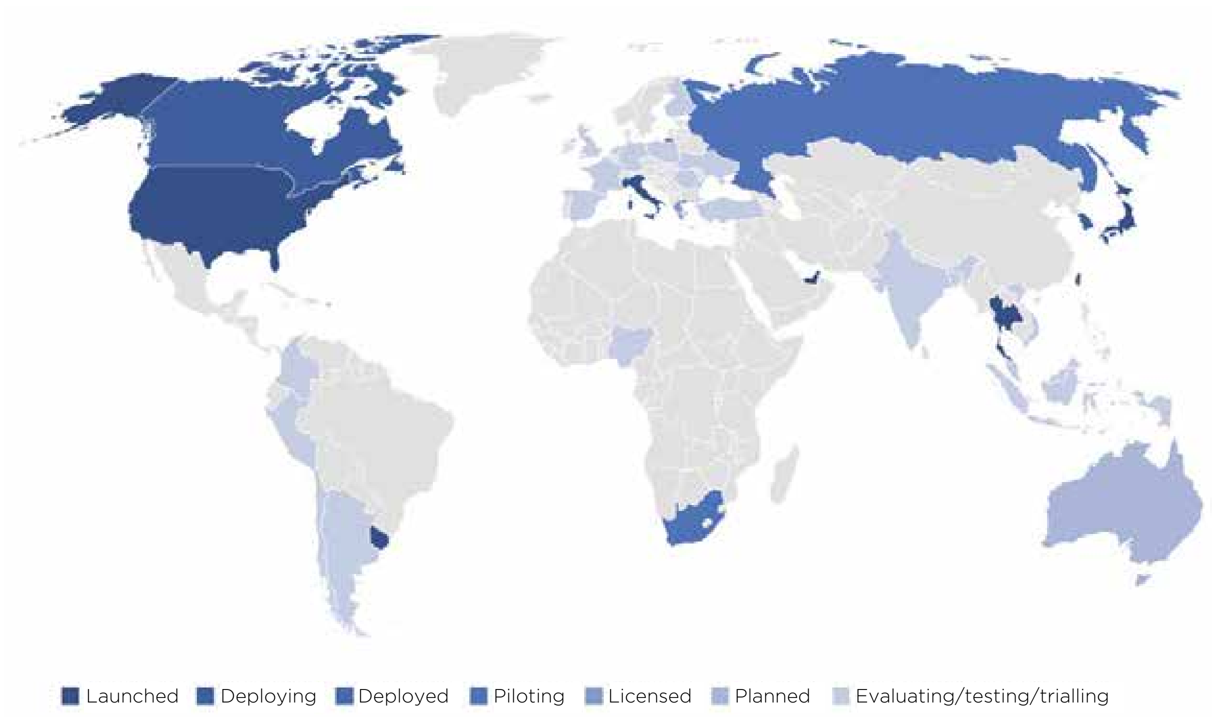


Figure 1 mmWave 5G investments across 24.25~29.5 GHz spectrum range by operators worldwide

Globally harmonised distribution of mmWave 5G spectrums is advancing steadily.

The mmWave frequency range between 24GHz and 86GHz was identified at the World Radiocommunication Conferences 2019 (WRC-19) hosted by the International Telecommunication Union (ITU) for International Mobile Telecommunications (IMT), including the frequency bands 24.25GHz to 27.5GHz, 37GHz to 43.5GHz and 66GHz to 71GHz harmonised worldwide. This marked a solid leap towards the best performance of mmWave and the maximum economic scale effect in the global industry. Nowadays, some countries and territories in the world have completed mmWave 5G spectrum allocation, assignment or auction. The US completed 28GHz and 24GHz auctions in January and May 2019 respectively, and further completed 37GHz, 39GHz and 47GHz band auctions in March 2020. The European Commission (EC) adopted an Implementing Decision in May 2019 to harmonise radio spectrums in the 26GHz band, so Member States can set common technical conditions for the open use of the band. Nowadays, Italy, Finland and Norway have completed designations or auctions on partial spectrums.

The mmWave 5G industrial chain is basically mature

Today, the mmWave 5G ecosystem for industry development is relatively complete, with deployment and commercialisation conditions are in place. [5] Major mobile communications equipment providers have launched base station equipment compatible with mmWave 5G, with some already selling their second or third generations of those. Chipmakers and device OEMs have also launched mmWave 5G products. As noted in the GSA report, 84 announced 5G devices explicitly support mmWave spectrum bands as of June 2020. [4]

Commercial mmWave 5G deployment has started

As global 5G network deployments have gained momentum, commercial mmWave 5G deployment has also unfolded. The major communications operators in the US including AT&T, T-Mobile US and Verizon offer commercial mmWave 5G services. Other operators including NTT Docomo [6] and KDDI (Japan); and SKT (South Korea) have started commercial deployments. According to GSA, 123 operators in 42 countries/territories were investing in 5G (in the form of trials, licences, deployments or operational networks) across the 24.25GHz to 29.5GHz spectrum range as of June 2020. See Figure 1 for details. [4]

mmWave 5G gets policy support in China

The Chinese government approved research, development and trials using 5G technology in mmWave frequency ranges (24.75GHz to 27.5GHz and 37GHz to 42.5GHz) as early as in July 2017. China's Ministry of Industry and Information Technology (MIIT) issued the Notice on Driving Accelerated Development of 5G in March 2020, stating: "In combination with the progress and arrangements of the national frequency planning, the organisation of performance tests on mmWave equipment, to pave the way for commercialising mmWave 5G technology; release partial mmWave 5G frequency band use planning in a timely manner." [7] China's IMT-2020 (5G) Promotion Group has made an overall planning since 2019 and promoted mmWave 5G trial work in three phases with focus on: Validate mmWave 5G key technologies and system features in 2019; validate functionalities, performance and interoperability of mmWave 5G base stations and devices in 2020; and to perform application validation in typical scenarios between 2020 and 2021.

[4] mmWave Bands – Global Licensing and Usage for 5G, GSA, June 2020.
[5] GTI mmWave 5G Spectrum White Paper, GTI, January 2019.
[6] https://www.nttdocomo.co.jp/english/product/data/sh52a/
[7] Notice on Driving Accelerated Development of 5G, China's Ministry of Industry and Information Technology (MIIT).

mmWave 5G will shine at the Winter Olympic Games

The 2022 Winter Olympic Games will be held in Beijing, China. The Beijing Organising Committee for the 2022 Olympic and Paralympic Winter Games has put forward new technical requirements for communications support and services in these leading international sporting events, in order to provide broad audiences, media broadcasters, event organisers and participants with superior event experiences and networking services, so 5G network deployments will play a critical role. Communication business scenarios at the Winter Olympic Games are complex and diverse, such as high-capacity communications with indoor hotspots and broad outdoor coverage, which create an excellent stage to showcase the technical advantages of mmWave 5G. As the only telecommunications services partner of the Beijing 2022 Winter Olympic Games, China Unicom will use a host of methods including mmWave 5G in an integrated manner to build smart wireless venues with ultra-large bandwidth and provide all stakeholders with superb networking services support. We can expect the application of mmWave 5G at the Winter Olympic Games to be an important milestone for large-scale commercialisation of this technology and rapid development of the mmWave 5G industrial chain in China.

mmWave 5G Standard Progress

mmWave 5G was a main component of 5G technologies since the beginning of 5G standard development and an important guarantee for 5G performance metrics. Standardisation of the mmWave 5G air interface has moved in parallel to the work on medium/low frequency. Today, the 3GPP has completed two releases of 5G standards, Rel-15 and Rel-16, with both including specifications for operation in mmWave bands. Figure 2 shows the 3GPP standard timeline.

[8] Articles posted on September 2, 3, 15 and 16 on the WeChat public account China's IMT-2020 (5G) Promotion Group.

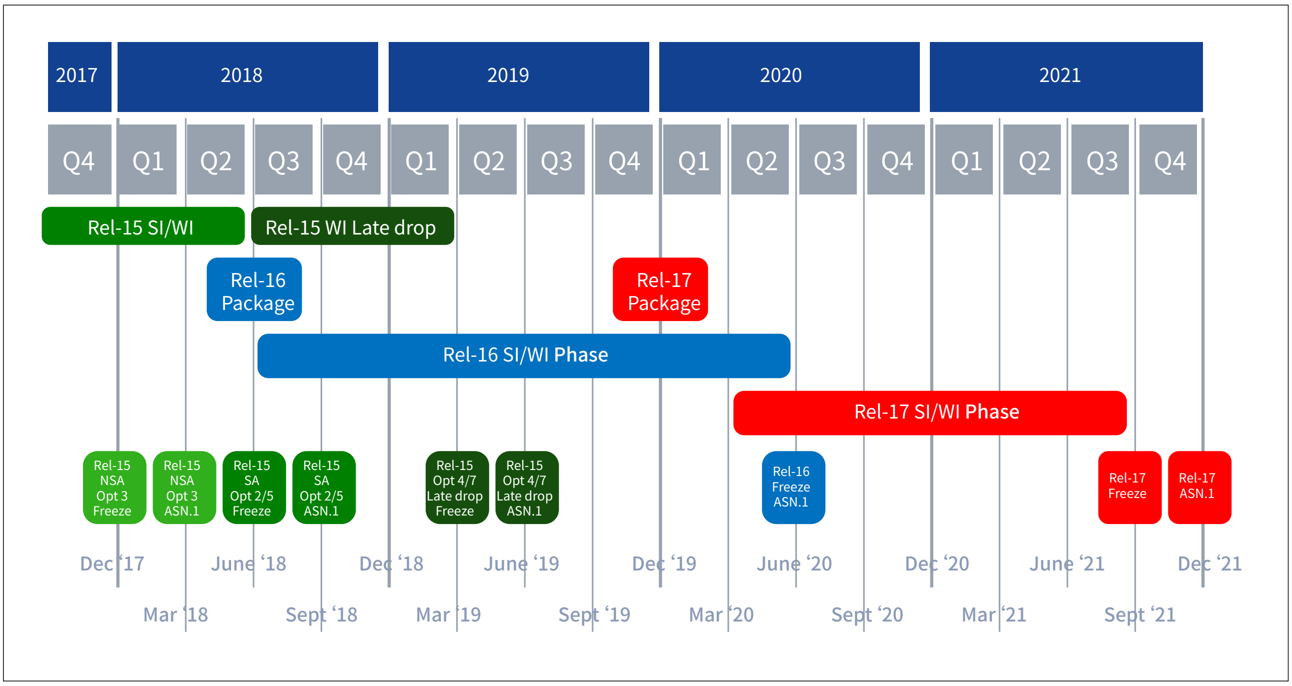


Figure 2 3GPP standard timeline

The second release of 5G standardisation was completed in 3GPP NR Rel-16, which compatible with NR Rel-15 and focused on enhanced vertical applications and increased overall system performance. NR Rel-16 features include enhanced carrier aggregation (CA), optimised beam management, added multiple Transmission and Reception Point (multi-TRP) mode and Integrated Access and Backhaul (IAB), as well as the positioning feature added to NR networks. Specifications for NR Rel-16 and ASN.1 were frozen in June 2020.

The first release of 5G standardisation, which includes mmWave, was completed in 3GPP New Radio (NR) Rel-15, including non-standalone (NSA) and standalone (SA) specifications, which can offer a plethora of scenarios with multiple services including enhanced Mobile Broadband (eMBB) and Ultra-Reliable Low-Latency Communication (URLLC) services. Specifications for the NSA 5G mode (Option 3 architecture) and ASN.1 were frozen in December 2017 and March 2018 respectively; specifications for the SA 5G mode (Option 2/5 architectures) and ASN.1 were frozen in June and September 2018 respectively; with late drops (Option 4/7 architectures) frozen in March and June 2019 respectively.

mmWave 5G features will be further enhanced with 3GPP NR Rel-17, the third release of 5G standards. The upper limit defined in NR Rel-15 for the mmWave 5G band is 52.6GHz (Frequency Range 2) and higher frequency bands will be considered in NR Rel-17, for example a study on bands beyond 52.6 GHz and focus on 52.6GHz to 71GHz. Moreover, NR Rel-17 will expand support for future manufacturing and industrial control, and enhance Industrial Internet of Things (IIoT) and Ultra-Reliable Low-Latency Communication (URLLC), such as: use beam scanning technology to improve transmission reliability and enable time-sensitive communication between devices in a broader range; enhance Multiple-Input Multiple-Output (MIMO) technology, in particular uplink multiple Transmission and Reception Point (multi-TRP) schemes, improved mobility management at the lower-layer air interface and providing more streamlined beam management mechanisms; enhance Integrated Access and Backhaul (IAB), support space division multiplexing (SDM) in access and backhaul links to increase spectrum utilisation; and support more precise location. Relevant specifications are expected to be frozen by the end of 2021.

2

mmWave 5G technology advantages

mmWave 5G technology advantages

Compared with low- and medium-frequency bands, mmWave 5G has many impressive advantages. The technology has attracted attention from the industrial sector because of these advantages and is regarded as a key enabling technology in delivering revolutionary improvements to user experiences and digital transformation in all industries.

1 Rich spectrum resources and large bandwidth

The first, and most important advantage of mmWave 5G is **rich spectrum resources and large bandwidth.** mmWave 5G is valued because it has richer spectrum resources compared with the Sub-6 GHz frequency band (FR1, shown in Figure 3), and is a main means of bringing Gigabit connectivity in the 5G network and a powerful guarantee for delivering on the original vision of 5G. It's not an exaggeration to say using mmWave 5G is a must to meet the requirements for the highest rates.

Multiple Gb/s peak throughput rates can be achieved easily in mmWave 5G networks. For example, by allocating 800MHz of continuous spectrum in the 26GHz band, using four or eight

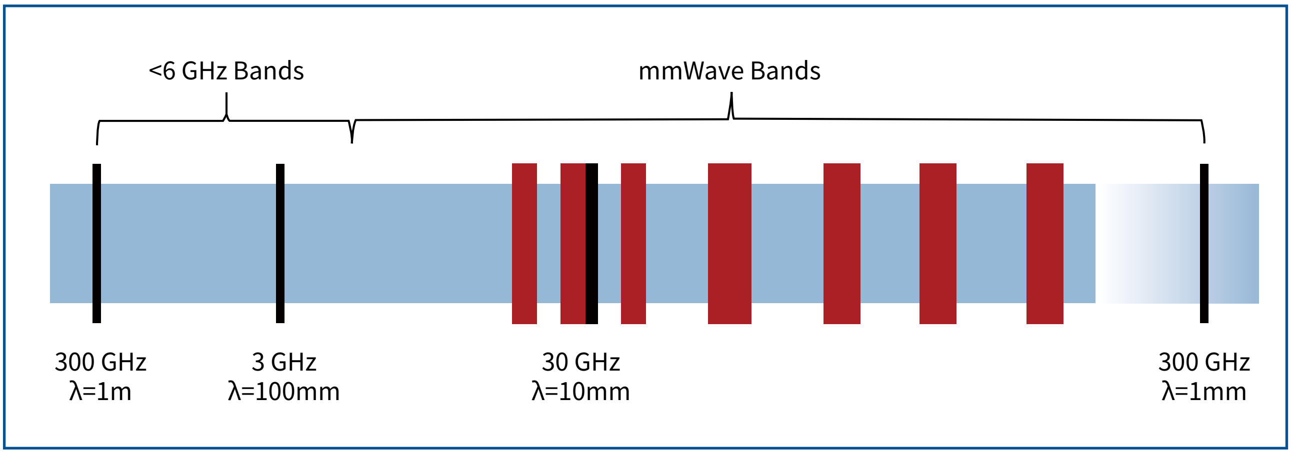


Figure 3 mmWave 5G spectrum resources

single carriers (200MHz or 100MHz) for carrier aggregation (4x200MHz or 8x100MHz), utilising channel width and modulation available in the 3GPP standard and combining advanced antenna design and RF processing technologies, the mmWave 5G system can achieve from about 7Gb/s (64QAM) to 10Gb/s (256QAM) peak data throughput. [7] Today, mmWave 5G is already commercially available in select countries and territories. Results of Speedtest® by Ookla® show average download speeds on the mmWave 5G band in live networks are four-times faster than on the sub-6GHz band (6GHz and below) and nearly 20-times faster than on LTE . mmWave 5G delivers lightning-fast speeds in excess of 2Gb/s, with average speeds of more than 900Mb/s. This result is achieved with 400MHz of bandwidth in the current mmWave spectrum deployment. Verizon, Ericsson and Qualcomm Technologies, Inc. teamed up in October 2020 and were the first in the world to demonstrate 5G peak speeds of 5.06 Gbps. [1] Therefore, compared with sub-6 GHz 5G, mmWave technology provides a substantial boost in user peak rates.

[1] https://www.qualcomm.com/news/onq/2020/06/01/mmwave-5g-devices-powered-qualcomm-snapdragon-can-deliver-4x-faster-5g
[7] Notice on Driving Accelerated Development of 5G, China's Ministry of Industry and Information Technology (MIIT).

2 Use of beamforming technology

The second advantage of mmWave 5G technology is **the use of beamforming technology.** Due to the high frequency band and short wavelength, mmWave 5G has space advantages in design and deployment, and can be combined with beamforming to enhance performance and reduce interference. Beamforming can offer good signal quality even in the case of low single-antenna power. The antenna array of a mmWave 5G device can contain more elements in a limited footprint thanks to relatively short wavelength. In particular, the number of antenna elements in a mmWave 5G base station can reach 256, 512 or more, resulting in a significant beamforming gain either on uplink or downlink. In a typical antenna array configuration, if a base station has 256 elements and a device eight, mmWave 5G can theoretically obtain the beamforming gain shown in Table 1.

When paired with beamforming technology, mmWave 5G signals boast a significantly increased communications distance and can be used for more scenarios beyond short-range transmission and indoor hotspot coverage. For example, when a mmWave 5G base station is used for outdoor coverage, the radius can reach hundreds of metres or even kilometres. In most cases, mmWave 5G base stations can be co-located and -sited with existing 4G base stations and medium-/low-frequency 5G small cells. In Figure 4, a comparative analysis of simulation is conducted when mmWave 5G base stations are co-sited with 4G LTE base stations (operating on Band2 and Band4). Based on field test results within an area of 0.8 square kilometres in some big cities, mmWave base station deployments on the 28GHz and 39GHz bands are compared, and the baseline deployment density of 4G LTE base stations is 73 small cells/ square kilometre. As shown in the figure, if mmWave 5G base stations are fully co-sited with 4G LTE base stations in equal quantity, the downlink coverage of the mmWave network can reach 77 per cent. If the number of base stations increases slightly, the downlink coverage can reach 95 per cent.

Table 1 Typical beamforming gain in the mmWave 5G frequency band

Antenna	Antenna elements	Theoretical beamforming gain
Base station	256	24dB
Device	8	9dB

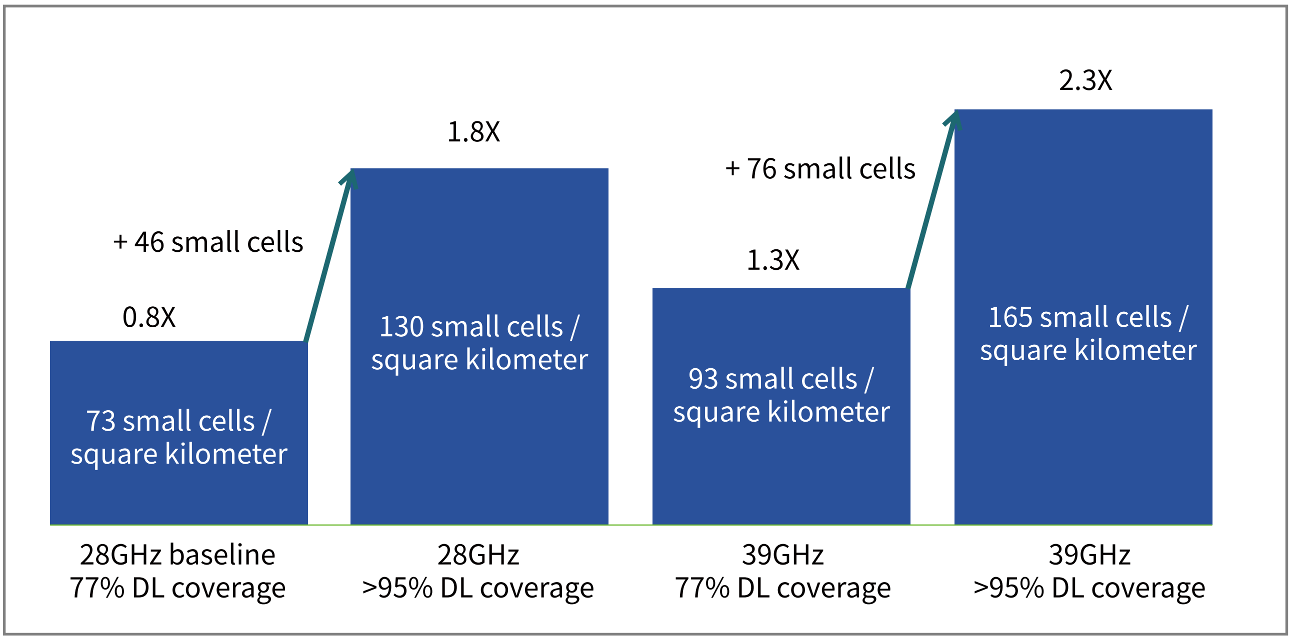


Figure 4 Coverage comparison when mmWave 5G base stations are co-sited with 4G LTE base stations

3 Ultra-low latency

The third advantage of mmWave 5G technology is **ultra-low latency.** Usually, data in the 5G network is scheduled in slots. The shorter the air-interface slot interval is, the lower the latency at the physical layer in the 5G network is. As shown in Table 2, the minimum air-interface slot interval in the mmWave 5G system can be 0.125 milliseconds (ms), one fourth of the air interface in the mainstream 5G low- and medium-frequency systems available today. If mini-slot scheduling is used, the air-interface latency can be even smaller. Therefore, the air-interface latency in the mmWave 5G system is obviously reduced compared with low- and medium-frequency systems, which is an effective guarantee for an air-interface latency of less than 1ms and a quality commitment to URLLC services in the 5G network, such as industrial internet, AR and VR, cloud gaming and cloud-assisted real-time computing. For example, millisecond latencies are required in AR/VR services to deliver excellent multi-sensory coordination experiences and interactivity. Industrial internet has clear requirements for low latencies. Millisecond latencies are required in typical industrial robot networks, and guaranteed rates are also needed in remote real-time control of production lines. Similarly, large-scale computing, required when AI is introduced to various fields such as industrial vision, also has higher requirements for air-interface latencies.

Table 2 Slot intervals on different bands in the 5G network

Band	Subcarrier spacing	Slot interval
1 GHz	15/30kHz	1/0.5ms
1 GHz ~ 6 GHz	15/30/60kHz	1/0.5/0.25ms
24.25 ~ 52.6 GHz	60/120kHz	0.25/0.125ms

4 Support for densified cell deployment

The fourth advantage of mmWave 5G technology is **support for densified cell deployment.** Different from the 5G low- or medium-frequency system, mmWave 5G can not only increase target signal gain with beamforming technology, but also focus signal energy on a specific direction with beam steering to reduce interference on other non-target objects to ensure the quality of communications in adjacent links or cells. Therefore, compared with low- or medium-frequency systems, mmWave 5G can be easily deployed in densely congested cells. This makes it suitable for deployment in large, densely-populated venues such as meeting rooms, music concerts, stadiums and underground rail stations. For example, AR based on mmWave 5G can provide virtual presence experiences for training and meeting in the telecommuting scenario. When watching football games at a stadium, the audience can enjoy competitions relating to their favourite sports stars in a virtual and augmented manner, as well as the effect of real-time motion images superimposed with video footage.

5 High-precision positioning

The fifth advantage of mmWave 5G technology is **high-precision positioning.** The technology features narrow beam, good directionality and excellent spatial resolution; meanwhile, due to a short signal transmission cycle and high time precision, mmWave 5G is expected to enable centimetre-level positioning, and also has advantages in precision and speed even compared with the Global Navigation Satellite Systems (GNSS). Especially in an indoor environment where GNSS signals are weak, the positioning capability of mmWave 5G will play a more important role as it can offer rapid high-precision positioning services in various usage scenarios, such as industrial internet, logistics and transportation, vehicle-to-everything (V2X), transportation hubs, large venues and campuses. High-precision positioning is needed for a multitude of industrial internet use cases, for example automatic transportation of materials; industrial robots performing precision machine operations such as riveting, welding, assembly and cut; and automatic product testing and packaging.

6 High integration

The sixth advantage of mmWave 5G is **high integration.** Thanks to the smaller size of mmWave 5G components, it is easier to make equipment small and miniaturized, compared with sub-6GHz equipment. When mmWave 5G is commercialised at scale, the cost of relevant components will be reduced sharply. The advantage of high integration in various fields, such as professional equipment; wearables; and smart components, means a broad application prospect. Moreover, the mmWave 5G base station has multiple advantages including small size, light weight and ease of installation, all of which is conducive to building a green, efficient and easy-to-deploy network.

TIPS: Six Advantages of mmWave 5G

Table 3 Six advantages of mmWave 5G technology

Advantages	Benefits
Rich frequency resources and large bandwidth	High peak and average rates (multi-Gb/s), massive capacity
Use of beamforming technology	Offers directionality, increased signal strength, enhanced performance and reduced interference
Ultra-low latency (submillimetre-level)	Support a broad variety of services such as industrial internet, AR/VR, cloud gaming and real-time computing
Increasing capacity thus more consistent through put to the customer	Suitable for large venues and transportation hubs
High-precision positioning	Can be applied to industrial internet, logistics & transportation, vehicle-to-everything (V2X) and indoor rapid high-precision positioning
High integration	Make base stations and devices small, miniaturised.

3

Challenges and solutions for mmWave 5G technology

1 mmWave 5G coverage optimisation

Relatively limited coverage due to high propagation loss and weak diffraction and diffusion capabilities in the mmWave 5G high-frequency band is the biggest challenge for the communications system. High-frequency communications suffer from huge path loss in propagation, increased outdoor-to-indoor penetration loss and high susceptibility to blockage (such as buildings, foliage or rain). As described in the Line-Of-Sight (LOS) path loss model of 0~100GHz radio waves in the urban area in the 3GPP TR38.901 [9], there is a positive correlation between free-space loss and carrier frequency. The path loss on the 26GHz carrier is approximately 17.42dB higher than the 3.5GHz carrier, and the theoretical propagation distance of the 26GHz carrier is only one sixth on 3.5GHz. Results of tests by China Unicom [10], show the penetration loss of mmWave 5G is far higher than that of sub-6GHz, as shown in Table 4. Meanwhile, bad weather conditions such as rain, snow and fog also have an adverse impact on mmWave propagation.

Because of this characteristic, people mistakenly think that mmWave 5G can only support LOS transmission, but now there are many solutions to addressing signal attenuation and blockage. Firstly, advanced

[9] 3GPP TR38.901, https://www.3gpp.org/ftp/Specs/archive/38_series/38.901/38901-g10.zip
[10] China Unicom mmWave 5G Technical White Paper, China Unicom, November 2019.

Table 4 Test result of mmWave 5G penetration loss

Tree crown (4m in diameter)	Human body (one-sided / surrounding)	Concrete bearing wall	Wooden door (5cm)	Common glass door	Caravan body
20dB	11~28dB	Impenetrable	6dB	5dB	17 ~ 23 dB

beamforming technology helps increase the Effective Isotropic Radiated Power (EIRP), enhance coverage capabilities, easily transmit signals for hundreds of metres and mitigate path loss. This technology is verified not only in simulation experiments, but also fully in field tests [11] and commercial deployments. Next, mmWave **beam management** becomes a work focus in mmWave 5G standardisation, including search, tracking and switching which allow the mmWave 5G system to quickly capture new beams and dynamically implement beam switching in the case of signals being blocked in some direction. Finally, technological advancements in silicon computation capability have driven rapid development of mmWave 5G technology and integration of large numbers of antenna elements and RF chains into cost-effective **phased-array** RFICs, successfully enabling smart beamforming, search and tracking, and thus providing strong support for the mmWave 5G system in hardware.

These technological advancements allow mmWave 5G to offset its challenges in propagation characteristics compared with low- and medium-bands, with the beamforming advantage. Furthermore, mmWave 5G can harness multi-path and reflection in an effective manner, and freely switch between different connections and paths with advanced beam management technologies. If LOS transmission paths are blocked, the system can still rapidly find, identify and rapidly switch to Non-Line-Of-Sight (NLOS) routes (such as reflection path) with smart beam search technologies, thus solving the problem of signals being blocked in LOS transmission.

In Rel-16, 3GPP has also supported **Integrated Access and Backhaul (IAB) technology** to enhance mmWave 5G network coverage capability and provide backhaul links with the ultra-large bandwidth of mmWave 5G, which helps when it comes to installing 5G antennas in places where it is difficult or too expensive to deploy fibre, such as high-rise buildings, islands or mountainous regions. This, in turn, reduces deployment costs, accelerates rollouts and delivers seamless 5G network coverage. When traditional backhaul links fail due to natural disasters, IAB can also play an important role. As shown in Figure 5, on one side, the IAB technology can expand mmWave 5G network coverage by providing backhaul for additional mmWave base stations: on the other side, the IAB technology increases capacity through sharing spectrum resources with access and backhaul links. Moreover, IAB

[11] https://www.ericsson.com/en/press-releases/2020/9/ericsson-qualcomm-and-u.s.-cellular-achieveextended-range-5g-data-call-over-mmwave

technology supports multi-hop and adaptive topology capabilities, and allows for arbitrary extension of mmWave 5G network coverage, more flexible inter-cell connections and less network topology limitations; supports OTA sync and node discovery functions, and allows for simpler inter-cell synchronisation, smarter interfaces and easier deployment; supports collaboration between access links and backhaul links, achieves integration in allocation of resources at the physical layer, beam and interference management, fully consolidates various link resources and improves overall resources; enhances the 5G network with improved mobility management at the MAC layer, rapid link recovery, QoS management and load balancing, increases network robustness and enables the network to rapidly respond to failures, and make dynamic adjustment and recovery.

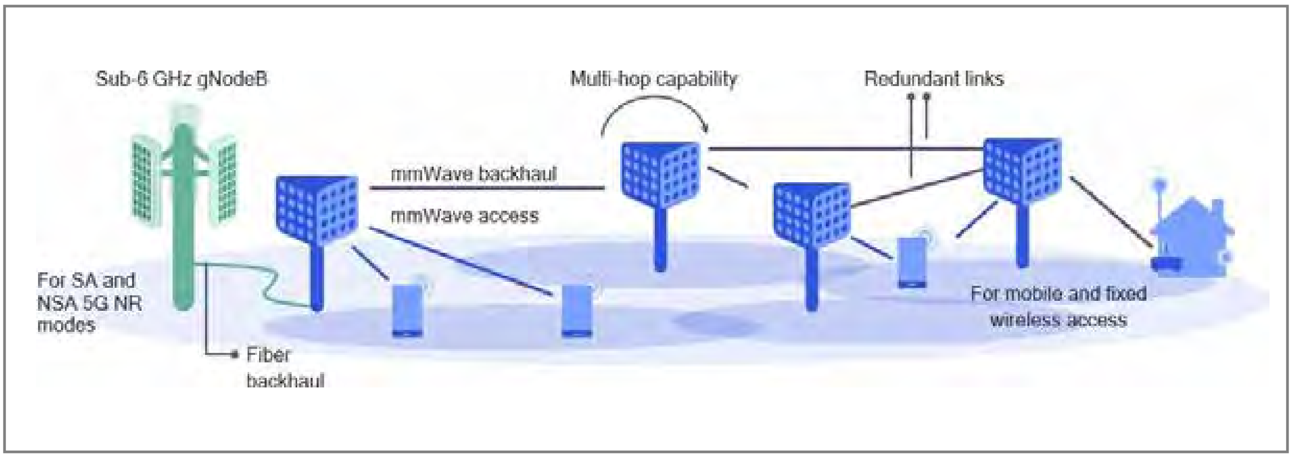


Figure 5 IAB can expand mmWave 5G coverage and increase capacity

Small Cell technology is another solution to solving the mmWave 5G coverage issue. It is difficult to address all communications demands and deployment scenarios with any single type of base station in the 5G era. Compared with low- and medium-frequency 5G macro cells, mmWave Small Cells feature a relatively smaller coverage radius and higher deployment density, ensures superior peak throughput by reducing communications distance and fully ensures a sound coverage effect by increasing deployment density.

The mmWave 5G Small Cell has a wide range of deployment scenarios in both indoor and outdoor environments. To match different deployment scenarios and use demands, mmWave 5G Small Cells can be available in various forms of network architecture, from distributed to centralised. Typical deployment scenarios of mmWave 5G Small Cells are all kinds of hotspot areas such as meeting rooms, large stadiums and concert halls, and various transportation hubs such as airports, train terminals and underground rail stations. On one side, there are generally higher 5G connectivity demand and higher load pressure in these scenarios. If only 5G low- and medium-frequency macro cells are chosen, this easily causes traffic overload on base stations and also possibly leads to user access failure and network user experience deterioration. The high-capacity nature of the mmWave 5G Small Cell can effectively balance loads on base stations, improve the success chance of user access, and ensure sound user connection stability and experience consistency. On the other side, high-density deployment of mmWave 5G Small Cells in these scenarios can avoid signal loss in wall penetration and eliminate worry about blockage such as rain and foliage. Due to the short coverage distance, mmWave 5G Small Cells boast guaranteed signal quality and can maintain high communication speeds stably.

Moreover, compared with the macro cell, it is easier to make the mmWave 5G Small Cell low-power, low-cost and lightweight, while being compatible, open and controllable. Therefore, the mmWave 5G Small Cell can simplify high-density network deployment; realise a plug-and-play, elastic and intelligent ultra-dense network (UDN); effectively reduce the installation requirement for base stations; and mitigate difficulty of macro cell site selection.

2 mmWave 5G mobility management

The second challenge associated with mmWave 5G is **mobility management.** The mmWave 5G cell generally has a small coverage radius due to the propagation characteristics of high-frequency signals, and devices on the go may suffer from data transmission interruption because of frequent cell handover. The 3GPP standard puts forward two key solutions to address difficulty of mmWave 5G mobility management and ensure seamless use experiences. Firstly, there are various **flexible, rapid cell handover solutions** to fully meet these demands in different scenarios, including intra- and inter-cell; and handover based on higher or lower signalling. Secondly, there is **a rapid beam failure recovery mechanism.** In the event of beam failure, the mmWave 5G system can recover beams at the millisecond level with no need to involve the core network and higher-layer signalling.

In addition, carrier aggregation (CA) technology and dual-connectivity (DC) technology can organically combine the low- or medium-frequency with mmWave 5G. Operators can adopt a deployment strategy of sub-6GHz/4G LTE + mmWave, shown in Figure 6, and use CA or DC technology to fully leverage the advantages of these two frequency bands, that is, the 5G sub-6GHz or 4G LTE network to ensure network coverage and offer channel acquisition, paging and mobility management, and mmWave 5G to offer multi-Gb/s speeds and ultra-high capacity. In particular, mmWave 5G and sub-6GHz have almost identical air interface protocols (such as common MAC layer) in the 3GPP standard, so mmWave and sub-6GHz networks can be integrated tightly to enable carrier aggregation.

Figure 6 Organic combination of mmWave 5G and sub-6GHz or 4G LTE networks delivers ultimate user experiences

In Rel-16, 3GPP also improved Multi-TRP features. A high-frequency mobile phone featuring Multi-TRP can simultaneously receive two beams. In this way, when the transmission link of one base station is blocked or attenuated quickly, another transmission link remains active, which effectively avoids the mmWave characteristic of awkward diffraction effect.

3 mmWave 5G product implementation

The third challenge associated with mmWave 5G is **high product complexity and implementation difficulty.** mmWave 5G base stations face at least three challenges. Firstly, mmWave 5G requires installing more antennas, so calibration becomes more complex. To realise precise beam forming required by 5G communications, the mmWave 5G base station needs to control the phase information of the antenna phase accurately. Due to the process technology limitation, relatively large initial phase calibration errors found on actual antenna arrays may lead to beamforming distortion and impact communications performance terribly. Therefore, mmWave 5G requires a focus on tackling the phase calibration difficulty of large-scale array antennas. Next, mmWave 5G requires higher EIRP. For the time being, the CMOS process meets the RF performance of the high frequency band, while GAAS and GAN processes with good performance have a sharp gap in cost and integration, leading to relatively high complexity and costs for mmWave 5G products. Thirdly, mmWave 5G MIMO has a potential possibility of realising higher data streams in the future, which also poses higher requirements for RF signal resolution and the digital processing capability of basebands.

The complexity and technical difficulty of mmWave 5G are also reflected on devices. Firstly, multi-antenna modules are needed. On one side, mmWave 5G has strong directionality and limited coverage. Figure 7 shows the signal strength of antenna modules at three different locations corresponding with three different directions. On the other side, mmWave 5G signals on a handheld device may be blocked by the human body. Therefore, design of mmWave 5G antenna modules must ensure that a mobile phone is effectively covered by different antenna modules, regardless of the device direction and handholding position, and has sufficient link margin when sending and receiving signals.

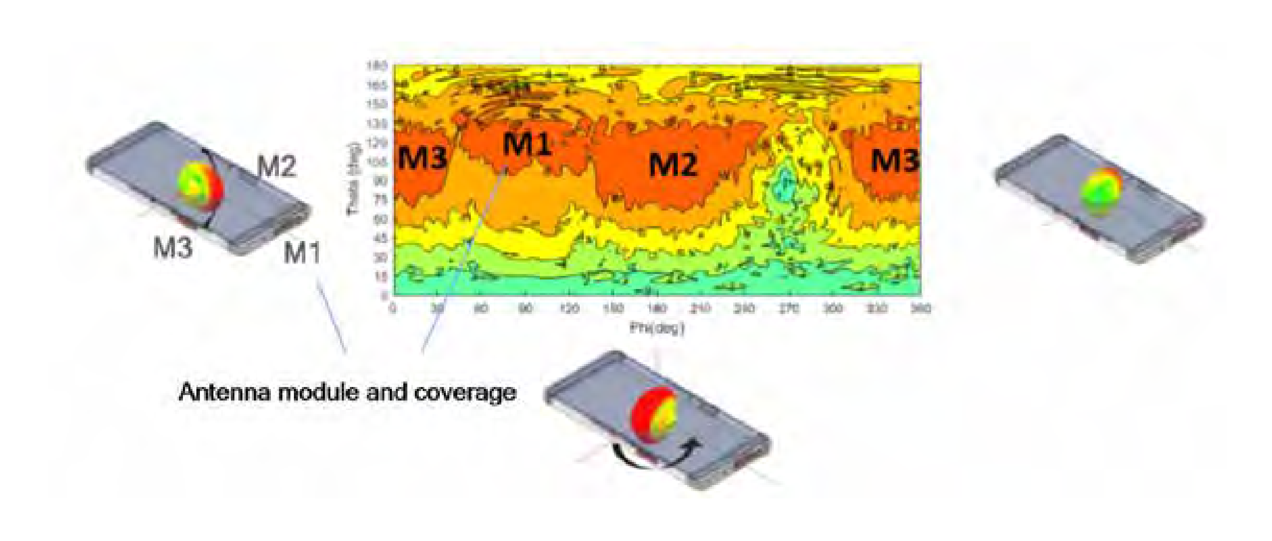


Figure 7 mmWave 5G antenna coverage

The main method of solving this issue is to implement multiple antenna modules on mmWave 5G devices and thus increase the robustness of mmWave 5G communications. For example, when a device is held for communication and some individual antenna module is blocked by the human body, the device can quickly discover and be handed over to a new transmission path by activating another antenna module, thus ensuring radio link stability.

The next challenge is relative difficulty in mmWave 5G antenna design. The number of phone antennas increases in the mmWave 5G era, but the footprint left for the phone is increasingly small. This is a main contributor to the trend of phone development and design. Firstly, 5G smartphones generally have a high screen-to-body ratio, boasting all-screen or even dual-screen designs to match the multimedia services offered in the 5G network, therefore leaving an increasingly small space for antenna installation. Secondly, in light of a growing number of cameras installed on the phone and increasing battery capacity, the antenna layout space is further squeezed. Moreover, as mmWave 5G phones generally support multi-mode communications, antennas must co-exist with 4G LTE and low- or medium-frequency 5G antennas and even share space. Meanwhile, high mmWave transmission loss and component processing precision entail very high requirements for antenna deployment and production. These physical constraints pose challenges in mmWave 5G antenna design.

To address these challenges, an Antenna in Package (AiP) scheme is proposed for mmWave 5G antennas, which integrates antennas, RF transceiver and RF front-end into a bundle based on advanced packaging material and technology and enables the system-level radio function. While adapting to the trend of an increasing silicon-based semiconductor process integration, the AiP technology balances antenna performance, cost and size.

The third challenge is mmWave 5G radio frequency (RF) module integration and low-power design. Key device components mainly include baseband, RF chips, high-frequency (HF) filters, HF power amplifiers (PA) and HF antennas, and other mmWave 5G front-end chips integrated with power-amplitude amplification and phase control functions. Compared with low- and medium-frequency bands, a multitude of characteristics need be taken into consideration in mmWave antenna RF design and manufacturing, such as small, lightweight, broadband-oriented, static and integrated, as well as a series of other issues including mass production and low cost. This poses higher requirements for process technology, component and chip integration and packaging in order to minimise power consumption and maximise the device battery life.

The device EIRP needs to be maximised to expand mmWave 5G coverage, but the resultant issues like power and cost increases will have an adverse impact on device size and selling prices, and finally affect widespread adoption of mmWave 5G devices. At present, some commercial antenna modules can address huge challenges these mmWave 5G devices face. Some commercial 5G chips are integrated with 5G New Radio (NR) radio transceivers, power management IC (PMIC), RF front-end (RFFE) components and phased antenna array, while covering up to 800 MHz of bandwidth in the 24.25GHz to 27.5GHz (n258); 26.5GHz to 29.5GHz (n257); and complete 27.5GHZ to 28.35GHZ (n261) and 37GHz to 40GHz (n260) mmWave bands. Advanced process technology helps integrate all these capabilities in a very compact footprint and thus build slimmer and more stylish mobile devices with mmWave 5G NR ultra-high speeds. The network delivers fibre-like speeds and low-latency services, and helps open up the new generation of connected applications and experiences.

4 mmWave 5G testing

The fourth challenge associated with mmWave 5G is **testing.** The system cannot be tested using traditional methods due to its high bandwidth, small antenna array, narrow beams transmitted and large propagation loss, so it is required to improve test efficiency and precision and reduce the duration. For example, as the RF cable loss is proportional to frequency, the RF cable linking the RF transceiver array with the antenna array will generate a relatively large loss in high-frequency communication and thus affect the equipment performance. To avoid the above loss, the transceiver and the antenna arrays must be integrated into a complete Active Antenna System (AAS). As the traditional transmission port for testing is unavailable in mmWave 5G base stations due to high airtightness, OTA RF requirements and test methods are needed. The industry has gained in-depth understanding of challenges in testing AAS indicators with the OTA method after years of exploration and completed standard development for mmWave 5G base station OTA test method in the Rel-15 phase.

There are generally three types of OTA field test schemes: Far-field, which has a large size and a very high cost; near-field, which has a relatively large size and a relatively high cost; and compact range, which has a relatively small size. Thanks to the advantage in construction cost, it is basically recognised in the industry that the compact range test is used as the major mmWave 5G OTA test scheme. A compact range uses reflector equipment to transform a spherical wave into a plane wave and realise the far-field performance at short range. It was originally used for measuring scattering characteristics of radar antennas and targets and is now introduced to the civil wireless communication measurement. In addition to building a hardware environment including a test field, instruments and a turntable in the OTA test system for mmWave 5G base stations, an automatic test platform is needed to automatically control the turntable and conduct spherical-radiated power testing and interface data processing.

Much progress has been made in mmWave 5G OTA RF spec test schemes, but there are some unresolved issues including base station tests need performance metrics in high and low temperature conditions, the compact range test environment requires constant temperature and humidity, and there is a contradiction between existing conditions and test requirements: the time taken and degree of uncertainty in tests. Now, relevant institutions and industry vendors are exploring and discussing the above technical directions and issues, and moving towards solutions. For example, ZTE Corporation proposed the Rayleigh Optimal Sampling Element (ROSE) solution, which includes two methods: Rayleigh resolution sampling and normalised wave vector sampling, which was adopted in the 3GPP standard. The compact range ROSE test system uses a small compact range test solution and supports 3GPP-specified in- and out-of-band RF spec test automation for mmWave 5G base stations. This test solution has solved key issues in 5G multi-antenna system testing, enabled accurate, rapid and low-cost RF spec tests for mmWave 5G base stations and improved efficiency more than 300-times.

In view of various requirements such as the increasing number of antenna array elements, minimum attenuation in the component and cost reduction, highly-integrated implementation is used in mmWave 5G devices to directly integrate RF transceiver links with antenna arrays. Therefore, there is no longer a RF connector in the device, the traditional test cannot be conducted and an OTA test scheme is also needed. For devices, 3GPP first completed the study on mmWave 5G device test methods in Rel-15, which developed detailed solutions for testing and validating RF, demodulation and radio resource management performance of mmWave 5G devices, involving various test methods such as direct far-field, compact range and near-field to far-field transformation. To evaluate the MIMO performance of mmWave, 3GPP conducted a study on mmWave 5G MIMO OTA test methods in Rel-16, and completed standard development for scenario definition, channel modelling and test methods in a static test environment.

Although the test methods developed in Rel-15 and Rel-16 can validate the basic performance of mmWave 5G devices, there remains issues and challenges. Test cases that need relatively high downlink signal power or relatively low uplink signal power cannot be supported; testing advanced technologies such as FR2+FR2 Inter-band CA cannot be supported; a test device with a single-polarised receiver cannot measure uplink modulation-related indicators accurately; beam management algorithms are not validated well in the static test environment; and it takes too long to test. 3GPP will continue studying the above issues and challenges in Rel-17, and further improve mmWave 5G device test solutions.

5 mmWave 5G co-existence with medium/low frequency

The fifth challenge associated with mmWave 5G is **co-existence with low- and medium-frequencies.** Commercialising mmWave 5G may be a gradual process. For example, first address blind areas and hotspots, vertical applications and necessary wireless backhaul scenarios; then unfold in dense urban areas and first-tier cities, gradually enhancing penetration and offering high-speed bandwidth access in most scenarios. As it is difficult to realise seamless continuous coverage in mmWave 5G deployments in the short run, co-existence with sub-6GHz, especially collaborative network planning and flexible workload sharing, switch between high and low frequencies and interoperability experience, is crucial. Dual Connectivity (DC) and Carrier Aggregation (CA) are the current major evolution paths. In comparison, it is easier to implement the DC approach and the difficulty of device support is slightly lower, while the CA approach has higher efficiency and can realise collaboration at a deeper level. Therefore, if only capacity is increased in hotspots, DC can be used to meet the demand. For long-term evolution and given certain requirements for downlink coverage continuity, the CA scheme can be taken into consideration.

Another technical challenge for co-existence between mmWave 5G and sub-6GHz is the issue of synchronisation in the carrier aggregation scenario. Due to differences in the hardware of communications components, the timing of mmWave 5G and sub-6GHz carriers is prone to errors, resulting in a sync issue in the CA system. Nowadays, issues arising from the CA system getting out of sync are already optimised in the 3GPP standard.

Moreover, low- and medium-frequency 5G and mmWave base stations often co-exist in the same site, and devices also support both. Physical constraints in co-existence of different systems, such as limited space and heat dissipation, are also one of the technical challenges for co-existence of mmWave and sub-6GHz systems. For example, 5G devices must be compatible mmWave and low- or medium-frequency signals. However, as the wavelength of low- and medium-frequency signals is relatively long, it is impossible to cover both that band and mmWave with one antenna. Therefore, to allow low- and medium-frequency and mmWave to co-exist, the device must be equipped with multiple sets of antennas with different functions. How to place 5G antennas in a way that is suitable for mobile devices, balance limited physical space, address coverage demands for different signals and not affect the performance of those antennas poses a new design challenge.

6 Flexible mmWave 5G air interface implementation

The sixth challenge associated with mmWave 5G is the issue of flexible air interface implementation. Demands for services arising from emerging vertical applications in the future vary significantly. For example, guaranteed high uplink speeds are required for video surveillance, mobile police robot and remote surgery, and guaranteed high downlink speeds are required for 4K/8K and VR/AR videos. But now, unbalanced up and downlink capacities of mmWave 5G technology cannot fully meet the demand for flexible deployment. As such, China Unicom proposed a flexible frame solution which uses three frame structures in the system and flexibly employs one structure based on business requirements to satisfy differentiated service demands. As shown in Figure 8, the DDDSU frame structure is suitable for large downlink services; DSUUU is suitable for large uplink services as it can increases the peak data rate by 2.5-times of DDDSU; and DDSUU is suitable for balanced uplink and downlink services in a ratio of 1:1.

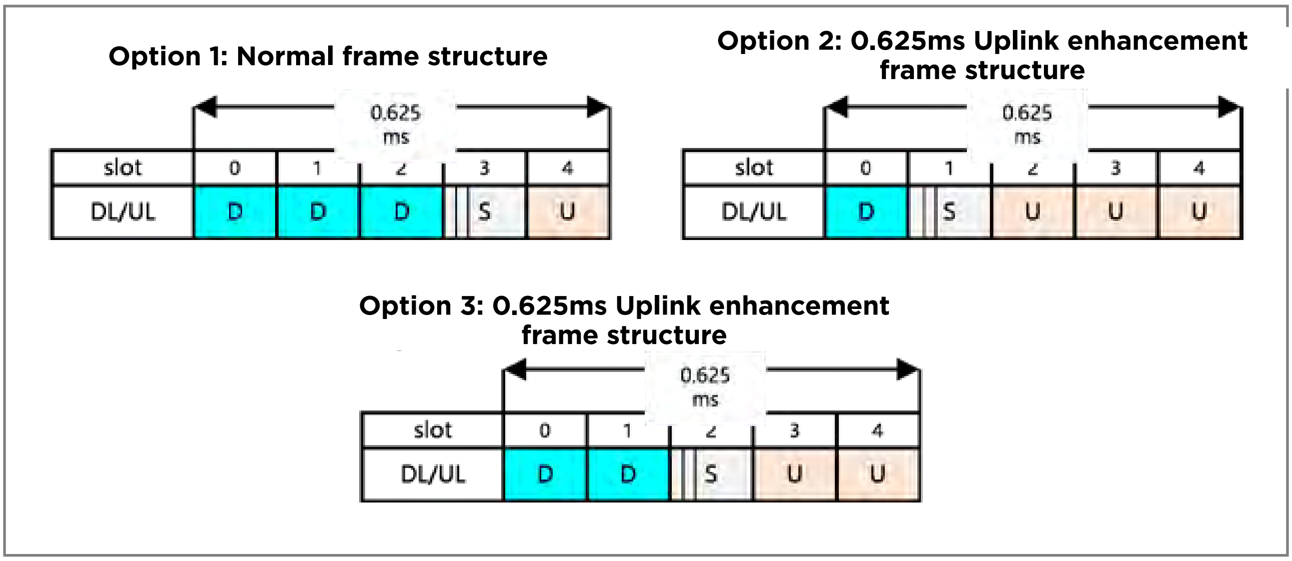


Fig 8. Flexible mmWave 5G frame structures meet differentiated demands in various services

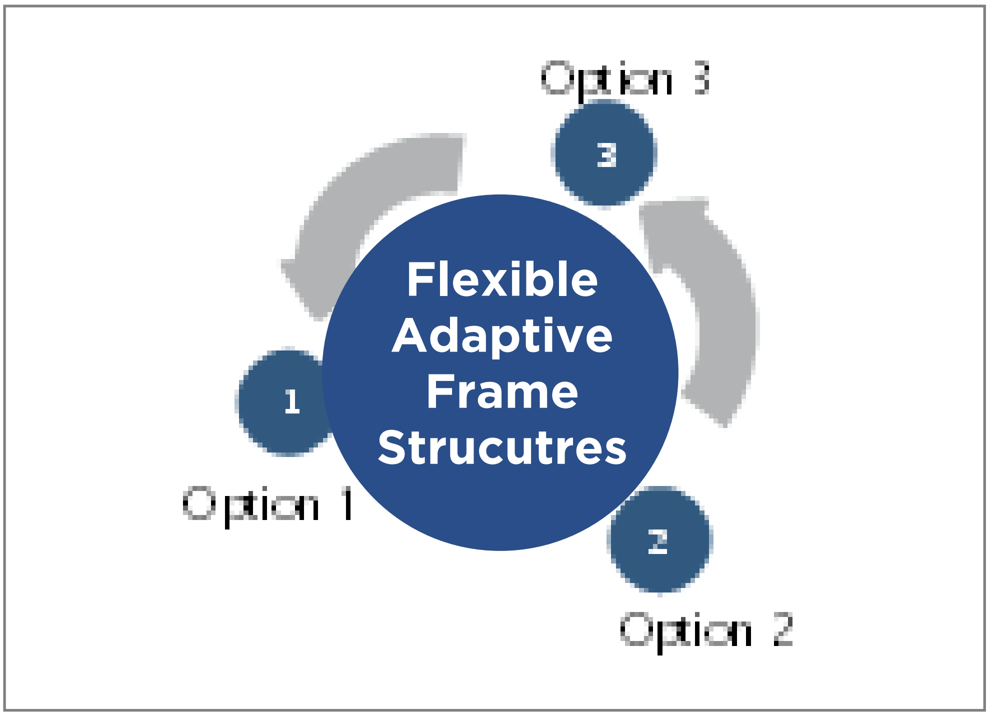


Figure 9 Flexible mmWave 5G frame structure adjustment solution

Moreover, the adaptive adjustment solution for flexible frame structures can bring advantages in three aspects, shown in Figure 9: 1. Perform predictive adjustment based on services over time in the area covered; 2. Adjust up and downlink frame structures in accordance with burstiness of 5G vertical applications; 3. Meet the 5G vertical application requirements while also effectively addressing public network scenarios with obvious uplink bandwidth burst demand, such as concerts, stadiums and gymnasiums. Therefore, flexible frame structure solutions can be used to cover changes in multiple scenarios and services, and more efficiently leverage the large-bandwidth advantage of mmWave 5G.

4

mmWave 5G usage scenarios and success stories

mmWave 5G usage scenarios and success stories

In terms of advantages and challenges of mmWave 5G, usage scenarios are mainly divided into three categories:

1 Hotspots such as indoor and outdoor transportation hubs and venues

Massive MIMO (large-scale array antenna) and beam forming, scanning and switching technologies are used to offset extra propagation loss in the mmWave frequency band, so mmWave 5G base stations can be used for outdoor cellular communication.[11] Typical outdoor hotspots include squares, stadiums and core main roads; and typical indoor hotspots include transportation hubs such as airports and train terminals, stadiums and shopping centres. The demand for data services during peak periods at these hotspots can be extremely high due to the number of users. In brand value zones, mmWave 5G can be deployed to offer ultra-high-quality services and thus enhance the brand value; in high-traffic zones, it can be deployed to offer precise coverage for traffic balancing and solve the issue of hotspot traffic.

For example, there are vast communications activities such as social media download, and video and picture upload on outdoor squares where a large number of people gather, so the demand for fast connections is extremely high. As Line-Of-Sign (LOS) propagation is fundamentally suitable for an open outdoor square where there are few high buildings, mmWave 5G base stations can be deployed for coverage around the square. In transport hubs, demand for short-time burst data services and system capacity is relatively high, due the volume of passengers and the short time they are typically on platforms. In these scenarios, mmWave 5G can offer efficient access to a multitude of users who move in and out of the area quickly by fully leveraging the advantages of high bandwidth, high instant data rates and high system capacity. Stadiums and gymnasiums have high population and centralised users. Large crowds gather at the centre of a stadium when a big concert is held or when a sports event is held. Due to the dense number of users, a relatively open environment and LOS propagation (few blockages and small signal attenuation) dominating the signal transmission path, it is conducive to avoiding the space propagation weakness of mmWave 5G and making the most of high system bandwidth, service rates and capacity to deliver high-quality 5G networking services to huge audiences.

[12] China Telecom 5G Technical White Paper, China Telecom, June 2018.

Case study 1: mmWave 5G coverage simulation at large subway station in China

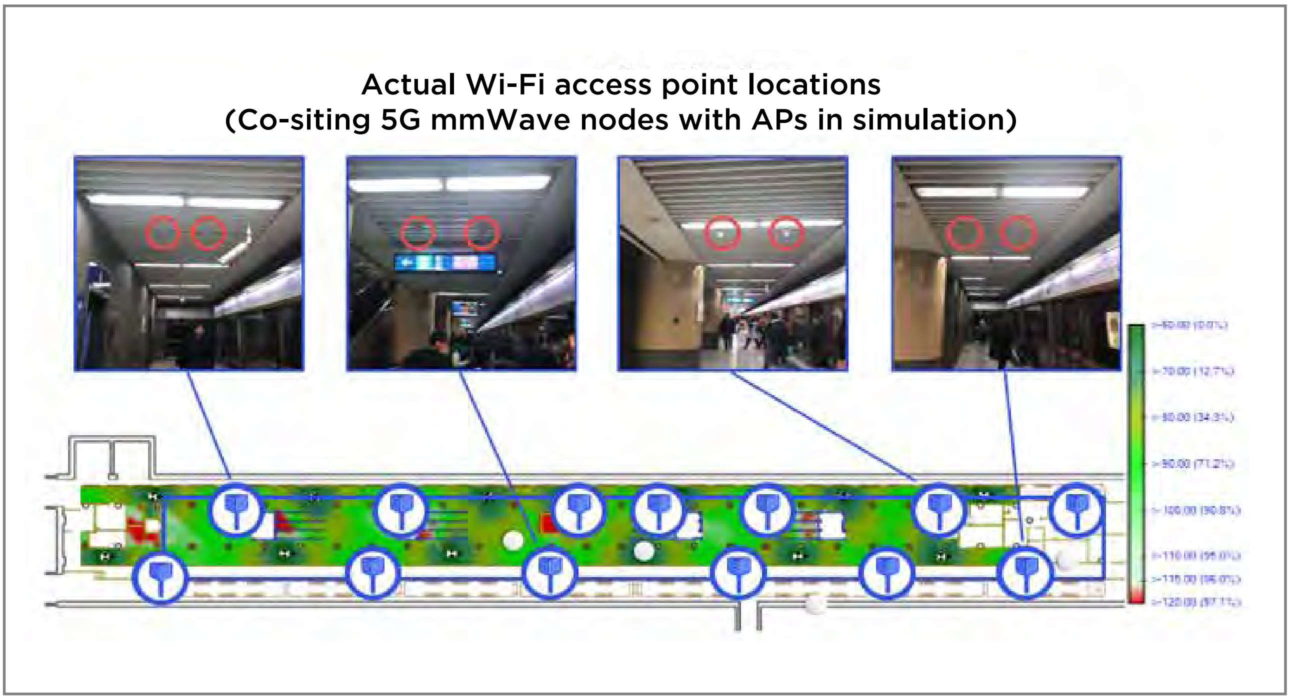


Figure 10 Signal distribution in mmWave 5G coverage simulation at the platform area of a typical subway station

In this case [13], the platform area at one subway station in a super tier-one Chinese city is chosen, with a total area of approximately 1,900 square metres. Assuming mmWave 5G base stations are located where 13 Wi-Fi system access points are actually deployed and a 128x2 antenna array is used, the simulated coverage of mmWave 5G signals in the 28GHz band is shown in Figure 10.

The simulation result shows the downlink coverage target in 5G network design (0.4 b/s per Hz) can be hit across 96 per cent of the platform area. Using 800MHz system bandwidth with 7:1 DL:UL TDD, the downlink median burst rate for a single user reaches 4.6Gb/s. This simulation result fully shows that for transportation hub scenarios such as underground rail stations, mmWave 5G deployment can offer excellent signal coverage quality and data services by reusing existing Wi-Fi or 4G indoor access point locations, without adding locations for new nodes.

[13] 5G NR mmWave outdoor and indoor deployment strategy, May 2019, https://www.qualcomm.com/media/documents/files/deploying-5g-nr-mmwave-for-indoor-outdoor.pdf

Case study 2: mmWave 5G network at Super Bowl stadium in the United States

mmWave 5G base stations are deployed on eight 28GHz bands with 400MHz system bandwidth at the Super Bowl stadium in the US in a way that the propagation paths of signals reaching audience seats are in LOS. There are also 100 4G LTE base stations deployed in the stadium. Figure 11 shows the measured coverage of 4G and 5G signals in each sector after the deployment is completed (signal coverage points in different sectors are indicated in different colours).

Actual measurement results of mmWave 5G signal strength (SS-RSRP) and comparison test results of 4G and mmWave 5G download rates are shown in Figure 12. It can be seen that only eight mmWave 5G base stations are needed to offer good coverage at the grandstand area in the Super Bowl stadium. The mmWave 5G download speed measured reaches **915Mb/s**, far higher than **98Mb/s** in 4G. (In view of the addition of 5G devices and the increase in data service demand in the future and in consideration of the issue of the simultaneous user numbers, additional mmWave 5G base stations may be needed.)

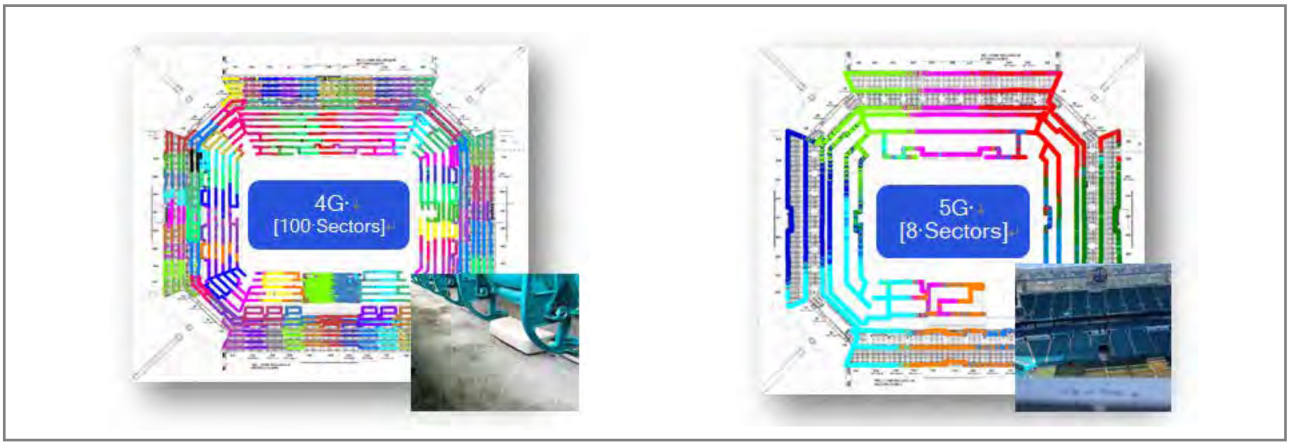


Figure 11 Signals at the grandstand after 4G and mmWave 5G are deployed

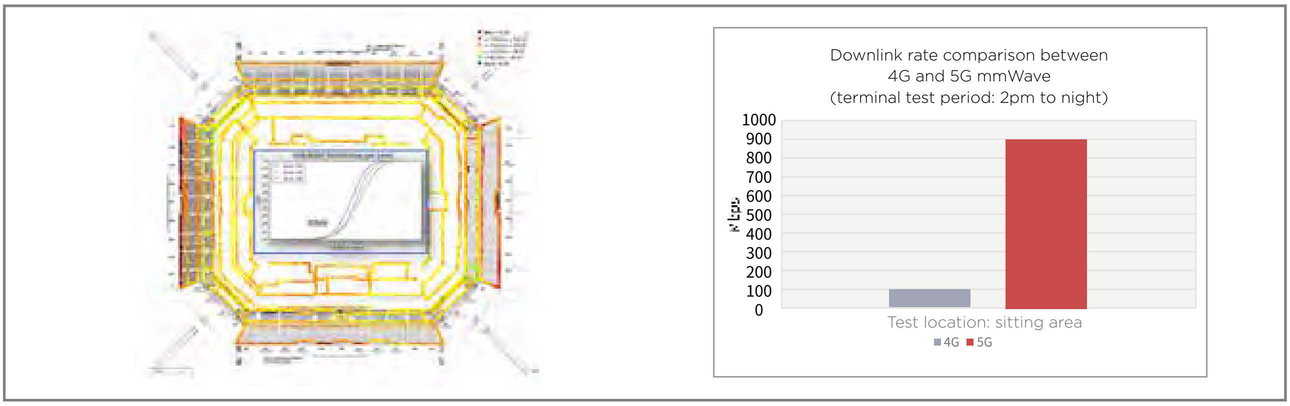


Figure 12 Actual measurement results and comparison test results of 4G and mmWave 5G download speeds after mmWave 5G is deployed

Case study 3: mmWave 5G Network at U.S. Bank Stadium in Minneapolis

The U.S. Bank Stadium in Minneapolis has a 67,000-seating capacity. To meet the high-speed wireless capacity demand during ultra-large events, one operator and Nokia deployed mmWave 5G base stations on the 28GHz band to all seating areas with mmWave signal coverage (>-103dB) in 16 sectors. Figure 13 shows actual coverage of mmWave 5G signals at U.S. Bank Stadium.

Data of speed measurements at multiple points in the stadium (Figure 14) show mmWave 5G can deliver experiences speeds of above 1000Mb/s and offer a far larger system capacity than LTE for use cases such as event livestreaming, high-speed internet access and VR/AR.

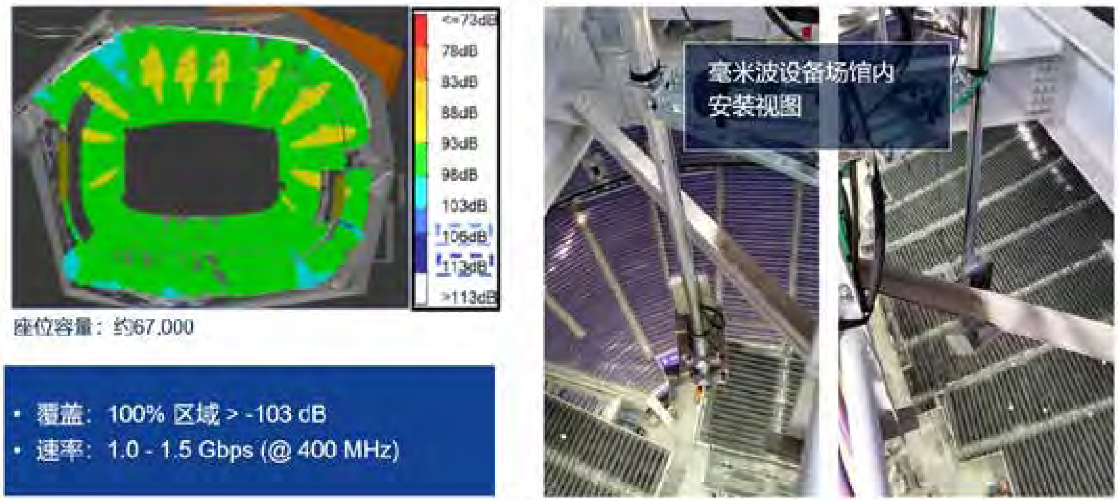


Figure 13 mmWave 5G deployment at U.S. Bank Stadium

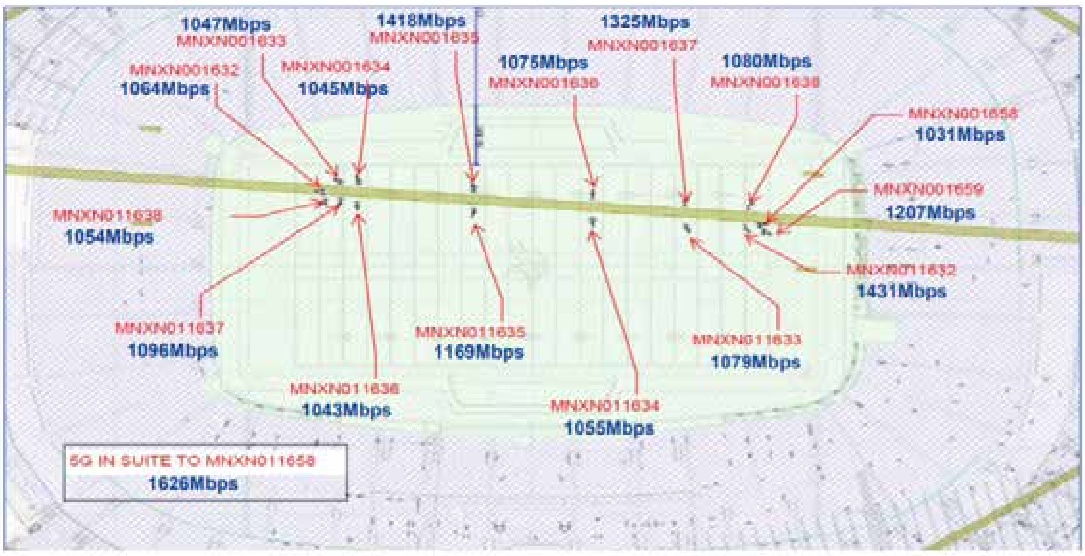


Figure 14 mmWave 5G signal speeds measured at multiple points in U.S. Bank Stadium

Case study 4: mmWave 5G network coverage in urban Chicago

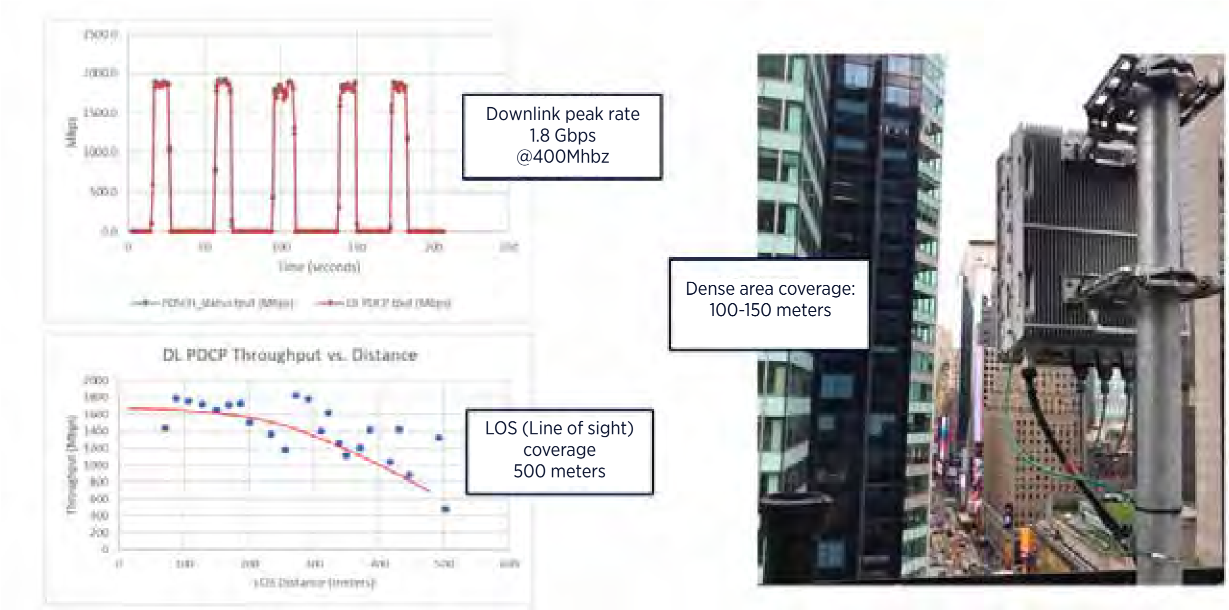


Figure 15 mmWave 5G network coverage in urban Chicago

An operator and Nokia commercially deployed 28GHz mmWave at service hotspots in urban Chicago, shown in Figure 15. mmWave can offer excellent coverage in streets, outdoor and open areas, which may reach approximately 500 metres in LOS scenarios of dense urban areas. For NLOS scenarios, the propagation loss measured >14dB at street corners beyond 10 metres and >21dB at street corners beyond 50 metres. Building materials like lime, brick walls and windows may result in propagation loss of 20dB to 50dB, so the scenario of indoor coverage with the outdoor mmWave band is basically not taken into consideration.

[China Unicom to Use mmWave 5G at 2022 Winter Olympic Games]

As the telecommunications service partner of the 2022 Winter Olympic Games, China Unicom has come up with a Smart Olympics solution covering three smart scenarios and serves six groups of people. China Unicom will build wireless venues with ultra-large bandwidth by applying multiple technical means such as mmWave 5G, innovate on many service applications like smart viewing and smart stadium for three major usage applications including watching, attending and hosting events, and offer exceptional viewing experiences and complete service guarantee for audiences, media broadcasters, event organisers and athletes/referees.

Various competitions at different stadiums have vast demand for UHD video streaming during the Beijing Winter Olympic Games, as well as the demand for uplink backhaul with support for large bandwidth. One business scenario is live video backhaul in which first time, lossless backhaul of HD video signals in multiple streams over the network to the cloud is required to meet the demand for access to event footage and images in a timely, effective and secure manner, so media video programmes can be captured, edited and broadcast all in the cloud. The previous event broadcast model is poised to be altered, which creates more possibilities for innovation at the Olympic Games. Another business scenario is to replace cable transmission like fibre with high-bandwidth, high-speed 5G networks for video backhaul at tracks and outdoor arenas where cables cannot be deployed and cameras cannot be installed. As a choice for ultimate 5G experiences, mmWave can be used for real-time video creation, holographic interviews, new visual services using AR and VR, multi-angle and 360-degree mobile video collection, video surveillance and security recognition services, while offering data transfer for field staff, audiences and media professionals.

2 Industry applications

Industry applications for mmWave 5G are mainly targeted at service access with large-bandwidth and low-latency, plug--and-play and mobility requirements. For example, as mobile video surveillance, industrial vision, automatic guided vehicle (AGV), drone control and image transmission, and production line control with collaborative robot services have extremely high requirements for bandwidth and latency, only mmWave can well meet those requirements and deliver intelligent connectivity. The technology can also be combined with private networks to enable operators to offer tailored services with flexible bandwidths, different from frequencies in the public network. It can also be combined with Multi-Access Edge Computing (MEC) and AI technologies to offer coverage areas with "high-capacity and high-speed plus local" intelligent solutions and customised campus private network services.

Remote-control systems 	Remote object monitoring and manipulation can be implemented to increase efficiency and improve safety in smart factories. Industrial processes that involve volatile chemicals or temperature-sensitive materials can be made safer by the remote operation of factory equipment. Efficiency can also be improved by allowing one remote operator to stop, slow, or accelerate any of the connected machines based on real-time feedback to a central control station.
Industrial robots 	Industrial robotics allow each piece of machinery within a smart factory to respond nearly instantly to requests and directions, enabling a rapid response in production to meet real-time shifts in demand. This also makes the customization of manufactured products possible at a scale previously unattainable. Communication between these connected devices could also increase efficiency.
Remote monitoring and quality control 	Real-time data collection and analysis, especially data-intensive processes such as high-speed imaging and virtual and augmented reality applications, can improve production and provide on-the-job training by enabling: • Employees to see real-time data on the factory floor and compare the images of defective machinery with those in working order; • New employees to be trained through virtual simulations; • Advisor/specialists to assist remotely when not on the factory floor or to put in place an automated process for workers to troubleshoot independently of the specialist.
Autonomous factory transport 	Similar to a broader transport setting, autonomous vehicles in a factory setting (e.g., carts, cranes, etc.) can communicate with a central control or monitoring center, as well as other machines, devices, objects, and broader infrastructure within the factory.

Figure 16 mmWave 5G application in industrial internet

[mmWave 5G application in industrial internet]

Industrial internet closely connects and integrates equipment, production lines and factories with the new-generation network platform; enables interconnection across equipment, systems, campuses and regions, and thus improves efficiency, driving the entire manufacturing and service system to become smart, and allowing all factors and resources in the industry's economy to be shared effectively. Building on the larger bandwidth of mmWave 5G spectrum, broad implementation of industrial automation will benefit from extra capacity. The technology will enable each autonomous robot to produce and receive a vast amount of data and support large-scale and dense deployment of these robots. However, industrial internet poses challenges for 5G development and application in many areas, such as application environment, latency and precise positioning, and puts forward more dimensions and combinations of requirements, simultaneously requiring high throughput, high connection density, high connection utilisation or high reliability. Typical industrial robot networks require 1millisecond latency and 99.9999 per cent connection availability; industrial handhelds and surveillance cameras demand support for higher definition and frame rates, and the device density required in actual production is very high. Therefore, mmWave 5G technology is indispensable in the industrial internet scenario.

First, the ultra-large bandwidth of mmWave 5G can meet the demand for transmitting a vast amount of data (such as production line video monitoring). Second, the ultra-low air interface latency of mmWave 5G can meet the demand for extremely-low latency in industrial-grade applications (such as mechanical arm control). Third, the highly-directional beam nature of mmWave 5G is suitable for high-density deployment, improving the spectrum spatial multiplexing ratio and meeting the demand for high connection density in industrial internet. Fourth, mmWave 5G can meet strict constraints for the deployment environment, enhance security in communications and reduce the possibility of eavesdropping, and strengthen data security. Fifth, the ultra-high time resolution and spatial resolution of mmWave 5G can enable high-precision (expected to reach centimetre-level) real-time positioning, and thus adapt to diverse requirements in industrial internet.

Typical mmWave 5G applications in industrial internet include remote control systems, industrial robots, remote monitoring and quality control, and autonomous factory transport, as shown in Figure 16.

Case study 5: Ericsson and Audi apply mmWave 5G in industrial internet

Figure 17 mmWave 5G supports AGV running

The manufacturing industry is evolving fast, and industry leaders such as Audi are searching for ways to stay ahead in their factories with increased flexibility in production automation and assembly processes, while also reducing personnel safety risks. 5G URLLC has the most powerful capabilities for ultra-high reliability and/or ultra-low latency communication at a variety of data rates. It can deliver data within specified latency bounds with required guarantee levels, even in heavily loaded networks, thus meeting critical IoT application demand. Typical use cases with demanding combinations of reliability, latency and data rates include AR/VR, autonomous vehicles, mobile robots, real-time human-machine collaboration, cloud robotics, haptic feedback, real-time fault prevention, and coordination and control of machines and processes.

Ericsson and Audi have been collaborating to expand the horizons of factories with 5G technologies. Following on from the pair's first announcement of a collaboration around automotive manufacturing in August 2018, and from previous developments with both Audi and SICK involving the introduction of safe AGV operation over a 5G network (shown in Figure 17), Ericsson and Audi have taken factory automation over a wireless network to the next level with 5G URLLC based on mmWave.

Figure 18 mmWave 5G URLLC capability demo

5G URLLC is used to run standardised protocols for automation communications – PROFINET and PROFIsafe – which demand very low latency and strict latency bounds with required guarantee levels to avoid triggering safety stops in the system. This is of significance for industrial automation. The door for safe human-robot collaboration has been opened, which could previously only be realised with wired networks. Cutting the cables is the real game changer in enabling Industry 4.0. It has proved the potential of 5G as a future-proof communication technology which can meet the high demands of automotive production.

Ericsson and Audi successfully tested 5G URLLC capabilities based on mmWave with real-life industrial automation applications at Ericsson's factory laboratory in Kista in January 2020. In the latest demo of 5G URLLC's power, they built a robot cell similar to those operating in Audi factories today, but over 5G connectivity. The arm of the robot is building part of a steering wheel (shown in Figure 18, in this case an airbag), while a laser curtain protects the open side of the robot cell. Thanks to the ultra-low latency and reliability of 5G URLLC, if a factory worker reaches into the cell the robot will instantly stop, making it safe for personnel to work with the machines. This instant response with guaranteed reliability is not possible through traditional Wi-Fi or previous-generation mobile networks.

Freeing automated machines from wires significantly increases the flexibility, mobility and efficiency of a production line, as robot cells using a wired network connection are restricted in terms of where they can be placed on the factory floor. With 5G URLLC based on mmWave, these machines require only a power connection, usually available anywhere in a factory, meaning the production set-up can easily be changed and units moved around on a day-to-day basis to maximise efficiency.

3 Fixed Wireless Access (FWA) in home and office environments

Thanks to relatively high frequency and short wavelength of mmWave 5G, more antenna arrays can be placed in the same footprint and the beam energy is more focused. The system can offer peak data rates of 7Gb/s (64QAM) or 10Gb/s (256QAM) on the band with 800MHz bandwidth, so mmWave 5G can be used as a radio backhaul link to solve issues when fibre cannot be deployed or the price of fibre is too high. It can also act as a supplement to the conventional last mile access, be used for backhaul at LTE/5G low- and medium-frequency base stations, offer broadband services for homes and office buildings with compatible customer-premises equipment (CPE), and provide good support for HD video and AR/VR services.

Case study 6: Home FWA Simulation in dense urban area, Latin America

A mmWave 5G CPE deployment coverage simulation was conducted at an area of 2 square kilometres in a dense urban area of Latin America. There are a total of 2,561 buildings in the simulation area, at an average height of 26 metres. Assuming CPE is installed on rooftops of residential buildings, the distribution of buildings and density of CPE deployed in the entire simulation area are shown in Figure 19.

Figure 19 Buildings and CPE deployment in the simulation area

Figure 20 Geographic distribution of CPE data download rates (simulation)

The detailed scheme used in the simulation is based on basic parameters including the number of families per floor in the building and typical home network service model. This is combined with other parameters including 5G service market penetration and service usage, and a Monte Carlo service simulation model used to simulate mmWave 5G data service performance on 800MHz of the 28GHz band at a 3:1 DL:UL TDD ratio. A total of 57 mmWave 5G sectors are placed in the simulation area (co-sited and co-located with existing LTE base stations in the live network), and on average 27 CPE have valid service connections per sector (related to the activation model used for simulation). The simulation result shows that mmWave 5G effectively covers 85 per cent of the total area. The simulation result of more than 15,000 families shows the average median data download rate of 159Mb/s and the highest value of over 1.95Gb/s. The geographical details are shown in Figure 20.

Case study 7: FWA trials in large office environments

(1) Simulation scenario: An area of approximately 2,500 square metres in one company's office building is chosen in this case [7], and 14 out of 20 Wi-Fi access points actually deployed are selected as locations for mmWave 5G access points. Assuming every access point is equipped with a 128x2 antenna array, the simulated mmWave 5G signal coverage is shown in Figure 21.

Using 800MHz downlink bandwidth and 100MHz up with 7:1 DL:UL TDD, the simulation result shows the statistical median data download rate in mmWave 5G coverage can reach 4.9Gb/s on the condition 98 per cent of the area is covered.

[13] 5G NR mmWave outdoor and indoor deployment strategy, May 2019, https://www.qualcomm.com/media/documents/files/deploying-5g-nr-mmwave-for-indoor-outdoor.pdf

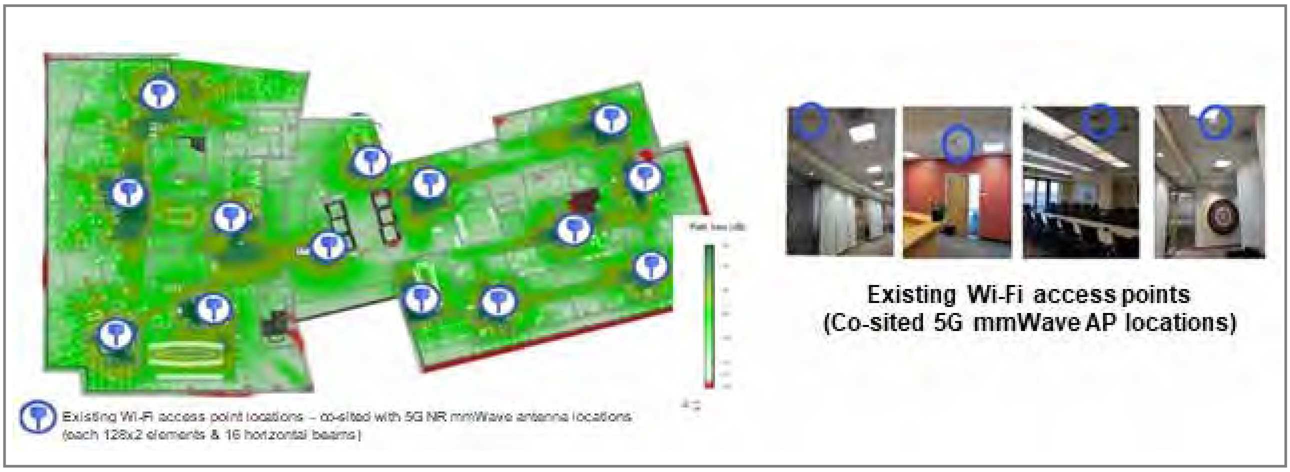


Figure 21 mmWave 5G access point locations and signal coverage strength simulation

(2) Measurement case: One mmWave single-sector base station is deployed on the 28GHz band with 400MHz of bandwidth in an office building, and the test is conducted at fixed points within the LOS (near and middle points) and NLOS (middle and middle/far points) ranges using commercial devices, which is compared with 4G data download rates. The case scenario is shown in Figure 22.

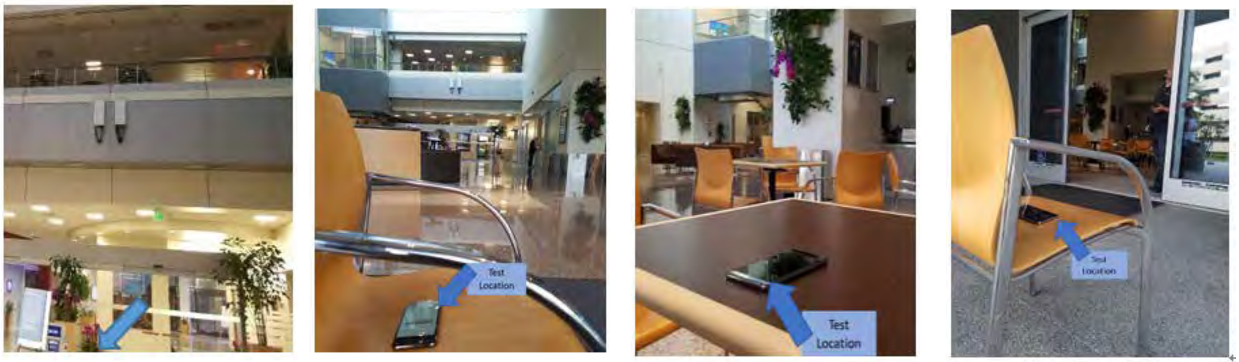
Figure 22 Indoor test scenario and path loss distribution

The test result is shown in Table 5. The difference of rates at test points is not significant. Even at the NLOS middle/far point location with relatively bad conditions for radio propagation, the mmWave 5G device can also get Gb/s download rates. This test result provides a compelling proof of the good coverage provided by mmWave 5G in the indoor office scenario.

Table 5 mmWave 5G indoor fixed-point test results

Test point	Test location	4G DL rate	mmWave 5G DL rate
1	LOS near	26 Mbps	1.55 Gbps
2	LOS middle	25 Mbps	1.53 Gbps
3	NLOS middle	25 Mbps	1.50 Gbps
4	NLOS mid/far	19 Mbps	1.09 Gbps

The locations of indoor fixed test points (TP) are shown in Figure 23.



Test Point 1
LOS near

Test Point 2
LOS middle

Test Point 3
NLOS middle

Test Point 4
NLOS far

Figure 23 Selected locations for fixed-point test

Case Study 8: FWA testing in rural locations

Qualcomm Technologies, along with Ericsson and US Cellular completed an extended-range 5G NR data call over mmWave in the United States. At its time this data call marked the farthest-ever connection of over 5 kilometres with speeds >100Mb/s on a commercial network.

These distances redefine perceptions that mmWave is limited to high-density deployments and demonstrates it can help close the connectivity divide and expand broadband services throughout rural, suburban, and urban communities.

This achievement is a key industry milestone which will help provide operators a cost-effective way to deliver fibre-like internet speeds wirelessly over mmWave to institutions including schools, hospitals and town halls, and for addressing some of the last mile challenges, particularly in rural areas.

For example, small towns can benefit from connected community spaces, such as FWA-enabled libraries, gyms, or recreation centres. With 5G, unique performances and immersive learning experiences could be offered virtually to underserved communities that historically may not have had access to high-speed networks.

Another example is small local businesses in remote and rural areas. 5G FWA will make it easier for these companies to expand their reach online. Whether managing their brand on social media, processing payments, product fulfilment, leveraging data analytics to grow site traffic, or managing third-party vendors, having stable high-speed internet is key to the growth of a home-based business or local store. With FWA, people in out-of-the-way places can capitalise on their unique offerings, feeding young consumers' appetite for rare, local, and authentic goods.

Additionally, in rural communities, 5G FWA can transform livestock farming, which requires constant monitoring of huge amounts of data spanning feed routines to breeding status. Bringing fibre to rural areas is cost-prohibitive for small-and-medium family farms, but with a central base station, CPE placed on barns and other structures would enable livestock to be monitored remotely, with data collected and updated through cameras and sensors. The future of small-scale, high-tech farming is all about live data, and 5G can make it more accessible.

Figure 24 The 5G fixed wireless access setup in Wisconsin

Conclusion

mmWave 5G has six technical advantages: rich frequency resources and huge bandwidth; easy combination with beamforming technology; low delay; intensive deployment support; high precision positioning; and high integration. It can release the full potential of 5G and become one of the core technologies for key deployment. It is the realisation of all the initial commitments and the core enabling technologies to achieve the initial mission. Having mmWave capability is a completed 5G, and the deployment of mmWave 5G is an important step to realise the whole mission of 5G."

mmWave 5G technology solutions supporting mobile communication are now mature. At present, the mmWave 5G industry chain and standards organisation has put forward many innovative solutions for the initial technical challenges of mmWave 5G, such as advanced beamforming and flexible beam management technology; IAB; fast and flexible cell handover management; fast recovery of beam failure; cross band and cross standard carrier wave aggregation and dual connection; and hybrid networking of macro and micro stations, among others. This helps to deliver optimised coverage and migration for mmWave, though in practice problems relating to large antenna arrays, management, installation in devices and OTA testing are yet to be overcome.

The technology is suitable for major application scenarios such as: indoor and outdoor transportation hubs and venues; industrial internet and other industrial applications; and wireless broadband access for homes and offices. It can meet the requirements of relevant businesses for large bandwidth, low latency, precise location and flexible deployment, and is proven by a number of successful application cases. mmWave 5G spectrum can provide manufacturers with necessary network conditions by providing high-capacity, low latency wireless connection deliver Industry 4.0 services including remote control systems; industrial robots; remote monitoring and quality control; and independent factory transportation, in turn delivering the full potential of interconnection equipment and automatic processes. At the 2022 Beijing Winter Olympic Games, mmWave 5G is expected to shine, providing spectators, broadcasters, event organisers and participants with high-quality viewing experiences and complete service guarantees.

At present, the mmWave 5G industry chain has the commercial ability, and the increasingly developed equipment ecosystem to support mobile operators' businesses. The successful commercial application of mmWave 5G needs further policy support and coordinated industrial development. In particular, it is necessary to consider the development of mobile communication industry and allocate mmWave 5G spectrum in time. This will determine the timing of application deployment, and then affect the rhythm and scale of the technology's rollout. mmWave 5G and sub-6 GHz spectrum are constructed by operators in an unified way, which can improve the utilisation efficiency of spectrum resources, ensure the integrity of the 5G industry, and make 5G bigger and stronger. At the same time, because operators have many years of experience and advantages in spectrum planning, deployment, operation and application, they can achieve effective coordination, reduce the possibility of spectrum interference and ensure spectrum security. In addition, the industry needs to vigorously promote formation of key technology research, standards, the commercialisation process, business demonstrations and industrial chain cooperation. It must also drive more supply chain enterprises to participate in innovation and R&D to deliver competitive products. Other areas to consider include fuelling new application business development with high bandwidth; actively exploring the application of mmWave 5G in vertical industries and typical scenarios, and ensure the technology is embedded as a basic requirement in devices. Operators play an important role in the mmWave 5G industry chain and the broader mobile industry is waiting for them to issue a clear signal around the technology. Operators can play an important role in issuing technical guidelines, actively conducting pilots, guiding formation of standards, steering equipment R&D, and promoting further maturity of the overall value chain.

Currently, development of mmWave 5G presents opportunities and challenges. In terms of opportunities, the mmWave 5G industry will develop rapidly with new infrastructure construction. Challenges remain around perfecting the key technologies, core devices and chips. International cooperation will help companies learn from one another, and new use cases will promote the overall development of the technology, in turn helping it to deliver huge social and economic benefits.

The future direction of mmWave 5G technology and product evolution mostly centres on the following:

- **Drive the industrialisation of mmWave 5G high frequency device development.** The capability index of high-frequency devices determines the equipment capacity and power consumption and energy efficiency of the overall system. The industrialisation maturity of high-frequency devices determines the equipment cost of the system, which has an important impact on future deployment schemes and landing application. It is necessary to gather the strength of the industry, universities and other researchers to jointly drive the industrial development of high-frequency analogue devices and create mature high-frequency band RF devices and chip industry chain.
- **Complete test programmes.** At the same time, the feasibility, reliability, accuracy, cost and efficiency of index test scheme are facing new problems and challenges. The cost of test sites, efficiency and accuracy are the problems which an OTA test scheme needs to consider and solve. At present, the relevant institutions and manufacturers in the industry are exploring and researching the technology direction. It needs the joint efforts of the whole industry from the aspects of test environment, instrument device and algorithm design to overcome the obstacles and promote the breakthrough and progress of OTA radio frequency index test technology for mmWave 5G base stations.
- **Support higher frequency bands.** mmWave high frequency band has rich spectrum resources, which is an inevitable course to meet the needs of future high-capacity communication. The upper limit of FR2 defined in 3GPP NR Rel-15 is 52.6GHz. At present, 3GPP NR Rel-17 has conducted communication research on the 52.6GHz to 71GHz mmWave band. Priority will be given to the development of 5G NR standard for the newly expanded 60GHz band, which was recently designated as an international mobile communication (IMT) band

in some countries and regions by the World Radiocommunication Conference. In 3GPP NR Rel-18 and later there is support for the mmWave band near 100GHz, and then furthermore up to 114.25GHz. These 5G mmWave bands are more abundant than the existing FR2 mmWave bands, providing higher peak throughput. It is predicted the future development direction of mmWave 5G will be extended to more than 100GHz, possibly even to 300GHz. Enabling this communication in higher frequency bands is expected to bring changes in many aspects including mobile data streaming; short distance machine communication; broadband distribution network; IAB networking; industrial internet; AR and VR; intelligent transportation; wireless connection of Data Centre, and more. mmWave 5G communication in higher frequency band will also bring complex technical problems, such as stronger phase noise; more serious loss during the communication; higher air absorption; lower power amplifier efficiency, et cetera, which will be the challenges of mmWave 5G technology in the future.

With the acceleration of 5G construction and increasing application terminals, mmWave 5G will also usher in broad developments. In a word, 5G's future prospect is exciting. More 5G innovations are in the pipeline and mmWave 5G networks will enable sustained technological breakthroughs in the next decade and beyond.

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