5G Services Innovation

November 2019

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1. INTRODUCTION

Over the last several years, 5G has emerged as the next major phase of mobile telecommunications standards however, it is promised to be so much more. As of November 2019, 46 5G networks[1] have been launched, and 5G subscribers are predicted to reach 1.9 billion as early as 2024 as shown in Figure 1.1. It is widely anticipated that 5G mobile technology will, like electricity or the automobile, benefit entire economies and benefit entire societies.

The global 5G standard will advance mobile communications largely from a set of technologies connecting people-to-people and people-to-information to a unified connectivity fabric connecting people to everything. The IHS 5G Economic Impact whitepaper[2] evaluates the potential of 21 unique 5G use cases that will affect productivity and enhance economic activity across a broad range of industry sectors and predicts that in 2035, when 5G's full economic benefit should be realized across the globe, a broad range of industries – from retail to education, transportation to entertainment, and everything in between – could produce up to $13.2 trillion worth of goods and services enabled by 5G mobile technology. The IHS whitepaper further predicts that the 5G mobile value chain could generate up to $3.6 trillion in revenue in 2035 and support up to 22.3 million jobs.

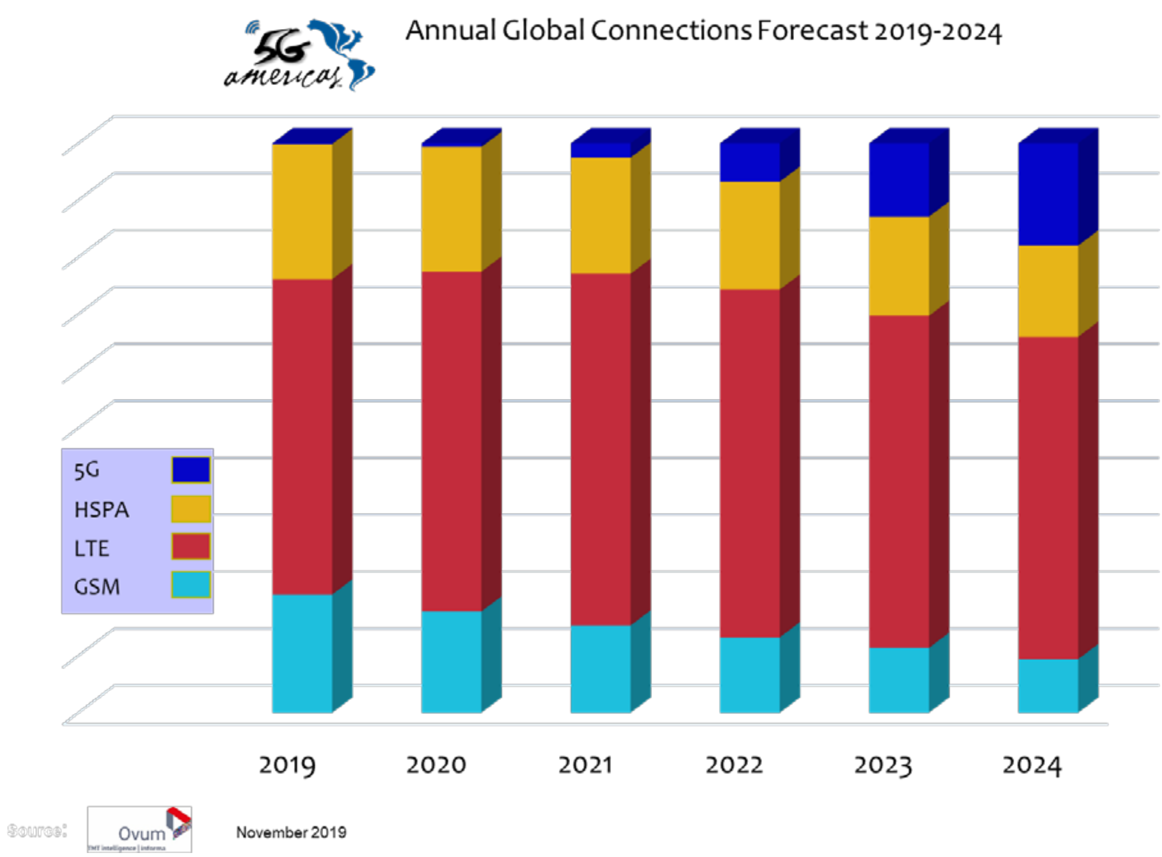

Figure 1.1. 5G Subscriber Growth Forecast.[3]

[1] Source: TeleGeography, https://www.5gamericas.org/resources/deployments/. November 2019.
[2] *The 5G Economy: How 5G Technology will Contribute to the Global Economy,* IHS Markit, November 2019.
[3] Source: Ovum, WCIS. Forecast, November 2019.

Figure 1.2. 5G Spectrum Options.[4]

5G is designed for a wide array of available spectrum bands and regulatory paradigms. Previous generations of wireless networks (for example, 2G, 3G and 4G) have operated mostly in licensed spectrum bands below 3 GHz. As shown in Figure 1.2, 5G introduces two major changes in spectrum use. 5G has been designed from the beginning to support not only licensed but also shared and unlicensed spectrum. Licensed spectrum will continue to be the heart of ubiquitous wireless connectivity and the mainstay of moving data from point A to point B. The use of licensed spectrum is exclusive, with more than 40 frequency bands reserved globally for LTE and many more for 5G. Beyond that, the flexible 5G framework is designed to also support shared and unlicensed spectrum, an important step in widening the path over which data can travel.

In terms of bands, as shown in Figure 1.3, 5G is designed to operate in bands below 1 GHz and up to 100 GHz and beyond. Below 1 GHz, the bands offer the wide area coverage needed for categories of 5G services like Massive IoT (MIoT). The bands between 1 and 6 GHz offer greater bandwidth for the categories of enhanced Mobile Broadband (eMBB) and mission critical control, where high reliability and low latency are important. A big change in 5G spectrum was the introduction of millimeter wave (mmWave) spectrum. An important objective of 5G is to lower the cost per bit of data compared to 4G LTE. One way to do that is to use newly available spectrum, including the mmWave range, in higher bands. mmWave will open vast amounts of bandwidth that were previously not usable for wide area mobile communications.

[4] Spectrum in 5G: The Innovation Boost Starts Here, Qualcomm Developer Network. 6 August 2019.

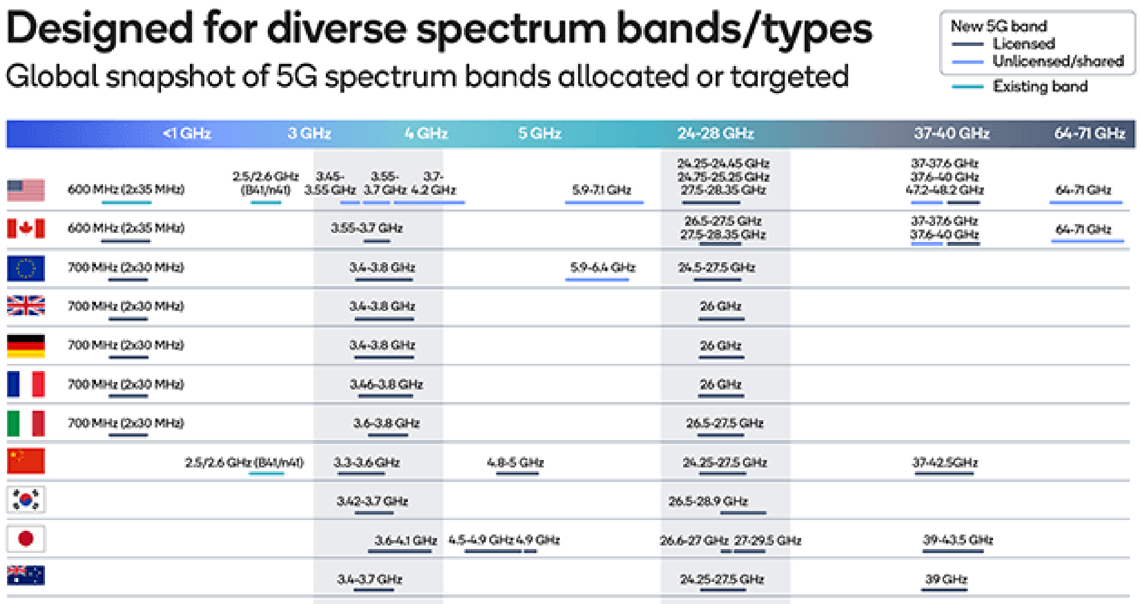

Figure 1.3. 5G Spectrum Diversity.[5]

In terms of deployment scenarios, 5G can scale from traditional wide area, to enterprise, and indoor/outdoor hotspot deployments. For example, most offices use Wi-Fi to connect computers, servers, printers and related devices, and co-siting a 5G small cell alongside an existing Wi-Fi access point allows both devices to share power and wired backhaul. 5G also enables dense venues such as convention centers, concert halls and stadiums, where huge numbers of mobile device users can exhaust available network bandwidth. 5G can also address deployment in transportation hubs like subway stops, airport terminals and train stations, co-siting 5G with Wi-Fi offers high coverage and connectivity with high speed.

1.1 5G SERVICE REQUIREMENTS

As a technology, 5G is designed for adaptability across a wide variety of requirements. 5G will usher in the next era of enhanced Mobile Broadband (eMBB) and immersive experiences with not only faster data rates, but also more uniform high data rates everywhere at lower latency. The enhanced Mobile Broadband category is the focus of 5G deployments in the first phase of 3GPP 5G specifications (Release-15) rolling out as of August 2019. As part of the second phase in Release-16 (Rel-16), due for completion in 2020, 5G will enable new mission critical services such as remote control of critical infrastructure, Industrial IoT (IIoT), vehicles, and medical procedures via a set of techniques known as Ultra-Reliable Low Latency Communication (URLLC) that enables ultra-reliable/available, low latency links. 5G will also be able to connect a massive number of things through the ability to scale down data rates, power and mobility to provide extremely lean/low-cost solutions.

An emerging trend, accompanying the evolution towards 5G, is the Wireless Edge to address the challenge posed by the required scaling in computation, as well as to address privacy and security concerns. In this paradigm, intelligence is not just associated with a central cloud, it is distributed to the devices that form

[5] *Spectrum in 5G: The Innovation Boost Starts Here*, Qualcomm Developer Network. 6 August 2019.

the Wireless Edge. The Wireless Edge expands the traditional concept of “edge computing” into three key components: cloud, edge cloud, and edge devices. These components work together to distribute responsibilities while pushing intelligence near to the edge or directly onto edge devices capable of powerful on-device processing as shown in Figure 1.4.

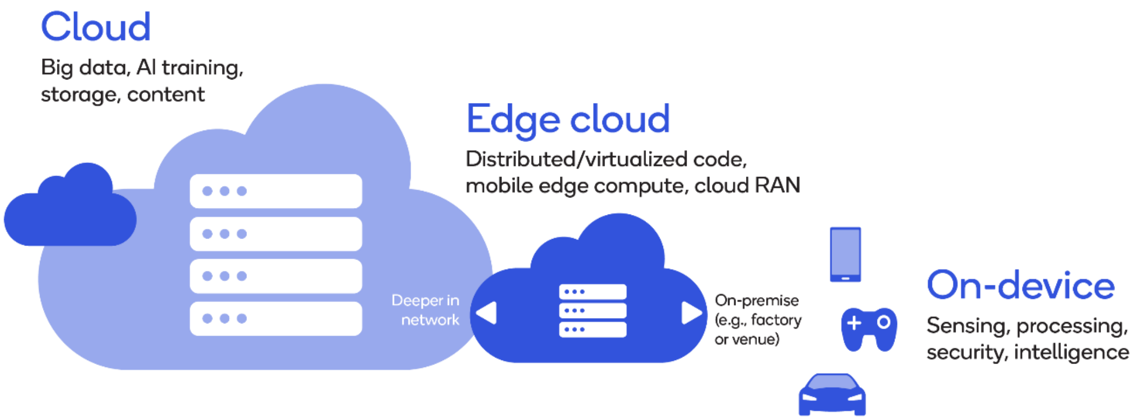

Figure 1.4. The Wireless Edge Components.[6]

1.1.1 3GPP SERVICE REQUIREMENTS

This section provides a brief overview of the work in 3GPP SA1[7] working group, which is responsible for defining service requirements. The description covers the last few 3GPP releases and provides highlights on the ongoing Release-17 work.

About February 2015, while 3GPP was working on Release-14 standards, the first 3GPP study on 5G Service Requirements started in SA1: *Feasibility Study on New Services and Markets Technology Enablers* (also indicated by the acronym “SMARTER”). As an outcome of the SA1 study, general use cases, aspects and requirements were captured in TR 22.891. Beyond that, several 5G use cases were further developed in four secondary studies: *Study on Massive Internet of Things* (TR 22.861), *Study on Critical Communications* (TR 22.862), *Study on Enhanced Mobile Broadband* (TR 22.863), and *Study on Network Operation* (TR 22.864). This became the basis for the standard 5G service requirements ultimately defined in Rel-15 (TS 22.261). In addition, SA1 defined other enhanced 5G requirements for “Verticals”, some examples of which are: Enhanced support of Vehicle-to-Everything (V2X), Mission Critical over 5G, Mobile Communications for Railways, and Remote User Equipment (UD) access via relay UE. Further Rel-15 requirements, covering specific areas, include Unlicensed Spectrum Offloading, Enhanced Calling Name Service, Enhancement of Background Data Transfer, and Home Public Land Mobile Network (HPLMN) Optimization in Network Selection.

As part of Release-16, SA1 continued expanding 5G requirements, starting with a continuation of the “SMARTER” work (phase 2), plus a large set of new use cases and enhanced requirements for “verticals”, including: 5G for Control Automation (for example, Industrial), Unmanned Aerial Systems (Drones), Integration of Satellite Access in 5G, 5G Positioning Services and Requirements, Maritime Communication Services over 5G, Access to Local Operator Services, Enhancement for Streaming/TV, Advanced Support

[6] *Taking Your Development to the Wireless Edge*, Qualcomm Developer Network. 25 September 2019.
[7] *3GPP SA1*, 3GPP. August 2019.

for V2X Services, Local Area Network (LAN)/Ethernet support in 5G, Enhancements of Public Warning System, Mobile Communications for Railways (Phase 2), Enhancement of Network Slicing, 5G Voice Service Continuity, Enhanced Quality of Service (QoS) Monitoring, User Identities and Authentication, and Enhancements for Real Time Services.

As of August 2019, Release-17 work on service requirements is ongoing and due by end of 2019. SA1 has continued to enhance 5G use cases, requirements and expand verticals support. A summary of Rel-17 SA1 work is captured in Table 1.1.

Table 1.1. Ongoing Rel-17 SA1 Projects - New 5G Use Cases, Requirements and Verticals.

New/Enhanced 5G & Verticals Requirements	Target Use Cases / Verticals (examples)	Reference Specifications	
		TR	***Target TS***
Network Controlled Interactive Services (NCIS)	XR, Cloud/Interactive Gaming	22.842	**22.261**
Audio-Visual Service Production (AVPROD)	Professional Audio/Video delivery	22.827	**TS 22.263, 22.261**
Requirements for Critical Medical Applications (CMED)	eHealth, Medical data delivery	22.826	**22.263, 22.261, 22.104**
Enhancements. for Control Applications in Vertical domains (eCAV)	Industrial automation/control	22.832	**22.261, 22.104**
5G Enhancement for UAVs (EAV)	Drones identification/control	22.829	**22.125, 22.261**
Enhanced Relays for Energy efficiency and Ext. Coverage (REFEC)	UE-to-NW relay (for example for IoTs in no/remote coverage)	22.866	**22.261**
Railways Mobile Communication – Gap Analysis	**Railway communications**	**22.889**	**22.279-282, 289**

Note: other ongoing SA1 work on R-17 5G Service Requirements include Support for Multi-USIM Devices (MUSIM); Asset Tracking (ATRAC), Multimedia Priority Service – Phase 2 (MPS2); Minimize service Interruption in emergency events (MINT).

1.2 PAPER ORGANIZATION

This paper will discuss a few important examples of the broad range of use cases and services enabled by 5G. The end-to-end architectural aspects of each use is discussed and the importance of 5G as a key component in that end-to-end architecture is explained. The requirements and Key Performance indicators (KPIs) expected from the 5G component on each architecture are presented. The activities around the deployment of each use case, and key issues that need to be addressed are explained for each use case.

The outline of the paper is as follows: a broad range of services related to healthcare and the corresponding 5G aspects are discussed in section 3. Section 4 describes the Fixed Wireless Access (FWA) use case, which is one of the very first use cases to take advantage of the enhanced Mobile Broadband (eMBB) capabilities of 5G. Section 5 presents the use cases related to ground vehicles, drones and robots that leverage the URLLC capabilities of 5G. Section 6 will discuss the emergency, disasters, and public safety related use cases enabled by 5G. Section 7 and Section 8 will discuss Extended Reality (XR) and Cloud Gaming respectively, which are use cases enabled by the edge computing paradigm discussed earlier. Section 9 will present the smart grid use case. Conclusions and final thoughts are provided in section 10.

2. USE CASE: HEALTHCARE

Healthcare use cases cover a broad range of scenarios, from personal wearables for health monitoring, through diagnosis and treatment in a medical setting, to high speed mobility communication between an ambulance and hospital. Personal wearables mainly fall into the IoT category of small data with infrequent transmission. However, as technology improves, new devices are being created that can take a more pro-active role in healthcare such as providing connectivity to a medical team for remote diagnosis and treatment. These new devices herald the coming of 5G healthcare.

2.1 INTRODUCTION TO 5G IN HEALTHCARE

Whether the diagnosis and treatment devices are remote or used in a clinical setting, they will rely on the Ultra-Reliable Low Latency Communications (URLLC) and time synchronization capabilities of 5G to support accurate and timely information sharing and control of treatment devices. The tasks to be supported by these devices may range from sharing video for diagnostic purposes, to controlling an insulin pump or performing a robotic surgery. Communications between an ambulance and hospital add the need for support of rapid mobility for similar diagnosis and treatment tasks.

2.2 ARCHITECTURE

A communications system architecture to support healthcare communications requirements needs to include multiple considerations to cover all healthcare related scenarios:

- Mobility: stationary, nomadic, high speed
- Data Patterns: infrequent small data, high quality streaming video, ultra-reliable low latency
- Coverage: in network, out of network

Figure 2.1 uses illustrations from TR 22.826[8] to show how 5G communication supports overall healthcare communications needs.

[8] *Study on communication services for critical medical applications,* Rel-17, 3GPP TR 22.826.

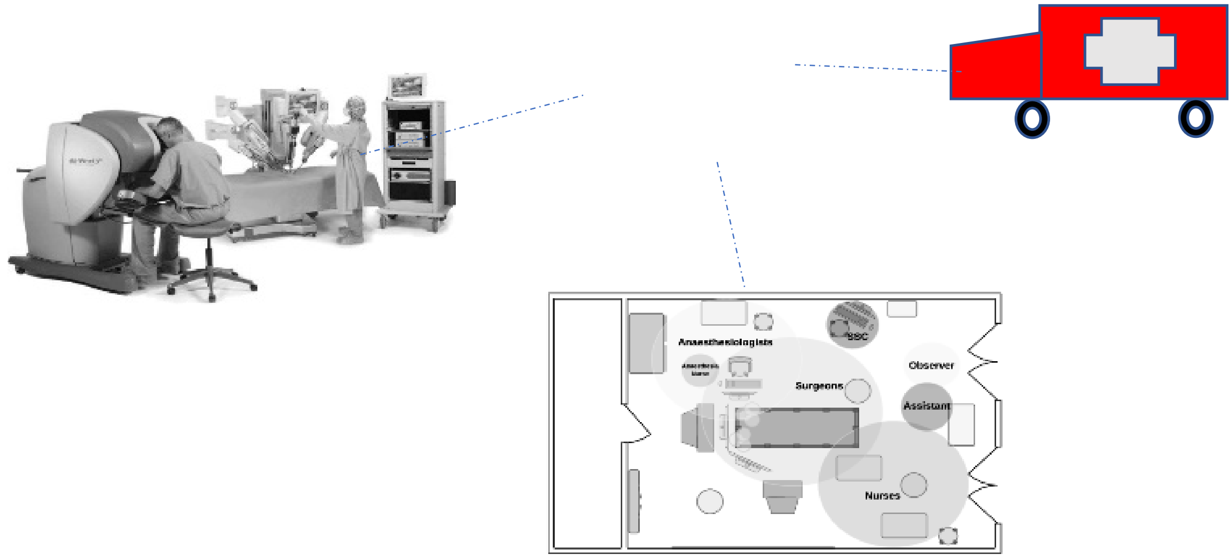

Figure 2.1. 5G Architecture Supports Healthcare.

2.2.1 5G QOS

The ability to meet specific Quality of Service (QoS) is essential for healthcare applications. Critical medicine is a specific topic being addressed in the SA1 requirements for Rel-17. As the downstream groups begin working on Rel-17 later this year, they will need to consider potential enhancements to meet the QoS requirements for the full suite of healthcare applications. Table 3.1 illustrates some of the key QoS considerations for a robotic telesurgery. In this scenario, a remote physician guides a robotic arm through a surgical procedure on a patient. During the procedure, real-time streaming video allows the physician to see exactly what is happening in the operating room. Haptic feedback from the robot allows the physician to determine the amount of pressure applied, the length of an incision, and other critical metrics. Data is sent from various monitors to allow the physician to determine the patient's condition throughout the procedure. Voice communications allow the physician to communicate with nurses and other personnel in the operating room. In this scenario, mobility is not a priority as the communications devices remain fixed in the operating room and physician's office throughout the procedure. The essential KPIs are the reliability of the system, that the communications paths remain stable and no data is lost in transmission, and low latency, that data is delivered with no perceptible delay -- giving the physician complete and timely control of the robotic actions. While not all healthcare applications require the same KPIs to be met, Table 2.1 provides a reasonable approximation of the types of QoS KPIs for healthcare applications.

Table 2.1. Typical Robotic System Setup for Teleoperations.[9]

	Data Types	Latency	Jitter	Packet Loss Rate	Data Ref
	2D Camera Flow	<150 ms	3-30 ms	$<10^{-3}$	<10 Mbps
Real-Time Multimedia Stream	3D Camera Flow	<150 ms	3-30 ms	$<10^{-3}$	137 Mbps - 1.6 Gbps [for good imaging this could be up to 4 Gbps]
	Audio Flow	<150 ms	<30 ms	$<10^{-2}$	22-200 kbps
	Temp	<250ms		$<10^{-3}$	<10 kbps
	Blood Pressure	<250 ms		$<10^{-3}$	<10 kbps
Physical Vital Sign	Heart Rate	<250 ms			<10 kps
	Respiration Rate	<250 ms			<10 kps
	ECG	<250 ms			72 kbps
	EEG	<250 ms			86.4 kps
	EMG	<250 ms			1.536 Mbs
Haptic Feedback	Force (considering human reaction)	3-10 ms (20 ms)	<2 ms	$<10^{-4}$	128-400 kps
	Vibration	<5.5 ms	<2 ms	$<10^{-4}$	128-400 kps

Other healthcare scenarios may require similar KPIs, with the addition of high-speed mobility. An example of such a case would be treatment of a patient in a medivac helicopter which is monitored by the physician at the destination. Reliable, real-time information provides the physician the right information at the right time to make the best decisions for a good patient outcome.

On the other end of the spectrum, a patient wearing a heart rate or glucose monitor may only need support for infrequent data transmission to be alerted if the heart rate or glucose levels rise or drop beyond a threshold. KPIs for a variety of scenarios are included in TR 22.826.

2.2.2 CELLULAR LAYOUT SCENARIO

Based on the varied uses and types of healthcare applications, it is clear that all cellular layouts must be considered. Ubiquitous coverage is needed to meet the varying use case scenarios. Outdoor coverage for both urban and rural areas is essential for the wearable scenarios, for ambulance scenarios, and even for tele-medicine in remote areas where there is a shortage of medical personnel. Indoor coverage of these

[9] *Study on Communication Services for Critical Medical Applications,* 3GPP TR 22.826. June 2019.

same scenarios is needed in homes and businesses as well as traditional medical settings such as clinics and hospitals.

2.2.3 MOBILITY SCENARIO

Given the wide range of healthcare applications and devices, the mobility needs are diverse. In a hospital or clinical setting, the devices may be completely stationary. Video and vital sign monitors may be permanently affixed in an operating or examining room. Other devices in such a setting may be nomadic. For example, vital sign monitors may be moveable from one room or one patient to another, with activity enabled only when connected to a given patient in a given bed. In other scenarios, devices may need to be connected for full mobility at speeds ranging from pedestrian for a wristband monitor to high speeds for devices in an ambulance or medivac helicopter.

2.3 REQUIREMENTS AND KPIS ON 5G

3GPP has identified KPIs for healthcare applications in three categories: static local, static remote and moving conditions. Within each category, characteristic parameters are identified for communication service availability, communication service reliability (Mean Time Between Failure), maximum end-to-end latency, bitrate, and direction. Influence quantities are also identified for message size, survival time, User Equipment (UE) speed in kilometer/hour (km/h), number of UEs, and service area.

A wireless operating room is an example of a static local condition. Using wireless communication in this environment provides comprehensive connectivity and communication between all devices, from vital sign monitors and medicine drips, to lighting and imaging machines. This type of comprehensive communication is typically not available today as manufacturers of different components use different technologies and even proprietary communications mechanisms for their products. Full communication and synchronization of all devices in an operating room gives the medical personnel the best and most accurate information of the patient's condition and allows them to make real-time decisions to improve patient outcomes. An additional benefit of a fully wireless operating room is the removal of cables, wires and cords which may impede movement around the patient and potentially be a source of increased infection risk.

Treatment in an ambulance is an example of a moving condition. Wireless communications, even at high speed, allows the Emergency Medical Techs (EMT) to communicate with the hospital while the patient is enroute. For medical conditions such as a stroke, where specific interventions are needed within a narrow time window for best patient outcomes, having this communication path established as soon as possible allows the tending physician to have information at the earliest possible moment and to provide the most accurate treatment guidance to the EMTs before the patient reaches the hospital.

The full set of KPIs can be found in 3GPP TR 22.826 however the KPIs for static local conditions is shown in Table 2.2.

Table 2.2. New Consolidated Performance Requirements over a PLMN in Static Conditions.[10]

Requirement	Characteristic parameter					Influence quantity				
	Communication service availability: target value in percent	Communi-cation service reliability: Mean Time between failure	End-to-end latency: maxi-mum	Bit rate	Direc-tion	Message Size [byte]	Survival time	UE speed (km/h)	# of UEs	Service area
5.3.2 - Compressed 4K (3840x2160 pixels) 60 fps 12 bits per pixel color coded (for example, YUV 4:1:1) real-time video stream 5.3.2 – Uncompres-sed 512x512 pixels 32 bits 20 fps video stream from ultra-sound probe	>99.999	>1 day	<20 ms	<200 Mbits/s	UE to network	~1500	~16 ms	Station-ary	1	Regional
5.3.3 - Stereoscopic 4K 60 fps 12 bits per pixel color coded (for example, YUV 4:1:1) real time video (loss less compressed)	>99.9999	>1 day	< 250 ms	< [4 Gbit/s]	Network to UE; UE to Network	~1500 - ~9000 (note 1)	~16 ms	Station-ary	1	National
5.3.3 - 4K 60 fps 12 bits per pixel color coded (for example, YUV 4:1:1) real time video (loss less compressed)	>99.9999	>1 day	< 250 ms	< [2 Gbit/s]	Network to UEs	~1500 - ~9000 (note 1)	~16 ms	Station-ary	<10	National
5.3.3 - Haptic Feedback	>99.9999	>1 day	<20 ms	<16 Mbits/s	Network to UE; UE to Network	<2000	~1 ms	Station-ary	1	National
NOTE 1: MTU size of 1500 bytes is not generally suitable to gigabits connections as it induces many interruptions and loads on CPUs. On the other hand, Ethernet jumbo frames of up to 9000 bytes require all equipment on the forwarding path to support that size in order to avoid fragmentation.										

[10] *Study on Communication Services for Critical Medical Applications,* 3GPP TR 22.8.2.6. June 2019.

2.4 DEPLOYMENT STATUS

Healthcare, specifically telemetry, is one of the leading IoT use cases expected to deliver the fastest spending growth over the 2017-2022 forecast period, as shown in Figure 2.2. Healthcare is also one of the industries with the fastest Compound Annual Growth Rate (CAGR) over the five-year forecast period (2017-2022) at 15.4 percent.[11] While the United States and China will be the global leaders for IoT spending in 2019 at $194 billion and $182 billion respectively, the countries that will see the fastest IoT spending growth over that period are all located in Latin America: Mexico (28.3 percent Compound Annual Growth Rate/CAGR), Colombia (24.9 percent CAGR), and Chile (23.3 percent CAGR).[12] Additionally, tele-medicine is expected to be of significant value in less developed areas where access to skilled medical personnel is limited. All of these factors indicate deployment can be expected on a global scale.

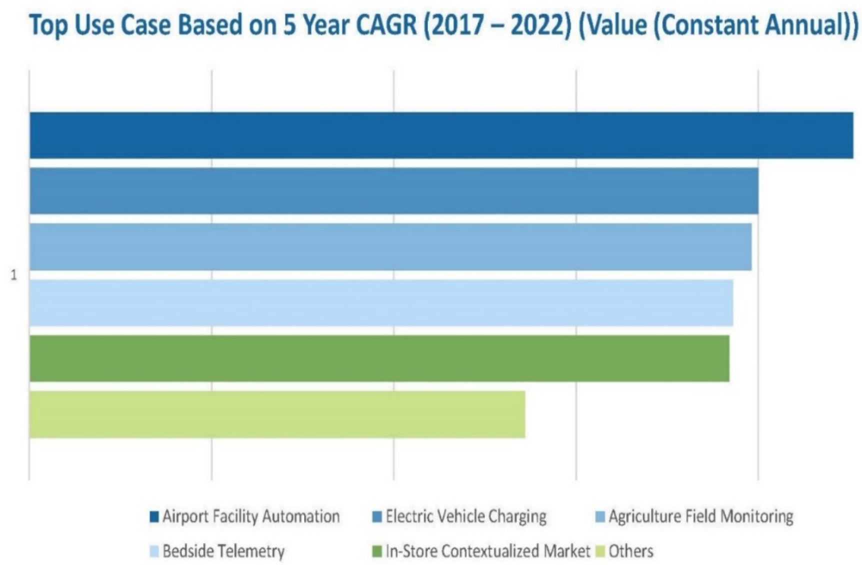

Figure 2.2. Top Use Cases Based on Spending Growth.[13]

2.5 KEY CHALLENGES FOR 5G HEALTHCARE

Security of personal medical data will be essential for wireless healthcare to succeed. Many regulations on the privacy and security of such information are in place today, including:

- Health Information Patient Accountability Act (HIPAA)[14]
- Health Information Technology for Economic and Clinical Health (HITECH)[15]
- General Data Protection Regulation (GDPR)[16]

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[11] *IDC forecasts worldwide spending on the Internet of Things to Reach $745 billion in 2019, led by the manufacturing, consumer, transportation, and utilities sectors, press release by IDC.* Press Release, IDC. January 2019.
[12] *IoT Report: How Internet of Things Technology Growth is Reaching Mainstream Companies and Consumers,* Business Insider, Peter Newman. 28 January 2019.
[13] Ibid.
[14] *U.S. Department of Health and Human Services Office for Civil Rights – Health Information Patient Accountability Act (HIPAA) Privacy Rule.*
[15] *111th Congress of United States of America – Health Information Technology for Economic and Clinical Health (HITECH) Act.*
[16] *Pre-Hospital Ultrasound: Current Indications and Future Perspectives,* Zanatta et al., International Journal of Critical Care and Emergency Medicine 2016, 2:019, Volume 2 | Issue 2, ISSN: 474-3674.

Compliance with these regulations must be ensured by the 5G system to fully support healthcare applications. Several new requirements have been identified in 3GPP TR 22.826 to ensure adequate protections are in place in Rel-17.

3. USE CASE: FIXED WIRELESS ACESS (FWA)

About half of the world's households – over 1 billion – do not have a fixed broadband connection. This large number of underserved households represents a profitable Fixed Wireless Access (FWA) growth opportunity for current 3GPP operators. 5G networks are now being built out, with performance and capacity gains available to be tapped by new use cases. One of the first is FWA.

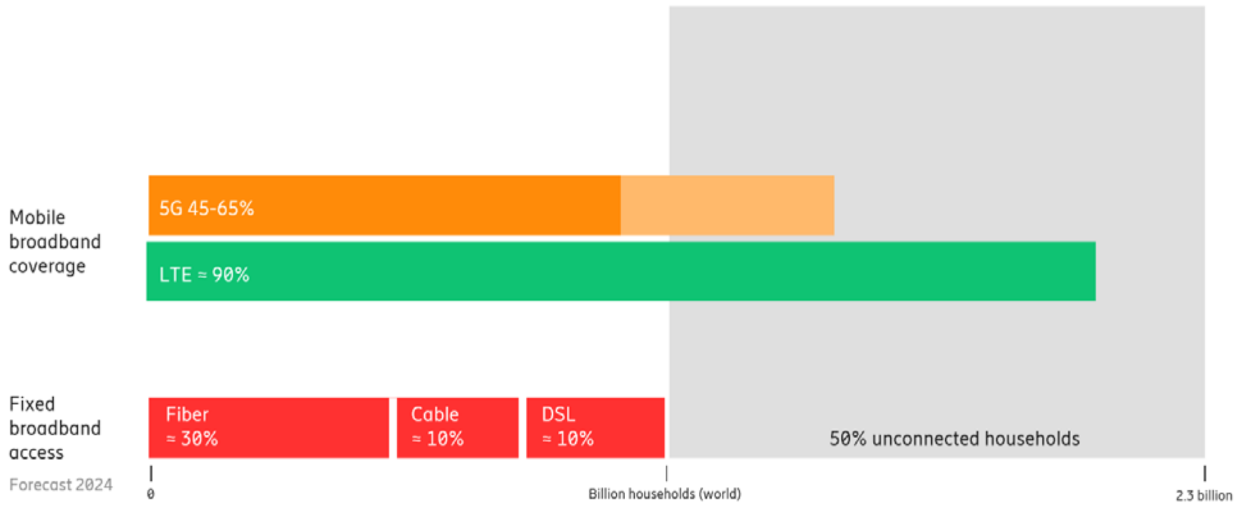

Figure 3.1. Mobile Broadband Coverage versus Fixed Broadband Access.[17]

3.1 INTRODUCTION TO FWA

Fixed Wireless Access is a more cost-effective and efficient alternative to providing broadband in areas with limited access to fixed broadband services such as Digital Subscriber Line (DSL), cable or fiber. And with the evolution towards 5G, FWA solutions are expected to achieve massive scale, with 10 to 100 times more capacity than 4G networks. 5G FWA eliminates the need for costly deployment of deep-fiber fixed access infrastructure while offering peak rates that few fixed technologies are able to match.

Advances in radio technology, gains in spectrum assets, and increasing demand for broadband everywhere indicate a strong market opportunity for 4G and 5G FWA offerings. By delivering broadband over existing 4G mobile networks and now available 5G ones, network operators now have the business opportunity to bridge the digital divide and offer connectivity to a broader population. Other opportunities for FWA, shown in Figure 3.2, include governments' ambitions to expand broadband availability, lower network cost and additional revenue. According to Ericsson, recent studies show Fixed Wireless Access investments typically have a payback time of less than two years for service providers.[18]

[17] *Fixed Wireless Access Handbook,* Ericsson, 2019.
[18] Ericsson.com.

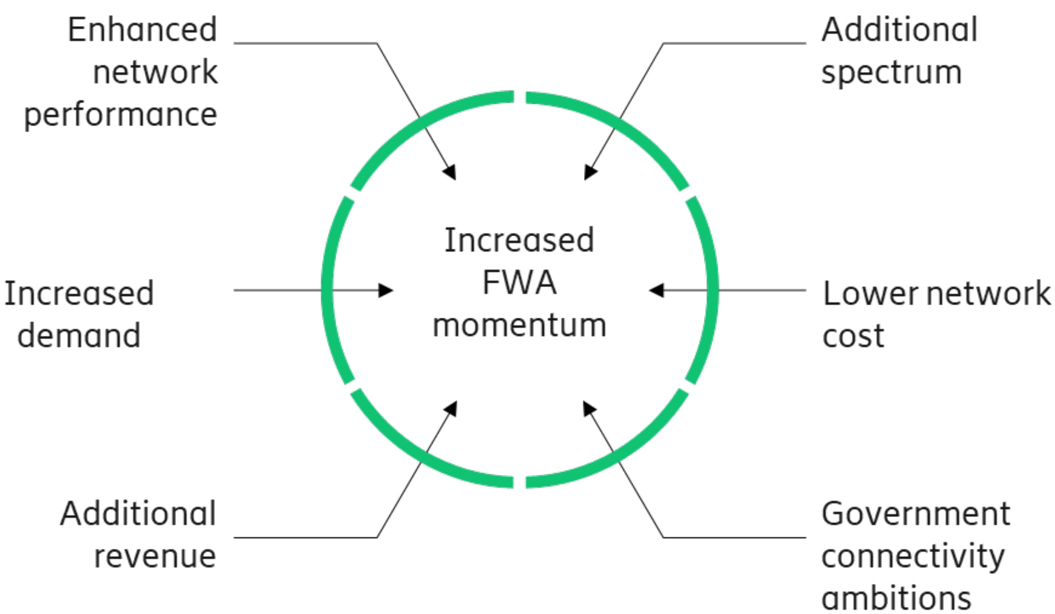

Figure 3.2. Increased FWA Momentum.[19]

Devices with form factors suitable for FWA Customer Premises Equipment (CPE), and without the stringent requirements of size, weight and power consumption that come with smartphones, will be among the first to reach the market. For FWA to be a viable alternative to fixed broadband, including xDSL, cable and fiber optic access technologies, it must be able to be dimensioned with comparable capacity and performance. FWA architecture, on the whole, emulates the mobile broadband network (MBB) architecture in terms of the Radio Access Network (RAN) and the Core network,

Operators across the globe are looking at utilizing 5G New Radio (5G NR) for FWA networks with differing requirements and uses. Even in a standalone FWA network, Quality of Service (QoS) may be required to offer differentiated services to users. This can differentiate the FWA offering from a standard tethering or best effort offerings that are typical of MBB.

In the majority of markets worldwide, the main spectrum band being made available for 5G networks is in the 3.5 GHz range. This is being made available in large sections of 50 – 100 MHz which can take advantage of the flexible numerology of the 5G NR radio network capability defined by 3GPP. The additional advantage of using this mid-band spectrum for the deployment of FWA is the range or reach of the site. Higher power cells can reach up to 10 kilometers (km+) with 100’s of Mbps in throughput for an individual user.

There are opportunities for operators to deliver broadband services to homes and small and medium-sized enterprises economically using FWA. However, the paradigms for fixed and mobile broadband are different, in both subscription offerings and dimensioning.

When dimensioning an FWA network, several characteristics must be considered to uphold user experience during busy hours. With FWA, the last hop is wireless, so all the characteristics of a wireless network apply. Unlike fiber, but similarly to xDSL loop length, connection quality will vary across households. And, unlike fixed broadband overall, the last hop is point-to-multipoint radio and therefore shared, which means that

[19] *Fixed Wireless Access Handbook,* Ericsson, 2019.

speeds will degrade with increasing cell load. All these characteristics must be considered when dimensioning an FWA network.

3.2 ARCHITECTURE

FWA architecture, on the whole, emulates the mobile broadband network architecture in terms of the Radio Access Network (RAN) and the Core network, either in Option 2 5G Packet Core (PC) or Option 3.x Enhanced PC (ePC).

A key component of the architecture definition is the spectrum availability. The mid-band spectrum (2.5 – 4 GHz ranges) which is typically available in multiple jurisdictions worldwide, provides a quality mix of bandwidth and range/coverage. This also impacts the size of the Radio Frequency (RF) components in use in both the transmitter and the receiver.

The primary difference between mobile networks and FWA networks are the Customer Premise Equipment (CPEs) along with the CPE management system that are used to enhance the capacity and coverage of the network.[20]

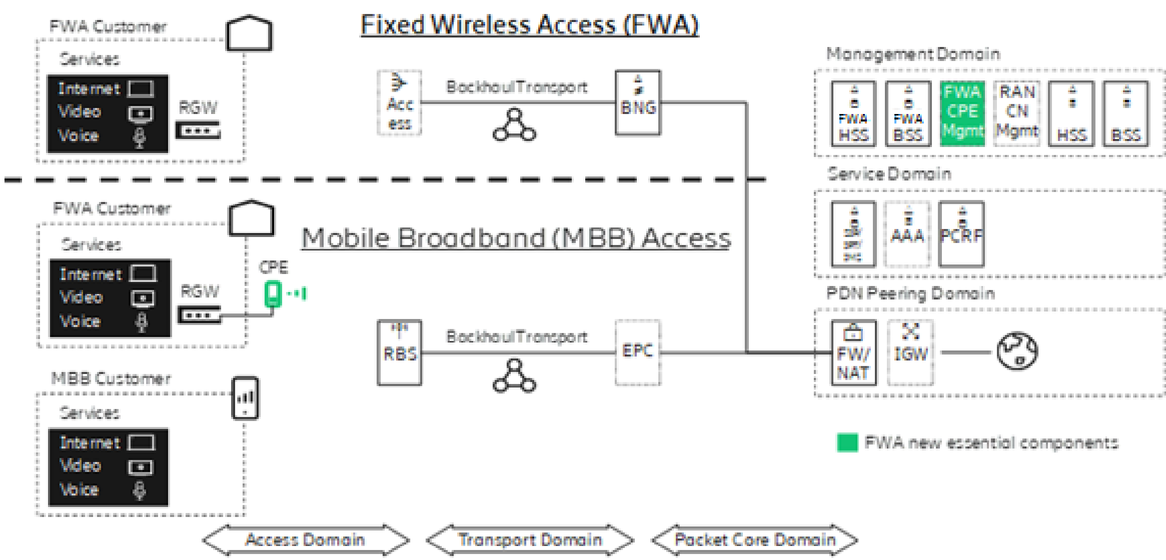

Figure 3.3. Fixed Wireless Access.[21]

Figure 3.3 outlines the overall architecture of Fixed Wireless Access and Mobile Broadband access networks. These have been augmented with the following FWA specific hardware and software components, highlighted in green in Figure 3.3.

- **FWA Customer Premise Equipment (CPE):**
  3GPP compliant device consisting of a modem and antenna for access to the mobile network
- **FWA CPE Management:**
  A management system that provides remote access to the FWA CPE for configuration, performance measurement, or troubleshooting purposes. For FWA or fixed/mobile converged operators, this can be an integral part of or extension to an existing Residential Gateway (RGW)

[20] *Mobility Report,* Ericsson, 2019.
[21] *Mobility Report,* Ericsson, 2019.

management system. The FWA CPE Management is controlled by a TR-069 compliant Auto Configuration Server (ACS) application

The CPE can be an indoor or outdoor CPE – the decision between choosing one or the other will depend upon multiple items such as jurisdictional planning, building type -- for example, Single Family Unit (SFU) or Multi-Dwelling Unit (MDU) -- and customer requirements such as mounting capability.

- **Outdoor CPE** – Two-device solution:
  The outdoor device contains the 4G/5G modem and antenna to connect with the 3GPP mobile network as well as a Gigabit Ethernet (GE) port providing LAN connectivity to the indoor RGW and power through PoE
- **Indoor CPE** – One device solution:
  The indoor device combines RGW and 4G/5G access functions in a single box. The device has inbuilt 4G/5G modem and antennas. External 4G/5G antennas can optionally be connected via Sub-Miniature version A (SMA) ports

Compared to Indoor CPEs (without external antennas), Outdoor CPEs provide much better performance in terms of spectral efficiency or throughput (Bps/Hz), assuming the antenna can be installed in an optimal position in direct Line of Sight (LOS) to the Radio Base Station (RBS). It also allows the use of a higher gain, directional antenna which reduces the impact of any cell overlap and reduces the need for mobility management.

While Indoor CPEs are generally easier to install, Outdoor CPEs are recommended for FWA deployments.

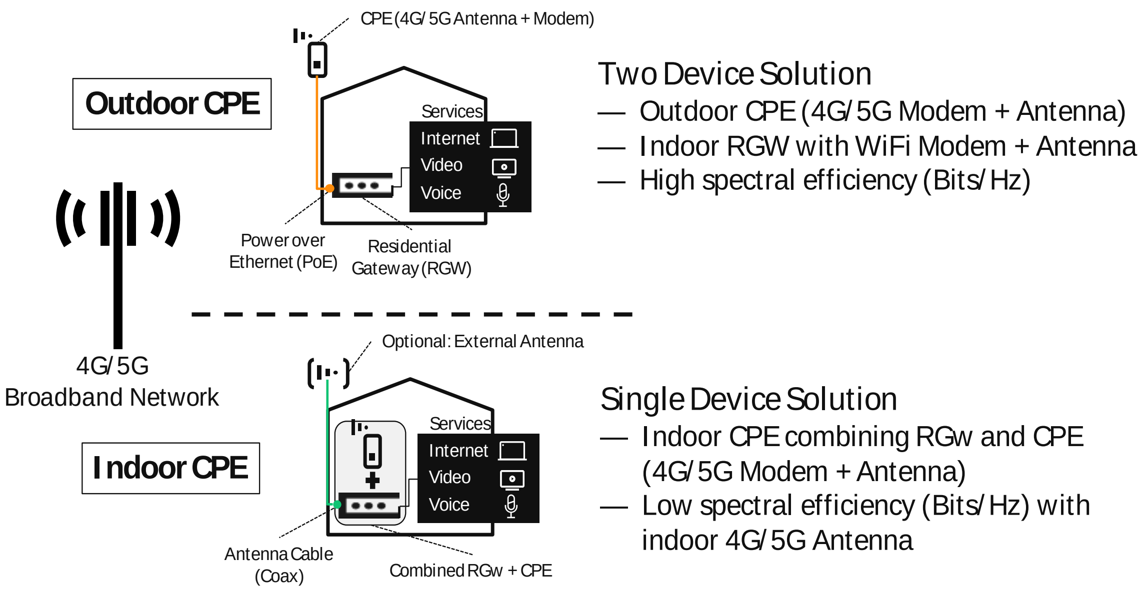

Figure 3.4. Outdoor CPE versus Indoor CPE.[22]

It is also important to evaluate the following elements when determining the CPE type to be used: Multip-Input Multiple-Output (MIMO) antenna capability, Carrier Aggregation (CA) and modulation schemes supported by the CPE.

[22] *Fixed Wireless Access Handbook,* Ericsson. 2019.

3.2.1 CAPACITY

An important aspect of the architecture definition for FWA networks is the capacity requirement. This will heavily depend on the offered services and expected requirements from the users. Different service offerings may allow for higher bitrates, from a simple browsing experience (Facebook, Google, email) up to 4K TV/Streaming. Some examples of bitrates required for these services are shown in Table 3.1.

Table 3.1. Bit-Rate Requirements.

Video application	Data rate requirements
Facebook	60 - 750 kbps
YouTube	250 kbps - 3 Mbps
Netflix SD Video (480p)	2-3 Mbps
Netflix HD Video (1080p)	4-7 Mbps
Netflix UHD Video (4K)	15 - 25 Mbps

The architecture on the RAN as well as the Core network must be correctly dimensioned for the penetration rate growth, business case Busy Hour (BH) throughput growth as well as service level offerings.

Other elements, such as traditional "Triple-Play" offerings may also need to be catered for in the architecture. This may call for the addition of an Internet Protocol Multi-Media Subsystem (IMS) element to the Core Network to provide Voice-over-LTE (VoLTE) and/or Voice-over-New Radio (VoNR) in addition to the Internet and Video services.

Another impact on capacity requirements may be the business requirement for maximum volume requirements in a billing period. If unlimited plans are to be offered, this may have an impact on users and contention-based scheduling on the RAN.

3.2.2 NETWORK SLICING

Various standardized and proprietary approaches are available to logically separate different tenants or services when sharing the same physical RAN, Transport or Core Network (CN) resources for operational, observability, business or other reasons.

Intra-PLMN network slicing architecture for 5G is addressed in 3GPP TS 23.501. Transport resource slicing is addressed by the Internet Engineering Task Force (IETF) and relies on following available technologies, among others:

- Virtual Private Networks (VPNs) (RFC 4026)
- Segment Routing (RFC 8402)

3.2.3 ACCESS AND MOBILITY CONTROL

In an FWA environment, it is preferred to deploy a network with more isolated cells while also utilizing the Outdoor CPE with a directional antenna (with a large Front to Back ratio) to minimize the need for mobility control.

When CPE devices come with the directional antenna layout (Outdoor CPE), the primary selection is done during installation by pointing the antenna to the desired (primary) cell that was planned to provide FWA coverage. If other cells overlap with this primary cell, operators might also want to control their usage, for example, for CPE failover or load balancing purposes.

When CPE devices, like Indoor CPEs, come with an omnidirectional antenna layout there is less or no installation-based control and the operator needs to control cell access and usage by other means such as:

- CPE Features
  - Device Locking (Physical Cell Identifier (PCI)/Cell ID, Absolute Radio Frequency Channel Number (ARFCN)/Frequency or by Band)
- RAN Features
  - Service Profile Identifier (SPID) / Frequency Priority, White/Blacklisting
- Core Network Features
  - Localized Subscription, Roaming Restrictions, Presence Reporting

Potential grid difference and specific planning aspects, such as knowledge of the subscriber's locations prior to planning the network, can also reduce any requirement for mobility management.

3.2.4 QUALITY OF SERVICE (QOS)

Even in a standalone FWA network, QoS may be required to offer differentiated services to users. This can differentiate the FWA offering from a standard tethering or best effort offerings that are typical of MBB. Figure 3.5 shows some of the differences between the typical offerings and FWA.

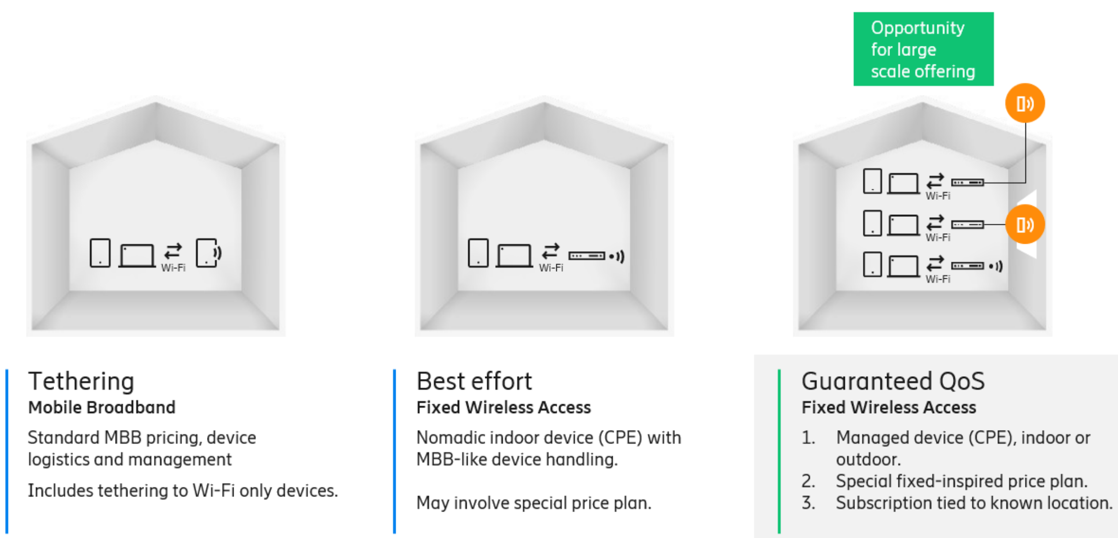

Figure 3.5. Quality of Service.[23]

[23]*Fixed Wireless Access Handbook,* Ericsson. 2019.

QoS can be used in existing MBB networks to differentiate the QoS levels required for FWA users. Separate QoS Class Identifiers (QCIs) can be used for internet traffic versus Video (Internet Protocol Television or IPTV) or Voice users who may subscribe to a non- Over-the-Top (OTT) service, instead requiring a minimum level of service.

A minimum bitrate can also be provided for FWA internet browsing, if this is a requirement of the customer offerings. The Core Network can be used to enforce these requirements as well as using enforcement of maximum data consumption and "top offender" restrictions.

Some examples of the possible QoS enforcement in an FWA environment are shown in Table 3.2.

Table 3.2. Quality of Service Enforcement.

Service Profile	Absolute Priority	Relative Priority	Minimum Bitrate (Mbit/s)	Maximum Bitrate[1] (Mbit/s)
IPTV	6	N/A	5	Unlimited
Premium Internet	8	1	10	60
Standard Internet	8	2	5	30

3.2.5 BACKHAUL/TRANSPORT

Another aspect of architecture which has a major bearing on the FWA and high throughput scenario, is the deployment of transport to the Transmission Point (TP) or Cell Site. This can have a major impact on the service offering, especially in the rural deployment areas.

In more urban areas, when spectrum in the mmWave band may be used for FWA, a major possibility for backhaul implementation could be Integrated Access Backhaul (IAB). This can be viewed as an alternative for rapid deployment due to the difficulty of getting backhaul to a node location. This is typically applicable up to a kilometer in a Line of Sight (LoS) environment.

In a suburban or, even possibly, a more rural environment, where the availability of fiber-based backhaul may be unavailable, microwave may be used as an alternative to wired backhaul. Multiple options are available, dependent on specific requirements like:

- Throughput (< 1 Gbps up to 10 Gbps)
- Line of Sight (NLOS reduces the possible throughput levels)
- Donor Site capability (Bandwidth to site, LoS)

The final main option for backhaul to FWA sites is the standard fiber optic delivery to the cell site. For some operators, especially if they have a fixed broadband network in place already, this may provide an easy path to backhaul provisioning. It may also be used in conjunction with a microwave link for the last mile deployment.

3.3 REQUIREMENTS AND KPIS ON 5G

Operators across the globe are looking at utilizing 5G NR for FWA networks with differing requirements and uses. Accordingly, the performance requirements from these FWA deployments will be highly dependent on usage scenarios. For an indoor residential scenario, the requirements and KPIs will primarily be to provide high data rates and high capacity.

In a rural scenario, the requirement will focus more on coverage maximization. Throughput/data rate requirements for rural scenarios are expected to be less stringent, however 5G NR ensures a minimum data rate is maintained and has a better performance than LTE.

Specific use cases in FWA may also be more niche such as broadband access for special events, stadiums and convention centers. These scenarios will demand very high bandwidth availability, a large number of simultaneous connected users and high uplink (UL) data traffic. Performance requirements highly depend on traffic scenarios.

Vertical scenarios with low latency and high reliability requirements include broadcast, and connectivity in high speed trains, vehicles and airplanes. Network access also needs to be supported in more extreme scenarios, with long range coverage, or in low end market scenarios, where access to power and backhaul facilities are not a given. Very large cell coverage areas of more than 100 km radius shall be supported with 1 Mbps downlink at the cell edge. For constrained circumstances, and even larger areas, 5G shall be able to support a minimum user experience with 100 kbps, end-to-end latency of 50 milliseconds (ms), and a lower availability of 95 percent.

There will also be vertical applications within FWA, such as broadcast, massive IoT for Machine-to-Machine (M2M) connectivity, critical M2M usage with extremely low latency and high delay sensitivity. For such use cases, 5G NR network and devices will need a different set of KPIs such as Round-Trip Time (RTT) Delay, number of devices connected, control channel capacity, and UE battery life.

Besides the vertical specific requirements and KPIs, there are broader KPIs that will apply to most, if not all, FWA networks.

- **Reliability:** the usual KPIs for the network and UE reliability apply to the FWA network
- **Availability:** while the usual KPIs apply for the FWA network, different verticals within the FWA segment will require more stringent values for availability. For example, higher availability KPIs will be needed for the residential broadband and critical Machine-to-Machine (M2M) applications
- **Latency:** requirements for latency have become more stringent, especially with the advent of online gaming and Virtual Reality/Augmented Reality (VR/AR) technologies. To make the VR world realistic, the latency should be sub-20 ms and preferably sub-7 ms. 5G will enable these lower latencies with air-interface values as low as 1 ms, dependent upon Sub-Carrier Spacing-Circuit Switched (SCS-CS) as well as the Edge Compute breakout for access
- **Packet Error Rate:** higher quality IPTV broadcasts and Mobile-to-Mobile services have more stringent requirements in 5G compared to 4G (and Standard Definition Television/SDTV versus High Definition Television/HDTV) for Packet Error Loss Rate. Some examples of the differences between services and technologies are shown in Tables 3.3 and 3.4.[24]

[24] *Prospects and QoS Requirements in 5G Networks,* Tikhvinskiy, V. and Bochechka, G., Journal of Telecommunications and Information Technology. January 2015.

Table 3.3. Packet Loss Error Rate and Broadcast Quality.

Video application / Broadcast with guaranteed quality	Packet loss Error rate
SDTV	10^{-6}
HDTV	10^{-7}
4k UHD	10^{-8}
8k UHD	10^{-9}

Table 3.4. Packet Loss Error Rate and Quality of Service.

QoS	Packet Loss Error Rate		
	3G	**4G**	**5G**
Without Guaranteed Quality (Non-GBR)	10^{-2}	10^{-3}	10^{-4}
With Guaranteed Quality (GBR)	10^{-2}	10^{-6}	10^{-7}

A few examples of the KPI requirements and business considerations for various FWA verticals are presented in Figures 3.6 through 3.10.[25]

[25] *Fixed Wireless Access Handbook,* Ericsson. 2019.

Figure 3.6. Rural Village FWA Vertical.

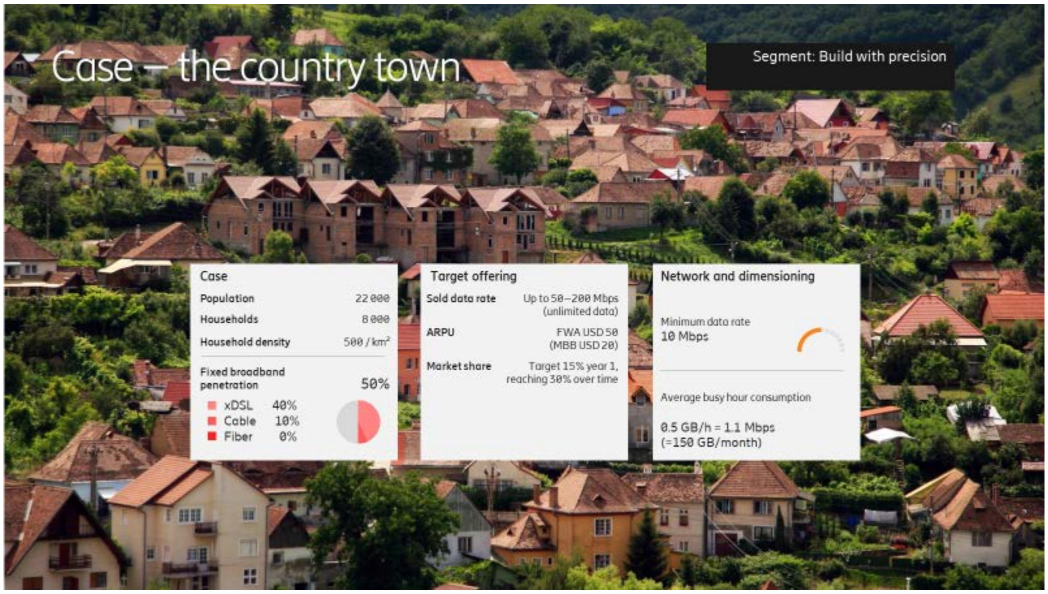

Figure 3.7. Country Town FWA Vertical.

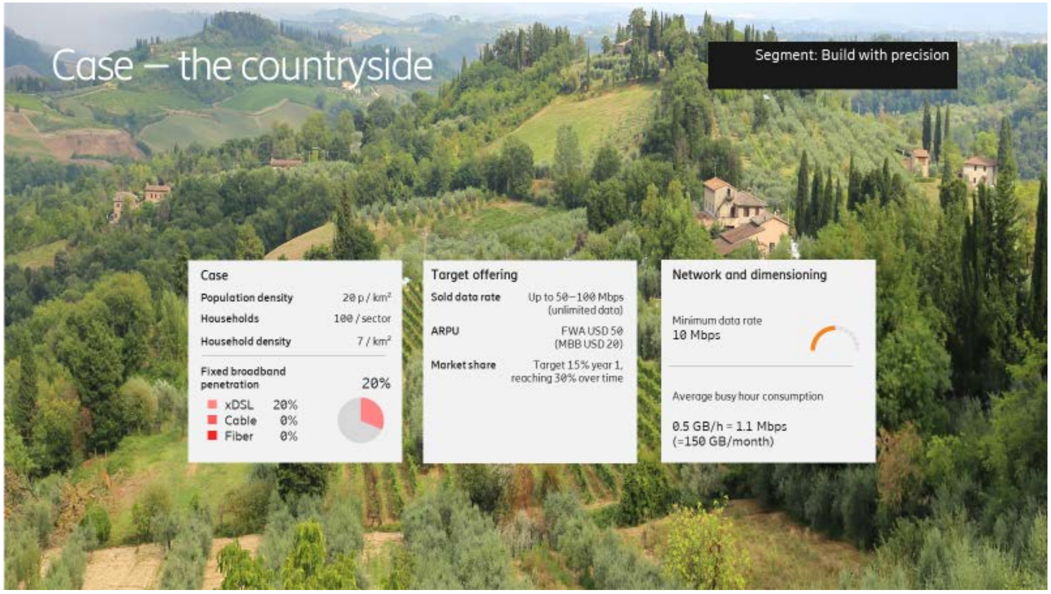

Figure 3.8. Countryside FWA Vertical.

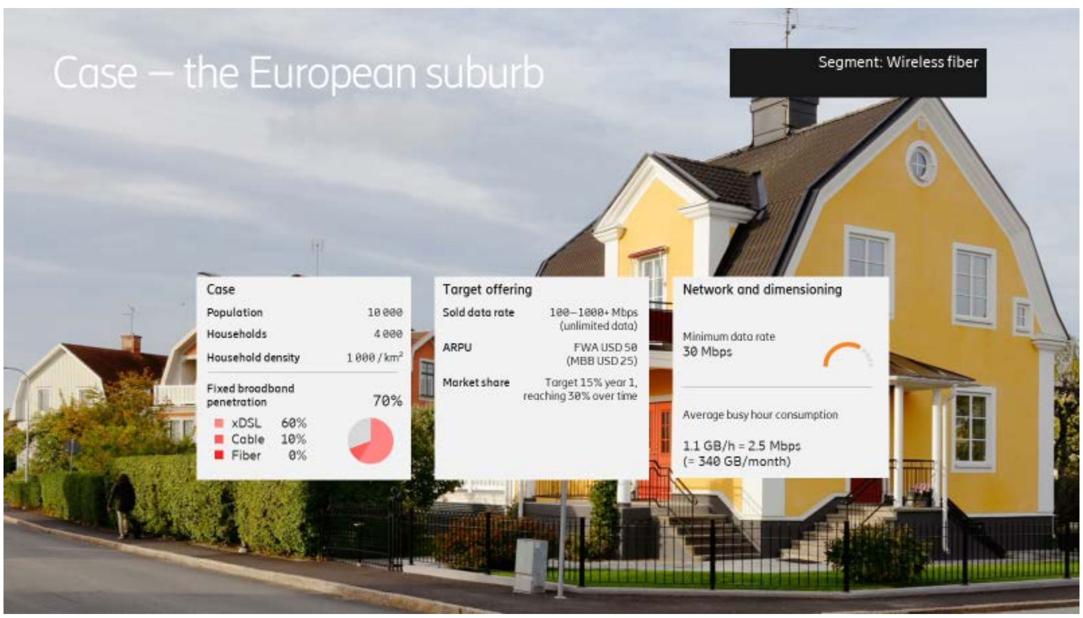

Figure 3.9. European Suburb FWA Vertical.

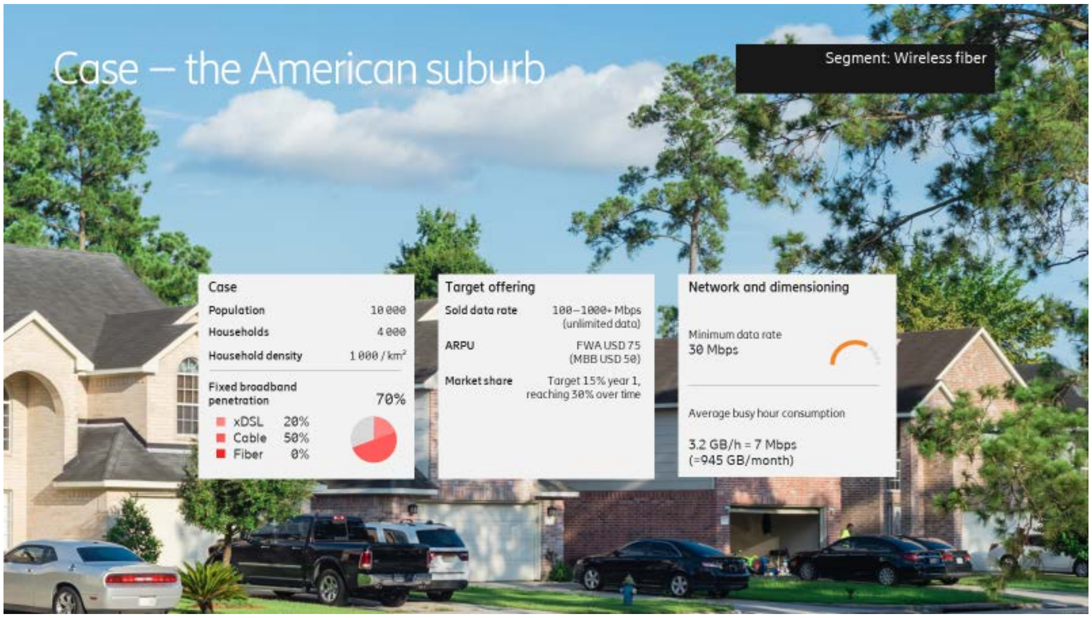

Figure 3.10. American Suburb FWA Vertical.

3.4 DEPLOYMENT STATUS – PRESENT DEPLOYMENT EXAMPLES AND FUTURE DEPLOYMENT CONSIDERATIONS

While FWA deployments are increasing in number, the initial concentration has been on LTE or 4G-based networks. This has a limitation of 20 MHz carriers and requires multiple carriers and carrier aggregation to provide the requisite throughput capacity.

Now that larger swathes of spectrum are being made available for 5G, FWA deployments are being considered. A large number of countries are creating National Broadband Plans (NBP) (Ireland: NBP; USA: CAF-Connected America Fund) to enable rural customers with broadband as a connected society. Beyond this, urban areas can also benefit from similar infrastructure to connect users in cities where additional cabling may be expensive or not possible.

3.4.1 WORLDWIDE

In the majority of markets worldwide, the main spectrum band being made available for 5G networks is in the 3.5 GHz range. This is being made available in large sections of 50 – 100 MHz which can take advantage of the flexible numerology of the 5G NR radio network capability defined by 3GPP.

The additional advantage of using this mid-band spectrum for the deployment of FWA is the range or reach of the site. Higher power cells can reach up to 10 km+ with 100's of Mbps in throughput for an individual user.

Another advantage of using this higher mid-band spectrum is the ability to use Multi-user MIMO (Multiple-Input Multiple-Output) to enable higher spectral efficiency and better user experience in a multi-user environment. Using beamforming techniques, this allows users to maximize their SINR (Signal-to-Interference Noise Ratio) and hence their maximum throughput levels.

Outdoor CPEs will be primarily used to maximize performance in these networks.

As mentioned previously in this section, initial networks have been deployed using 4G/LTE, but these may be upgraded to 5G NR networks once spectrum and equipment becomes available.

3.4.2 REGIONAL/AMERICAN 5G

In North America, particularly the U.S., there are restrictions today on the availability and use of mid-band spectrum in the 3.5 GHz range for FWA due to incumbent users, for example, military/government, satellite users, and restricted spectrum use in Citizens Broadcast Radio Service (CBRS) which was only defined for LTE in 2018.

However, some initial deployments which commenced in 2018 used spectrum which is more available in the U.S., such as mmWave spectrum at 28 GHz. Due to the limited propagation of this spectrum, it was used along with a Multi-User Multiple-Input Multiple-Output (MU-MIMO) antenna deployment in an urban environment, providing internet access to individual homes via CPEs.

Deployment of this mmWave-based FWA was limited initially and is being reviewed to determine whether to focus on this spectrum for future deployments.

The mid-band spectrum at 3.5 GHz is more available in other markets in the Americas, including Canada, Mexico and Central and South America.

3.4.3 FUTURE CONSIDERATIONS

In the U.S., the CBRS band has already been approved by the CBRS Alliance to run NR on this band. 3GPP has already ratified the definition of this spectrum for NR and the CBRS Alliance should complete standards definition for 5G NR by the end of 2019.

This will allow the definition for 5G NR carriers in the CBRS band; however, the spectrum sharing nature and allocation of spectrum elements in a disparate manner using 10 MHz chunks may prevent the full utilization of the 3.5 GHz spectrum in the U.S. for FWA. This may still be overcome by 5G NR's increased capacity, especially on the smaller carriers, for example, 100 versus 106 Physical Resource Blocks (PRB) when comparing an LTE and 5G NR carrier respectively, and may see the deployment of 5G NR replacing existing carriers' CBRS FWA deployments which are starting today in LTE.

Another possibility in the U.S. is the allocation of the "C-Band" spectrum for 5G NR. This is being advocated by multiple groups including Multiple Systems Operators (MSO) who could utilize 5G NR FWA to offer a superior broadband service to subscribers replacing existing Digital Subscriber Line (xDSL) networks without having to deploy new fiber optic network at high cost in rural environments.

In non-U.S. markets, while the initial deployments of 3.5 GHz spectrum will allow the early deployment of 5G NR based FWA networks, the addition of higher band spectrum like mmWave spectrum will allow the addition of needed capacity in certain areas or also specific hotspots to provide for a subset of users (by replacing select CPEs only).

3.5 KEY CHALLENGES FOR 5G MMWAVE DEPLOYMENT

FWA will provide a key use case for 5G, however, there are some challenges of a technical, operational regulatory and business nature that will need to be addressed for mmWave deployments.

3.5.1 TECHNICAL CHALLENGES

For FWA to compete against Fixed Broadband with coax or fiber, it will require a large amount of RF spectrum. RF spectrum in the needed hundreds of MHz or GHz is only available in mmWave. Some expected key challenges to address for an acceptable FWA service to consumers will be mmWave RF propagation, antenna technology for narrow beamforming, limited coverage and LoS requirements.

3.5.2 OPERATIONAL CHALLENGES

Given the dense deployment requirements of mmWave for coverage and performance, labor costs related to deployment (tower climbers, RF engineering, propagation analysis on the ground, and etcetera) in semi-urban, suburban and rural environments will be a significant challenge to overcome. Associated challenges of energy usage and backhaul requirements also deserve a closer look for a profitable FWA deployment using mmWave 5G technology.

3.5.3 REGULATORY CHALLENGES

Cities and town municipalities are increasingly getting aggressive in legislating policies for deployments of small 5G cells typical of mmWave deployments. The concerns are related to aesthetics and health hazards associated with their misunderstanding about health effects of the high power mmWave radiation so close to residences and human inhabitants.

Additionally, legacy regulations from the U.S. Federal Communications Commission (FCC) requiring municipalities to provide broadband services and the associated network requirements tend to be a hurdle for FWA deployments. The FCC regulations for municipalities delivering broadband services is still with the assumption that these services are offered through fixed equipment/technology – compliance to which can be a challenge for FW operator.

3.5.4 BUSINESS MODEL CHALLENGES

The residential use case for 5G fixed wireless is more complex, because not only is the network build more expensive, the competition from existing cable and telco providers adds downward pricing pressure on the market. This makes for a more difficult return on investment. FWA broadband deployment with 5G mmWave will need small cells and a very dense footprint, which gets expensive and has geographical limitations.

4. USE CASE: UNMANNED AERIAL VEHICLES

Ultra-Reliable Low Latency Communication (URLLC) is a key requirement for 5G and coupled with robotics will usher in a new era of remote medicine, factory robotics, drones or Unmanned Aerial Vehicles (UAV), and Unmanned Ground Vehicles (UGV).

4.1 INTRODUCTION TO UNMANNED AERIAL VEHICLES

An Unmanned Aerial System (UAS) is the combination of an Unmanned Aerial Vehicle (UAV or Drones) and a UAV controller. The UAV is controlled from an operator on the ground via a UAV controller and may have some autonomous flight capabilities. The communication system between the UAV and UAV controller is described in the 3GPP (TR 22.125) specification. This is illustrated in Figure 4.1.

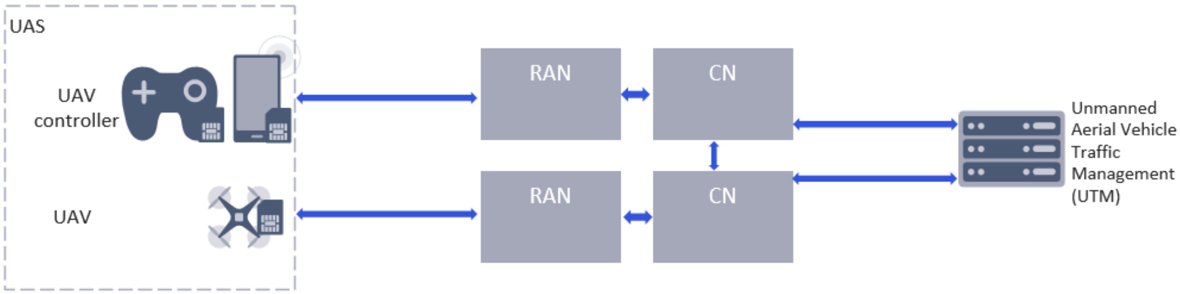

Figure 4.1. Initial Authorization for operation.[26]

The range of size and weight for UAVs varies from small, light aircraft often used for recreational purposes to large, heavy aircraft which are often more suited to commercial and military. Regulatory requirements vary across this range and vary on a regional basis.

The communication requirements for UAS cover both the Command and Control (C2) between UAV and UAV controller, but also data uplink and downlink (DL) to/from the UAS components towards both the serving 3GPP network and network servers.

3GPP standards are evolving beyond the initial introduction of Mobile Enabled Drones in Release 15, which is addressed in TR 36.777. This standard primarily focused on how LTE networks can provide services for low Altitude UAVs and how the overall performance of an LTE network is impacted by the user equipment (UE) deployed by the UAV.

3GPP plans to complete Release 16 by mid-2020, including additional standards such as the Remote Identification of Unmanned Aerial Systems Stage 1 (TR 22.825). This study identifies requirements for remote Identification of UAS through the use of control data centralized in an Unmanned Aerial Vehicle Traffic Management System (UTM).

For Release 17, 3GPP has agreed to work on Enhancement for Unmanned Ariel Vehicles Stage 1 (TR 22.829). The 3GPP study proposes new use cases, KPIs and requirements for UAV applications for communication latency, mobility and reliability. This also includes communication between the UAV and the UTM, security and surveillance applications, an optional radio access node aboard a UAV, discovery process between UAV controllers and UAVs, and the required KPIs that regulate the traffic between the UAV and the UAV controller.

The UTM is used to provide UAS identification and tracking, authorization, enforcement, and regulation of UAS operations. The UTM stores the data required for the UAS to operate and gives authorized users (for example, air traffic control, public safety agencies) the ability to query a UAV and its' controllers identity and metadata.

5G UAV use cases will be mainly Beyond-Visual-Line-of-Sight (BVLOS), and that enables the flight of a UAV across longer distances without relocating equipment, which in turn enables the collection of more data. This makes mobility connectivity a critical enabler for BVLOS of UAV. 5G will enhance UAV capabilities and the UTM operations by enabling: higher bandwidth for video (for example, 4K/8K), lower latency for fast detection and avoidance triggers by off-board data sources, Multi-Access Edge Computing (MEC) for offloading the detect and avoidance compute from the UAV, and Network Slicing for enabling the

[26] *Remote Identification of Unmanned Aerial Systems Stage 1,* Rel-16. 3GPP TR22.82.

creation of a dedicated logical slice with the specific characteristics required for the UAS and UTM optimized operation support.

4.2 ARCHITECTURE

Architecture for UTM initiated originated in the U.S. with the National Aeronautics and Space Administration (NASA). Building on its legacy of work in Air Traffic Management (ATM) for manned aircraft, National Aeronautics and Space Administration (NASA) began researching prototype technologies for a UTM System that could develop airspace integration requirements for enabling safe, efficient, low altitude operations.

4.2.2 UTM ARCHITECTURE

The entire UTM System is a concrete technical implementation including software, the necessary infrastructure for running the software, and the drones themselves. The system provides distinct services through public or restricted standard interfaces. The UTM concept covers all type of UAS operations in very-low-level airspace, in all categories, ranging from simple remotely piloted aircraft systems to complex autonomous operations and beyond.

The 3GPP standards enable the UTM to associate the UAV and UAV controllers and identify them as a UAS. Based on TS 22.125, a UAS shall send the UTM the UAV data which could contain: the UAV's unique identity (UAS-ID, this may be a 3GPP identity), UE capability of the UAV, make and model, serial number, take-off weight, position, owner identity, owner address, owner contact details, owner certification, take-off location, mission type, route data, and operating status. The 3GPP system shall enable a UAS to send different UAS data to the UTM based on the different authentication and authorization levels which are applied to the UAS.

Figure 4.2 is UTM system from NASA.

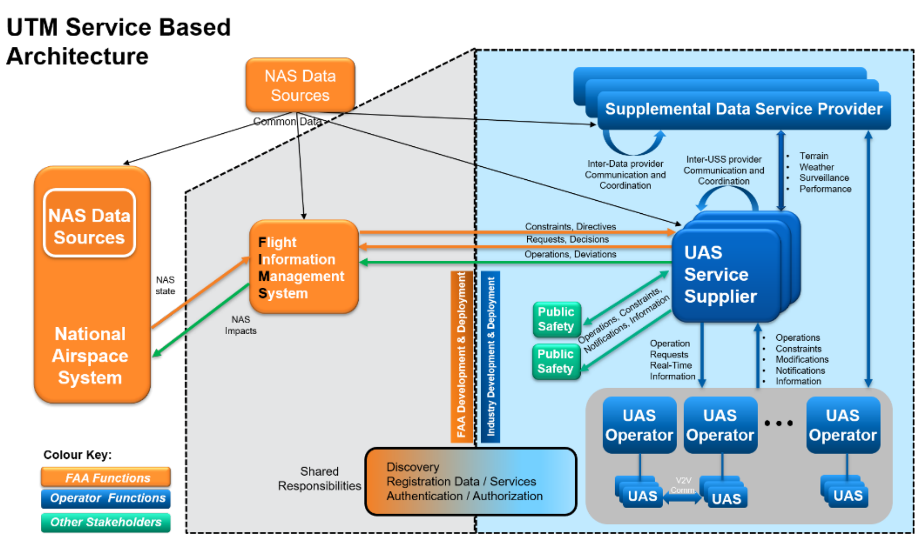

Figure 4.2. NASA UTM System.[27]

[27] *NASA: UTM UAS Service Supplier Development: https://utm.arc.nasa.gov/docs/UTM_UAS_TCL4_Sprint1_Report.pdf.*

4.2.3 MOBILE NETWORKS AND UAV

Existing mobile networks will be reused to support UAV/UAS traffic since they support 3GPP standards today and can be easily scalable with a high degree of reliability and availability. With the increasing growth of UAV/UAS systems, this means that low altitude airspace will be required to support traffic management systems. A high degree of automation will be required in order to manage and control the lower airspace resulting in the need for an existing mobile solution. Figure 4.3 depicts how the mobile network could interact with UTM and their stakeholders.

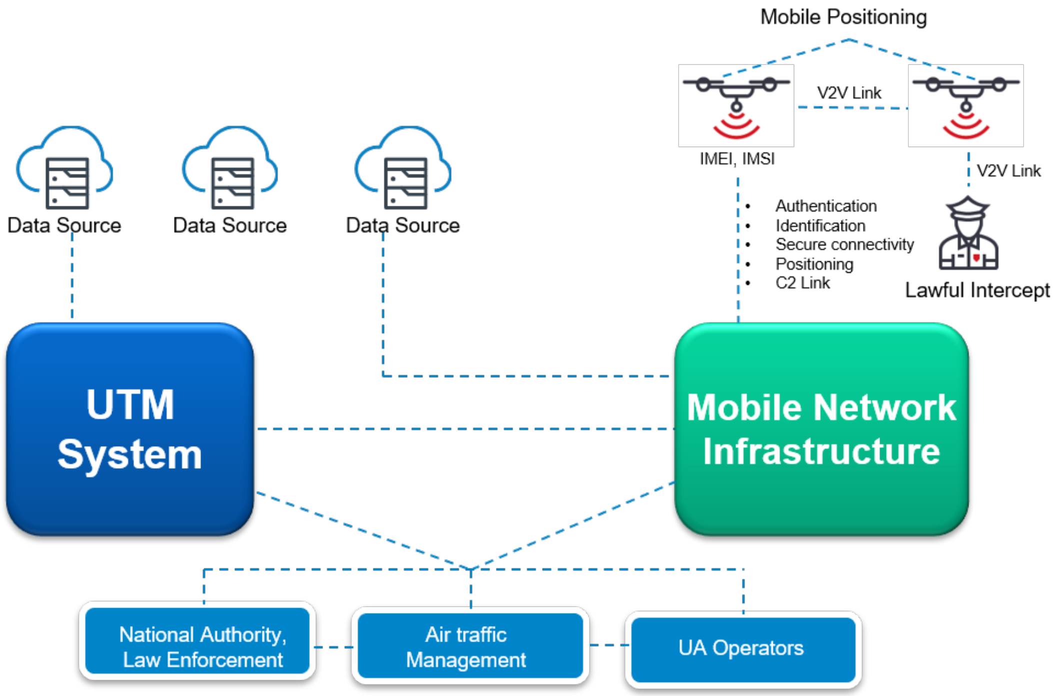

Figure 4.3. Mobile Network & UTM Interaction.[28]

4.2.4 5G QOS REQUIREMENTS FOR UAV

It is important to provision UAS services by guaranteeing QoS for the C2 communication.

4.2.4.1 UAS COMMANDS AND CONTROL (C2) USE CASE

Based on the 3GPP requirements (TS 22.829), the UAS Command and Control (C2) use case requires the consideration of safety concerns, including the risk of mid-air collision with another UAV, the risk of loss of control of a UAV, the risk of intentional misuse of a UAV, and the risk of various UAS users, for example, business, leisure, and others sharing the airspace. Therefore, to avoid the safety risks, when considering the 5G network as the transport network, it is important to provision UAS services by guaranteeing QoS for the C2 communication. Figure 4.4 depicts the four different types of communications models in the C2 use case.

[28] GSMA: Using Mobile Networks to Coordinate Unmanned Aircraft Traffic 2018.

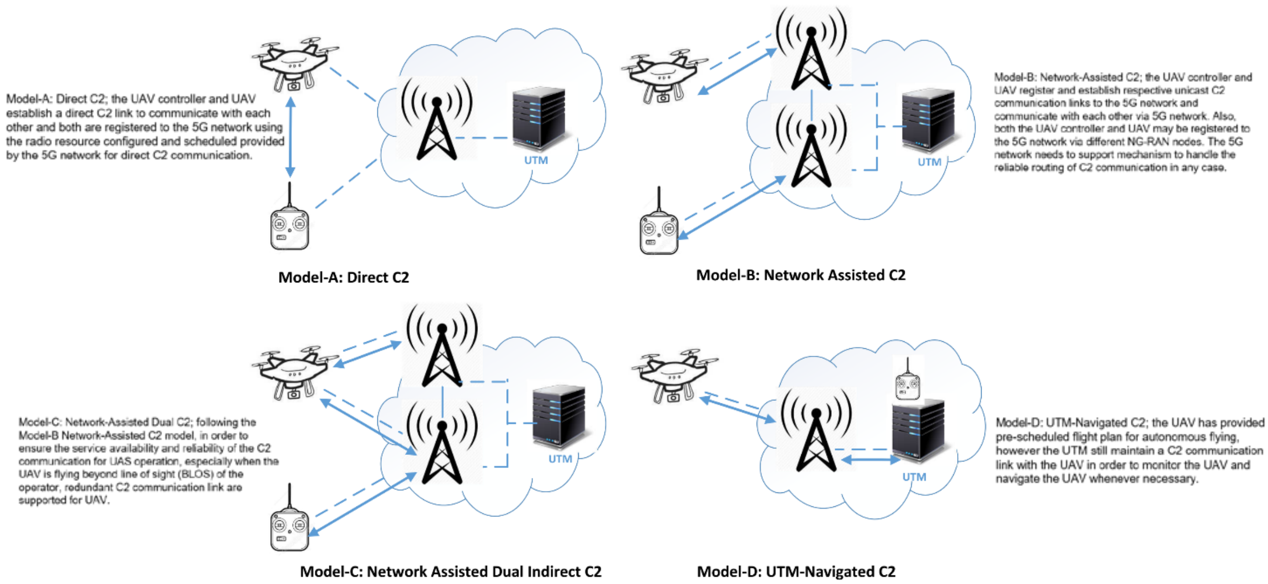

Figure 4.4. Four C2 Communication Models.[29]

Note: blue arrows show C2 communication links

To avoid the risk for losing control of the UAV, it is critically important to maintain 5G connectivity for C2 communication.

Similarly, the bandwidth and latency KPIs for different traffic types can be considered for C2 communication via the 3GPP network as provided in Table 4.1.

Table 4.1. KPIs for the Considered Use Cases for C2 Communications.[30]

Traffic Type for C2	Bandwidth	Latency
Command and Control	0.001 Mbps	VLOS: 10 ms Non-VLOS: 360 ms
Telemetry	0.012 Mbps w/o video	1 sec
Real-Time	0.06 Mbps w/o video	100 ms
Video Streaming	4 Mbps for 720p video 9 Mbps for 1080p video [30 Mbps for 4K Video]: optional	100 ms
Situation Aware report	1 Mbps	10-100 ms

Furthermore, according to the type of the UAS services, some types of traffic may require higher priority in C2 communication for responding to urgent events, for example the, sudden appearance of a flock of birds in the UAV's flight path. As a result, based on 3GPP, the 5G system shall support a mechanism to provision

[29] 3GPP TS 22.829.
[30] 3GPP TS 22.829.

the required QoS, priority, and reliability for one or more C2 communication sessions between the UAV and UAV controller.

4.2.4.2 USE CASE OF SIMULTANEOUS SUPPORT OF DATA TRANSMISSION FOR UAVS AND EMBB USERS

Another 3GPP use case requiring guaranteed QoS for UAVs is the simultaneous support of data transmission for UAVs and eMBB users. Under limited bandwidth resources, a base station may need to support the simultaneous data transmission for UAVs in the air and for eMBB users on the ground. For example, in live broadcast scenarios, a UAV over 100 meters in altitude needs to transmit the captured pictures or video to the base station in real-time, which requires a high transmission rate to support the large bandwidth. At the same time, the base station also needs to provide the required QoS for ground users (for example, eMBB users.) The 3GPP standard dictates that interference between these two types of communication shall be minimized.

4.2.4.3 USE CASE FOR AUTONOMOUS UAVS CONTROLLED BY AI

The use case for autonomous UAVs controlled by Artificial Intelligence (AI) essentially has the following steps:

1) The UAVs collect real-time information (including high precision three-dimensional surface topographic data, real-time pictures, real-time video)
2) This real-time information is transmitted to the AI system via the 5G network
3) The flight path of the aircraft in a fixed route is processed by the AI system, and the AI system processes the proper calculation
4) These instructions are sent to the UAV via the 5G network

In the case of a UAV controlled by AI, the UAV's requirements of the wireless network to provide both a high uplink transmission rate and a low delay downlink rate need to be considered. The 5G system will be able to provide the required QoS (for example, reliability, end-to-end latency, and bandwidth) for a service to support the prioritization of resources when necessary, along with providing high precision positioning information to the AI system to assist in the calculation and decision-making process for UAV flight.

4.2.4.4 USE CASE: RADIO ACCESS NODE ON BOARD A UAV

From the wireless communication perspective, using a radio access node on board a UAV (therefore, UAV evolved NodeB/ next generation NodeB/ next generation-evolved, User Defined NodeB (eNB/gNB/ng-eNB, UxNB) has already attracted interest from the community, especially using UxNB to enhance coverage in variety of scenarios. For example, emergency situations, temporary coverage for mobile users and hotspot events due to their fast deployment and large coverage capabilities.

TR 38.811 documents the radio aspects of using Unmanned Aircraft Systems (UAS), including High Altitude Platform Stations (HAPS), as a base station. In TR 38.811 the altitude of the UAS can be between 8 km and 50 km. Due to its lower altitude, usually around 100 meters (m), a UAV with an on-board base station (for example, UxNB) is more flexible than that of a UAS from a coverage and speed of deployment perspective. The UxNB acts as either a base station or a relay, as shown in Figures 4.5 and 4.6.

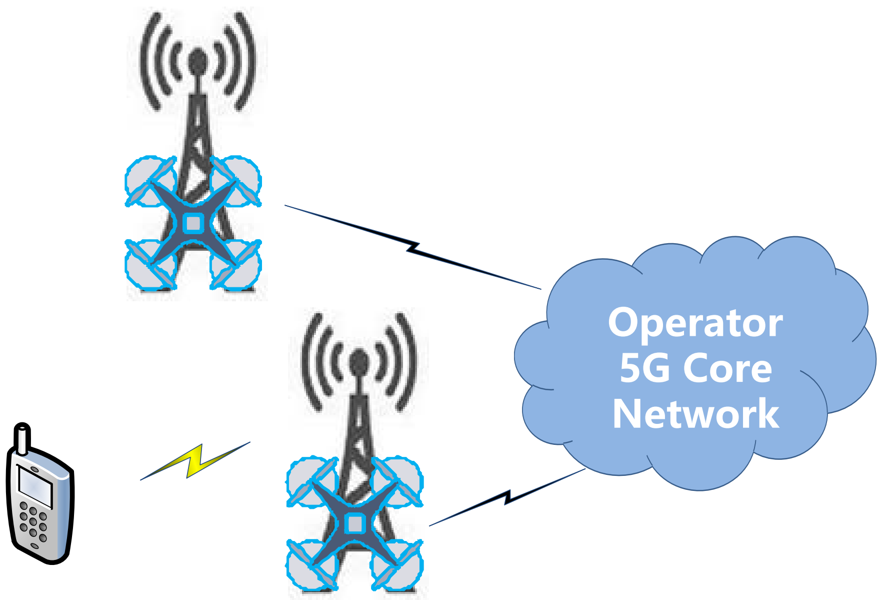

Figure 4.5. UxNB Acts as Base Station.[31]

Figure 4.6. UxNB Acts as Relay.[32]

4.3 REQUIREMENTS AND KPIS ON 5G

Table 4.2 is a summary of the KPIs highlighted in the 3GPP TR 22.829 standard.

[31] 3GPP TR 38.811: https://www.3gpp.org/DynaReport/38-series.htm.
[32] 3GPP TR 38.811: https://www.3gpp.org/DynaReport/38-series.htm.

Table 4.2. Consolidated KPIs for UAV.[33]

	Services	Uplink data rate(UAV to Net) Note 7	Service control data rate(Net to UAV)	Data latency	Control latency	Position-ing accuracy	Altitude	Higher accuracy location latency	Region
1	8K video live broadcast	100 Mbps	600 Kbps	200 ms	20 ms	0.5 m	<100 m	-	Urban, scenic area
2	Laser mapping/ HD patrol	120 Mbps Note 1	300 Kbps	200 ms	20 ms	0.5 m	30-300 m	-	Urban, rural area, scenic area
3	4*4K AI surveillance	120 Mbps	50 Mbps	200 ms	40ms Note 2	0.1m	<200 m	10 ms Note 3	Urban, rural area
4	Remote UAV controller through HD video	>=25 Mbit/s Note 4	300Kbit/s	100 ms	20 ms	0.5m	<300 m Note 5	-	Urban, rural area
5	Telemetry	0.012 Mbps w/o video	Note 6	-	Note 6	-	-	-	Urban, rural, countryside
6	Real-Time Video	0.06 Mbps w/o video	Note 6	100 ms	Note 6	-	-	-	Urban, rural, countryside
7	Video streaming	4 Mbps for 720p video 9 Mbps for 1080p video	Note 6	100 ms	Note 6	-	-	-	Urban, rural, countryside

NOTE 1: The flight average speed is 60km/h.
NOTE 2: The latency is two-way network delay, therefore, UAV to Net plus Net to UAV.
NOTE 3: The latency is the time of the 5G system provide higher accuracy location information of a UAV to a trusted third party.
NOTE 4: Referring to TS 22.125 [8] clause 5.3, the absolute flying speed of UAV in this service can be up to 160km/h.
NOTE 5: Referring to TR 36.777 [10], the maximum altitude is 300 m.
NOTE 6: Relevant KPIs refer to Table 7.X.2-1. The KPIs is also compatible for service 1~4.
NOTE 7: In addition to service data, it is possible to transmit the following UAV management parameters simultaneously.

- **Flight time of UAV**
- **Real-time Position, Height and Moving Speed of UAV**
- **Vibration Coefficient and Sloshing Coefficient of UAV**
- **Current pitch angle, heading angle and roll angle of UAV**
- **Status of Airborne Sensors such as Gyroscope and Barometer of UAV**
- **Working state of UAV satellite positioning module**
- **Battery Volume and Working State of Unmanned Aerial Vehicle**
- **UAV Control Link State**

[33] *Enhancement for Unmanned Aerial Vehicles (UAVs),* Rel-16, 3GPP TS 22.829. 2018.

4.3.1 FRAMEWORK FOR STEERING KPIS OF UAV

UAVs may be steered remotely by the UAV controller or from the UTM. Several modes of UAV steering can be considered. The choice of mode depends on the UAV itself, the source of the control, and the operational situation.

Each of these modes dictates its own requirements for communication KPIs in terms of data rate, message rate, reliability, latency and may require immediate feedback to the pilot. Video is used in some modes as additional feedback to the pilot.

All KPIs are defined at an application service layer. Video feedback is neither required nor expected to be used for steering in this mode.

Table 4.3. KPIs for Mode-A "Waypoints" UAV Control.[34]

Function	Message Interval	Message Size	Latency	Reliability (Note 2)	Direction	Positive ACK required	Comments
Steering control message	1-indefinite, S	100 B (Note 1)	1 s	99.9 percent	Net to UAV	Y	
Steering feedback message	1 s	84-140 B	1 s	99.9 percent	UAV to Net (Note 3)	N	It may be possible to transmit this message on an event driven basis for example, approaching a geo fence

Note 1: Varies based on type of command. Sending a new mission requires more data than pausing a mission, for example. Message size is payload only and excludes all headers, security, and etcetera

Note 2: Message reliability is defined as the probability of successful transmission within the required latency

Note 3: This feedback messages can be sent to both UAV controller and to the UTM

[34]*Enhancement for Unmanned Aerial Vehicles (UAVs),* Rel-16, 3GPP TS 22.829. 2018.

Table 4.4. KPIs for Mode-B "Stick and Rudder" UAV Control.[35]

Function	Message Interval	Message Size (Note 1)	Latency	Reliability (Note 2)	Direction	Positive ACK required	Comment
Steering control message	40 ms (Note 3)	24 B	40 ms	99.99 percent	Net to UAV	Y	
Steering feedback message	100 ms	84-140 B	140 ms	99.99 percent	UAV to Net	N	A 1 Hz slow mode also exists

Note 1: Message size excludes headers and security

Note 2: Message reliability is defined as the probability of successful transmission within the required latency

Note 3: UAVs on board controllers typically update at either 50 Hz (20ms) or 25Hz (40ms)

Table 4.5. KPIs for Video Feedback.[36]

Scenario	Data rate	Latency	Reliability (Note 1)	Direction	Positive ACK required	Comment
VLOS (visual line of sight)	2 Mpbs at 480 p, 30 fps	1 s	99.9 percent	UAV to Net	N	
Non-VLOS	4 Mbps at 720 p, 30 fps	140 ms	99.99 percent	UAV to Net	N	

Note 1: Message reliability is defined as the probability of successful transmission within the required latency

4.3.1.1 UAV PERFORMANCE

Based on 3GPP standards, the flight performance of UAV shall meet the requirements from Table 4.6.

Table 4.6. KPIs of UAV Performance.[37]

Working height	Flight speed	Horizontal hovering accuracy	Vertical hovering accuracy	Maximum climb rate	Maximum decline rate	Roll Angle stability	Pitch stability	Deviation stability
<=400 m	<=120 km/h	>=2 m	>=2 m	5 m/s	3 m/s	±0.5 °	±0.5 °	±0.5 °

4.4 DEPLOYMENT STATUS

Depending upon the location, the use and the mobility requirements, there are different possible deployment scenarios for UAV radio access, and several are described in the following sections.

[35] *Enhancement for Unmanned Aerial Vehicles (UAVs),* Rel-16, 3GPP TS 22.829. 2018.
[36] *Enhancement for Unmanned Aerial Vehicles (UAVs),* Rel-16, 3GPP TS 22.829. 2018.
[37] *Enhancement for Unmanned Aerial Vehicles (UAVs),* Rel-16, 3GPP TS 22.829. 2018.

4.4.1 ISOLATED DEPLOYMENT OF RADIO ACCESS THROUGH UAV

A UAV has limited flying time available which impacts the overall operating time of the network equipment that is installed on a UAV. There are scenarios where a UAV is deployed to a remote or isolated location and where no backhaul connectivity is available for communication between a private group of users. Thus, a UAV carrying network equipment is dispatched as an airborne network where no ground communication infrastructure exists. The UAV's weight and battery capacity limit the airborne network maximum flying time.

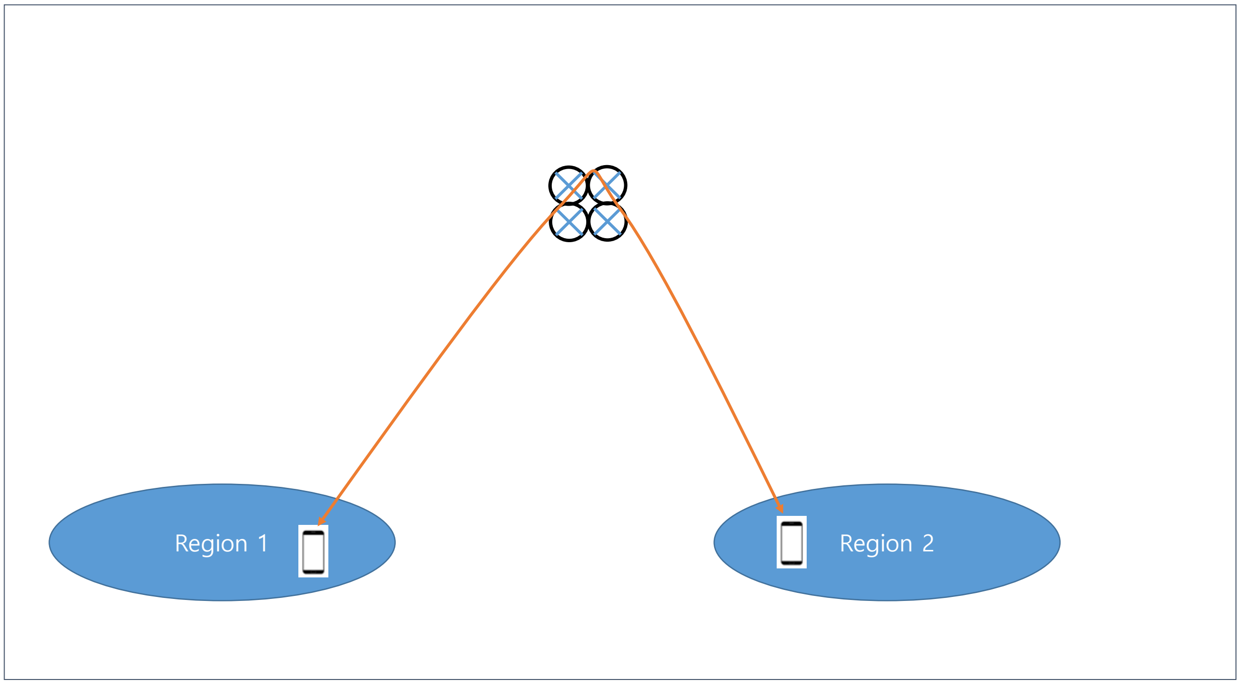

Figure 4.7. Use of Airborne Network for an Isolated Situation.[38]

Figure 4.7 is an example of a project taking place in a remote area where no wireline communication equipment is installed, with two remote operation regions. To assist communication between the site equipment and workers, it is decided to use an airborne network. The airborne network is located where it can provide communication service for the UEs both in region 1 and in region 2. Workers and equipment cans move between the two regions. The UAV, with the mounted network equipment, adjusts its location to provide optimal communication services while minimizing power consumption. Communication service among the UEs covered by the airborne network is possible, and as a result, the UEs on the ground identify to which UEs they can communicate before actually transmitting data.

4.4.2 RADIO ACCESS THROUGH UAVS

Based on the 3GPP TR22.829 document, UAVs currently available have a limited flying time, typically in the range of 10 minutes to 1 hour. Due to complex relationships among weight, battery power, payload, aerodynamics, controllability, regulations and so on, the flying time cannot be increased arbitrarily.

[38] *Enhancement for Unmanned Aerial Vehicles (UAVs),* Rel-16, 3GPP TS 22.829. 2018.

When a UAV is functioning as a flying radio access network, the weight of the UAV will increase due to the payload of radio access network equipment. This, in turn, will further reduce the actual achievable flight time of the UAV.

The effectiveness of a UAV as a mobile radio access network platform will further be impacted by deployment scenarios. For example, a flying radio access network is typically required for the area where ground-based radio access network equipment cannot be installed. So, the UAV has to fly some distance from the base area to the remote area, and the UAV has to fly back to base camp before it runs out of power. This is shown in Figure 4.8.

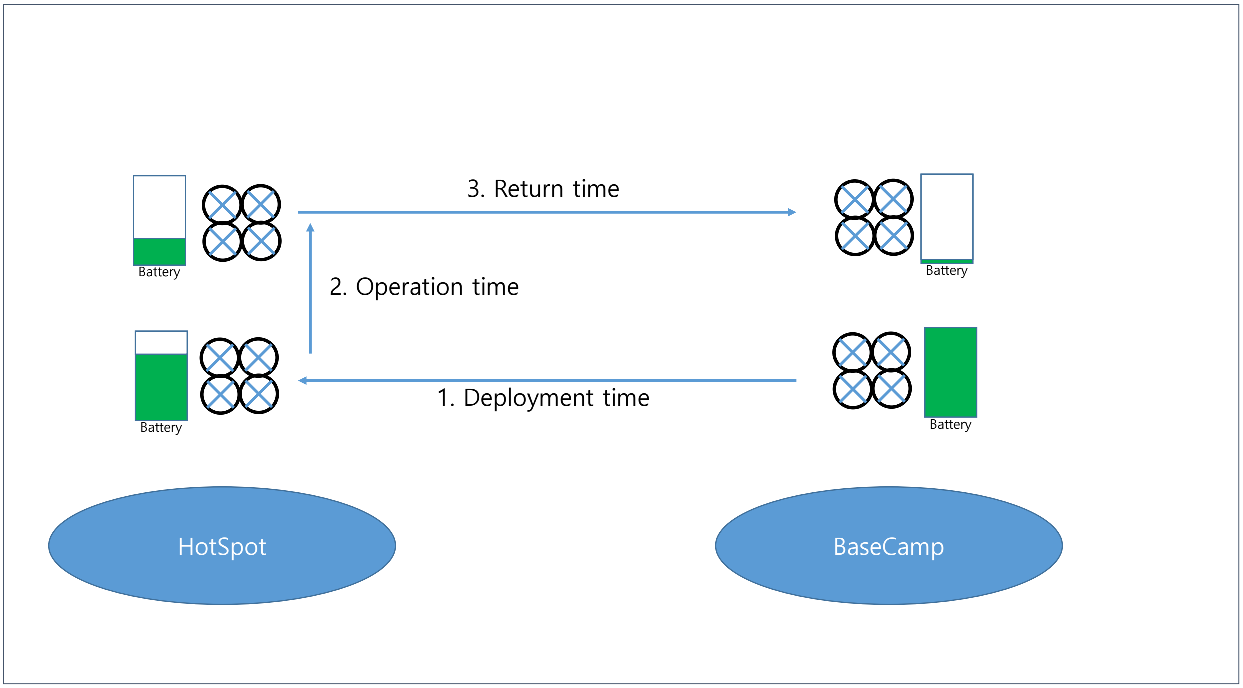

Figure 4.8. Time Analysis of UAV Operation.[39]

The total amount of time for each operation in Figure 4.8 should be smaller than the maximum flying time of the UAV. Therefore, the actual operation time for the flying radio access network will be even smaller.

To provide continuous communication services through UAVs, several UAVs are needed to replace UAVs whose batteries are exhausted.

4.4.3 SEPARATION OF UAV SERVICE AREAS

Existing networks have antennas for cellular communication mounted on cell towers and tilted in a slight downward direction since humans are typically either on the ground or in a building.

[39] *Enhancement for Unmanned Aerial Vehicles (UAVs),* Rel-16, 3GPP TS 22.829. 2018.

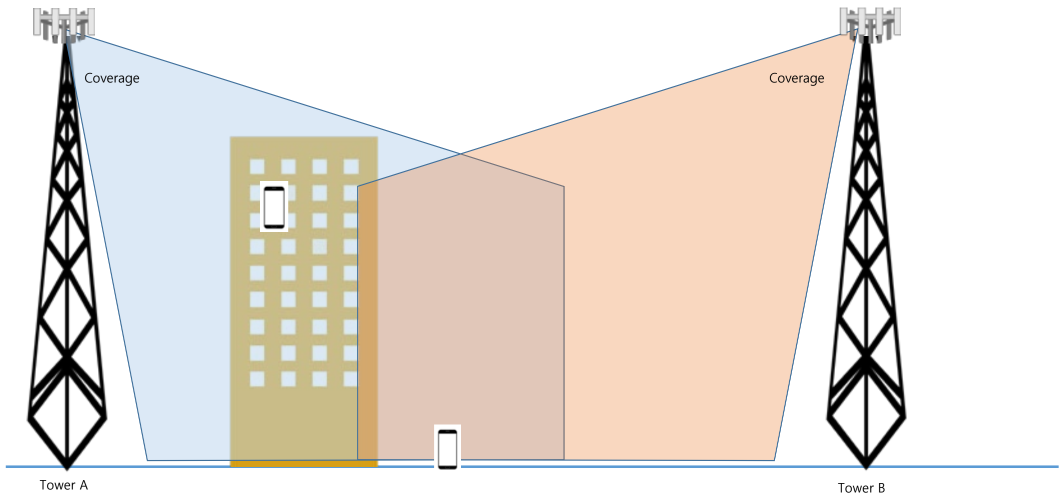

Figure 4.9. Coverage Provided by Cell Tower for Typical Users.[40]

With the introduction of communication services to UAVs, some UEs are located above conventional coverage. Thus, there is a need to adjust the antenna systems so that there is coverage at the height where UAVs operate. In some cases, additional equipment can be installed. This is illustrated in Figures 4.10 and 4.11.[41]

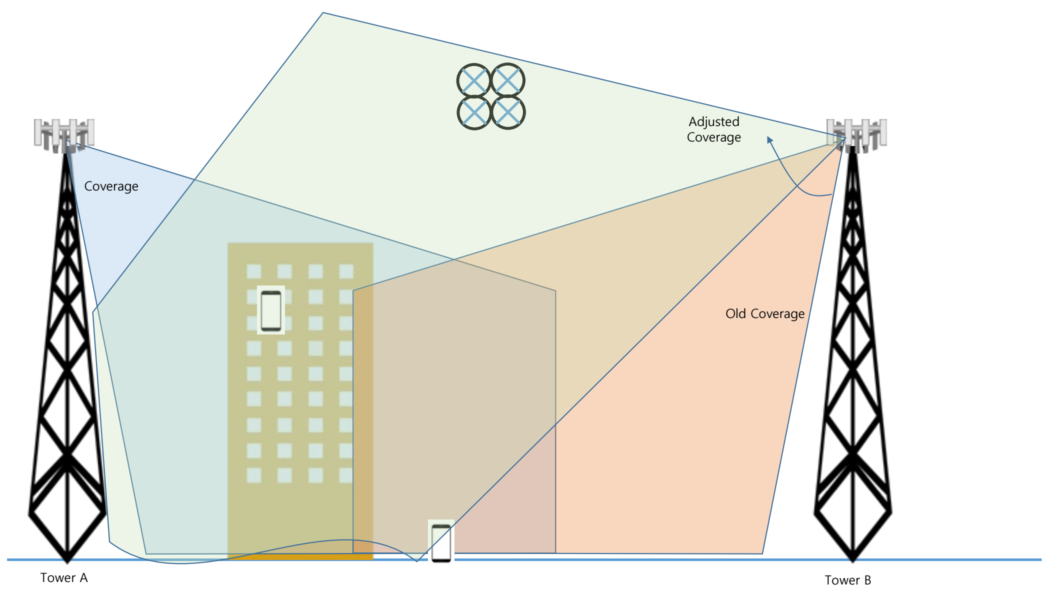

Figure 4.10. Change of Tilting to Accommodate UAV.

[40] *Enhancement for Unmanned Aerial Vehicles (UAVs),* Rel-16, 3GPP TS 22.829. 2018.
[41] *Enhancement for Unmanned Aerial Vehicles (UAVs),* Rel-16, 3GPP TS 22.829. 2018.

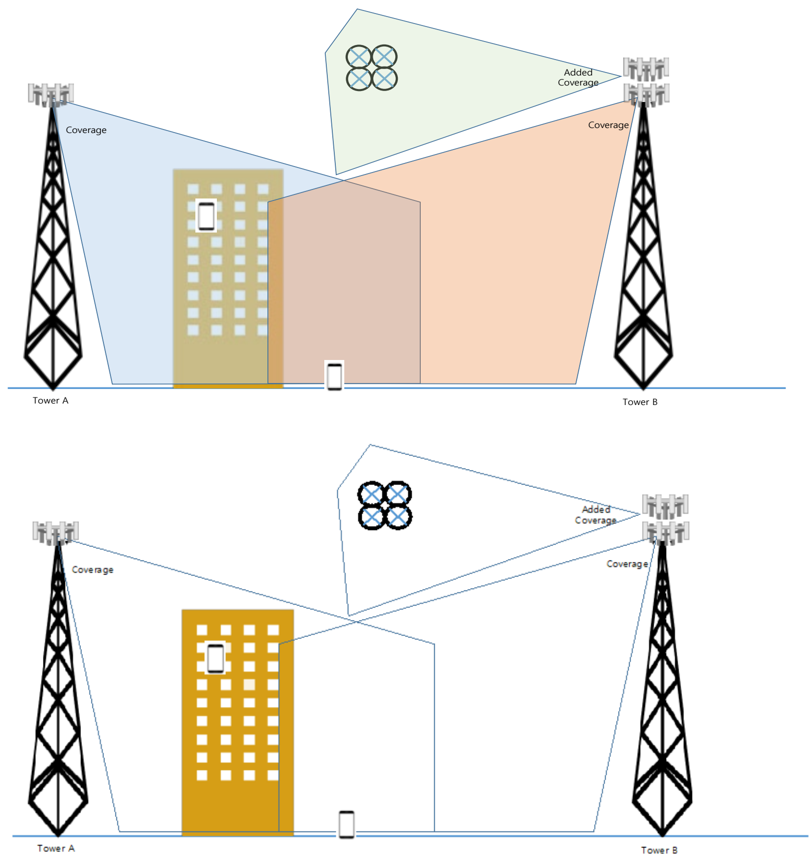

Figure 4.11. Addition of Equipment to Accommodate UAV.

As a result, it is necessary to differentiate service offerings to various UEs. In the above scenario, where and what can be provided to UAV UEs is different from where and what can be provided for other non-UAV UEs.

4.5 KEY CHALLENGES TO 5G UAVS

4.5.1 NR MODIFICATIONS TO SUPPORT THE NON-TERRESTRIAL NETWORK DEPLOYMENT SCENARIOS

Based on 3GPP TR 38.811, 5G New Radio (NR) impacts are identified for each deployment scenario. For each of the NR features that may require adaptations to support NR operation via satellites or HAPS, the problems or issues are stated, their effects are listed, and potential areas of impact on NR protocol are identified in Table 4.7.

Table 4.7. Areas of Impact on NR to Support Non-Terrestrial Networks.[42]

Non-Terrestrial Network Specifics	Effects	Impacted NR Features
Motion of the space/aerial vehicles (especially for Non-GEO based access network)	Moving cell pattern	Hand-over/paging
	Delay variation	TA adjustment
	Doppler	Init synchro downlink
		DMRS time density
Altitude	Long latency	HARQ
		MAC/RLC Procedures
		Physical layer Procedures (ACM, power control)
Cell size	Differential delay	TA in Random access response message
		RACH
Propagation channel	Impairments	DMRS frequency density
		Cyclic prefix
Duplex mode	Regulatory constraints	Access scheme (TDD/FDD)
Satellite or aerial Payload performance	Phase noise impairment	PT-RS
	Back-off	PAPR
Network architecture	RAN Mapping	Protocols

Satellite and Aerial systems operate in allocated frequency bands as per International Telecommunication Union-Radiocommunication Sector (ITU-R)/national allocation regime.[43]

5. USE CASE: NON-TERESTRIAL NETWORKS WITH 5G

Similar to the anticipation that 5G will revolutionize the telecommunications industry, the space industry is also on the precipice of a similar revolution as a result of innovation and investment in the areas of Low Earth Orbit (LEO) satellites and High-Altitude Platform Station (HAPS) systems.

5.1 INTRODUCTION

Ventures such as Amazon’s Project Kuiper, Elon Musk's SpaceX Starlink and OneWeb aim to establish constellations of LEO satellites ranging in size from hundreds to thousands of individual satellites, while companies like Airbus and Alphabet Inc. spin off Loon, among others, are developing fleets of HAPS vehicles that will continually fly in the Stratosphere. These LEO and HAPS systems represent a new opportunity for network operators around the globe to establish Non-Terrestrial Networks (NTN) which can serve any number of use cases that would otherwise be difficult via traditional earthbound networks. Some of the more prevalent or commonly considered use cases include Rural or Remote Connectivity, Agriculture, Transportation and Public Safety coupled with Disaster Recovery.

[42] *Study on New Radio (NR) to support non-terrestrial networks,* Rel-15, 3GPP TR 38.811. 2018.
[43] *Study on New Radio (NR) to support non-terrestrial networks*, Rel-15, 3GPP TR 38.811. 2018.

5.2 ARCHITECTURE

Non-Terrestrial Network access typically features the following system elements:

- **NTN Terminal:** 3GPP UE or a terminal specific to a satellite (if the satellite doesn't directly serve 3GPP UEs)
- **Service link:** The radio link between the user equipment and the space/airborne platform. Additionally, the UE may also support a radio link with a terrestrial-based RAN
- **Space or an airborne platform:** A platform which may implement either a bent pipe or a regenerative payload configuration:
  - Bent Pipe payload: Radio frequency filtering, frequency conversion and amplification
  - Regenerative payload: Radio frequency filtering, frequency conversion and amplification as well as demodulation/decoding, switch and/or routing, coding/modulation. This is effectively equivalent to having base station functions (for example, gNB) on board the space/airborne vehicle
- **Inter-satellite (ISL)/inter-aerial links (IAL):** In the case of regenerative payloads and a constellation of satellites, ISLs may operate in RF frequencies or optical bands.
- **Gateways:** Systems connect the satellite or aerial access network to the core network
- **Feeder links:** The radio links between the gateways and the space/airborne platform

It is also helpful to distinguish between satellite and UAV systems with inter-satellite links (ISL) or inter-aerial links (IAL) and those without ISL/IALs.

For UAV networks, the configuration of base station functions onboard the airborne vehicle is to provide the 5G service to handheld devices.

The possible options of NTN (Non-terrestrial Network) architecture are depicted in Figures 5.1 through 5.4.[44]

Figure 5.1. NTN Featuring an Access Network Serving UEs and Based on a Satellite/Aerial with Bent Pipe Payload and gNB on the Ground (Satellite Hub or Gateway Level).[45]

This will be referred to as Architecture A1 where the satellite or the UAV will relay a "Satellite friendly" NR signal between the gNB and the UEs in a transparent manner.

[44] *Study on New Radio (NR) to support non-terrestrial networks,* Rel-15, 3GPP TR 38.811. 2018.
[45] *Study on New Radio (NR) to support non-terrestrial networks,* Rel-15, 3GPP TR 38.811. 2018.

Figure 5.2. NTN Featuring an Access Network Serving UEs and Based on a Satellite/Aerial with gNB on Board.[46]

The architecture depicted in Figure 5.2 will be referred to as architecture A2 where the satellite or the UAV includes all, or part, of a gNB to generate/receive a "Satellite friendly" NR signal to/from the UEs. This requires sufficient onboard processing capabilities to be able to deploy gNB or Relay Node functions.

Figure 5.3. NTN Featuring an Access Network Serving Relay Nodes and Based on a Satellite/Aerial with Bent Pipe Payload.

The architecture from Figure 5.3 is referred to as A3 where the satellite or the aerial will relay a "Satellite friendly" NR signal between the gNB and the Relay Nodes in a transparent manner.

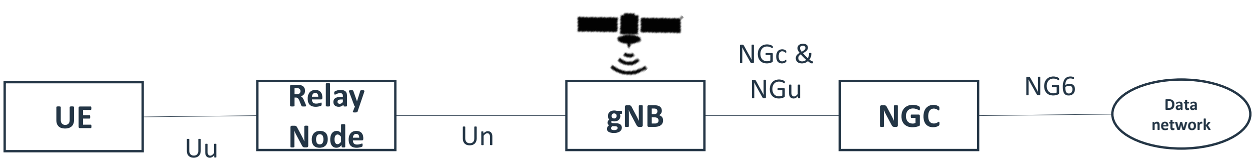

Figure 5.4. NTN Featuring an Access Network Serving Relay Nodes and Based on a Satellite/Aerial with gNB.

The last architecture, depicted in Figure 5.4, will be Architecture A4; the satellite or the aerial includes all, or part of, a gNB to generate/receive a "Satellite friendly" NR signal to/from the Relay Nodes. This requires sufficient onboard processing capabilities to be able to deploy gNB or a Relay Node functionality.

Note: In the Figures 5.1 through 5.4, a satellite represents both satellite and aerial platforms.

[46]*Study on New Radio (NR) to support non-terrestrial networks,* Rel-15, 3GPP TR 38.811. 2018.

Table 5.1. 5G System Elements Mapping in NTN Architecture.[47]

5G Elements - NTN Elements Mapping			
NTN Architecture Options	**NTN Terminal**	**Space or HAPS**	**NTN Gateway**
A1: access network serving UEs via bent pipe satellite/aerial	UE	Remote Radio Head (Bent pipe relay of Uu radio interface signals)	gNB
A2: access network serving UEs with gNB on board satellite/aerial	UE	gNB or Relay Node functions	Router interfacing to Core network
A3: access network serving Relay Nodes via bent pipe satellite/aerial	Relay Node	Remote Radio Head (Bent pipe relay of Uu radio interface signals)	gNB
A4: access network serving Relay Nodes with gNB on board satellite/aerial	Relay Node	gNB or Relay Node functions	Router interfacing to Core network

5.3 REQUIREMENTS AND KPIS ON 5G

5.3.1 CHARACTERISTICS OF NTN (NON-TERRESTRIAL NETWORKS) TERMINALS FOR SATELLITE/AERIAL ACCESS NETWORK

Table 5.2 provides the minimum RF characteristics of the terminals operating respectively in Ka band (for example, very small aperture terminals) and in S band (for example, handheld terminals).

Table 5.2. Typical Minimum RF Characteristics of UE in Satellite and Aerial Access Networks.[48]

	Very Small Aperture Terminal (fixed or mounted on moving platforms)	Handheld or IoT devices (3GPP class 3, see [2])
Transmit Power	2 W (33 dBm)	200 mW (23 dBm)
Antenna type	60 cm equivalent aperture diameter (circular polarization)	Omnidirectional antenna (linear polarization)
Antenna gain	Tx: 43.2 dBi Rx: 39.7 dB	Tx and Rx: 0 dBi
Noise figure	1.2 dB	9 dB
EIRP	45.75 dBW	-7 dBW
G/T (NOTE 1)	18.5 dB/K	-33.6 dB/K
Polarization (NOTE 2)	Circular	Linear

NOTE 1: For the computation of G/T or figure of merit, following formula applies in dB:

G/T = Ga – NF – 10*LOG (To+(Ta-To)/(10^0.1*NF))

$$G/T = Ga - NF - 10 \cdot \log\left(To + (Ta - To)/(10^{0.1 \cdot NF})\right)$$

Where:

- **Antenna Gain: Ga in dBi**
- **Ambient Temperature: T0 (usually 290 K)**
- **Antenna Temperature: Ta (typically 290 K with 0 dBi gain and 150 K with >30 dBi gain)**
- **Noise Figure: NF in dB**

NOTE 2: For S band, we assume that the User Equipment has an omni-directional antenna of linear polarization, while the antenna on board space-borne or airborne platforms features typically employs circular polarization. Hence a polarization mismatch of 3 dB has to be taken into account for the radio link budget computation. This will impact the UE RF characteristics as below:

- **Equivalent EIRP of 20 dBm (-10 dBW) under satellite coverage**
- **Equivalent G/T of -36,6 dB/K under satellite coverage**

[47] *Study on New Radio (NR) to support non-terrestrial networks,* Rel-15, 3GPP TR 38.811. 2018.
[48] *Study on New Radio (NR) to support non-terrestrial networks,* Rel-15, 3GPP TR 38.811. 2018.

5.3.2 COVERAGE PATTERN OF NTN

Satellite or aerial vehicles typically generate several beams over a given area where the footprint of the beams is typically elliptic shaped.

The beam footprint may be moving over the earth with either the satellite or the aerial vehicle motion on its orbit. Alternatively, the beam footprint may be earth-fixed, and in such case some beam pointing mechanisms (mechanical or electronic steering features) will compensate for the satellite or the aerial vehicle motion.

Table 5.3. Typical Beam Foot Print Size.[49]

Attributes	GEO	Non-GEO	Aerial
Beam footprint size in diameter	200 – 1000 km	100 – 500 km	5 - 200 km

Typical beam patterns of various NTN access networks are depicted in Figure 5.5.

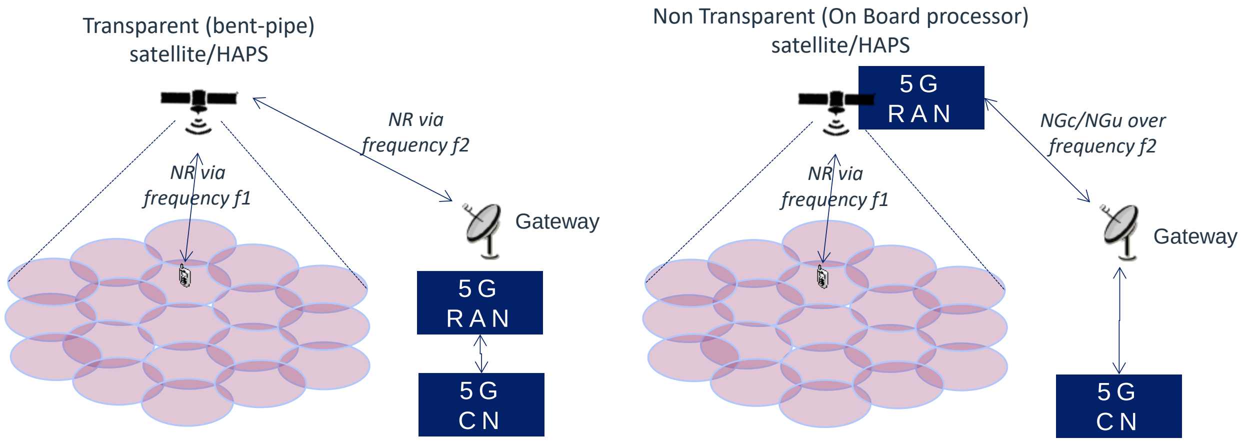

Figure 5.5. NTN Beam Patterns.[50]

5.4 DEPLOYMENT STATUS

3GPP has about 11 reference deployment scenarios selected for study and evaluation of Non-Terrestrial Networks.

5.4.1 NR NON-TERRESTRIAL NETWORKS (NTN) DEPLOYMENT SCENARIOS

The Non-Terrestrial Network (NTN) reference deployment scenarios in Table 5.4 have been selected by 3GPP for the study and used for evaluations.[51]

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[49] *Enhancement for Unmanned Aerial Vehicles (UAVs),* Rel-16, 3GPP TS 22.829. 2018.
[50] *Enhancement for Unmanned Aerial Vehicles (UAVs),* Rel-16, 3GPP TS 22.829. 2018.
[51] *Study on New Radio (NR) to support non-terrestrial networks,* Rel-15, 3GPP TR 38.811. 2018.

Table 5.4. Reference Non-Terrestrial Network Deployment Scenarios to be Considered in the NR-NTN Study.

Main Attributes	Deployment-D1	Deployment-D2	Deployment-D3	Deployment-D4	Deployment-D5
Platform orbit and altitude	GEO at 35 786 km	GEO at 35 786 km	Non-GEO down to 600 km	Non-GEO down to 600 km	UAS between 8 km and 50 km including HAPS
Carrier Frequency on the link between Air / space-borne platform and UE	Around 20 GHz for DL Around 30 GHz for UL (Ka band)	Around 2 GHz for both DL and UL (S band)	Around 2 GHz for both DL and UL (S band)	Around 20 GHz for DL Around 30 GHz for UL (Ka band)	Below and above 6 GHz
Beam pattern	Earth fixed beams	Earth fixed beams	Moving beams	Earth fixed beams	Earth fixed beams
Duplexing	FDD	FDD	FDD	FDD	FDD
Channel Bandwidth (DL + UL)	Up to 2 * 800 MHz	Up to 2 * 20 MHz	Up to 2 * 20MHz	Up to 2 * 800 MHz	Up to 2 * 80 MHz in mobile use and 2 * 1800 MHz in fixed use
NTN architecture options	A3	A1	A2	A4	A2
NTN Terminal type	Very Small Aperture Terminal (fixed or mounted on Moving Platforms) implementing a relay node	Up to 3GPP class 3 UE	Up to 3GPP class 3 UE	Very Small Aperture Terminal (fixed or mounted on Moving Platforms) implementing a Relay node	Up to 3GPP class 3 UE [2] Also Very Small Aperture Terminal
NTN terminal Distribution	100 percent Outdoors	100 percent Outdoors	100 percent Outdoors	100 percent Outdoors	Indoor and Outdoor
NTN terminal Speed	up to 1000 km/h (for example, aircraft)	up to 1000 km/h (for example, aircraft)	up to 1000 km/h (for example, aircraft)	up to 1000 km/h (for example, aircraft)	up to 500 km/h (for example, high speed trains)
Main rationales	GEO based indirect access via relay node	GEO based direct access	Non-GEO based direct access	Non-GEO based indirect access via relay node	Support of low latency services for 3GPP mobile UEs, both indoors and outdoors
Supported Uses cases	1/ eMBB: multi-connectivity, fixed cell connectivity, mobile cell connectivity, network resilience, Trunking, edge network delivery, Mobile cell hybrid connectivity, Direct To Node multicast/ broadcast	1/eMBB: Regional area public safety, Wide area public safety, Direct to mobile broadcast, Wide area IoT service	1/eMBB: Regional area public safety, Wide area public safety, Wide area IoT service	1/ eMBB: multi-homing, fixed cell connectivity, mobile cell connectivity, network resilience, Trunking, Mobile cell hybrid connectivity	1/ eMBB: Hot spot on demand

6. USE CASE: XR – AUGMENTED REALITY (AR) & VIRTUAL REALITY (VR)

eXtended Reality (XR) applications are some of the most important edge applications under consideration in the Industry. XR is an umbrella term for different types of realities as shown in Figure 6.1 and refers to all real-and-virtual combined environments and human-machine interactions generated by computer technology and wearables. It includes representative forms such as Augmented Reality (AR), Mixed Reality (MR) and Virtual Reality (VR) and the areas interpolated among them.

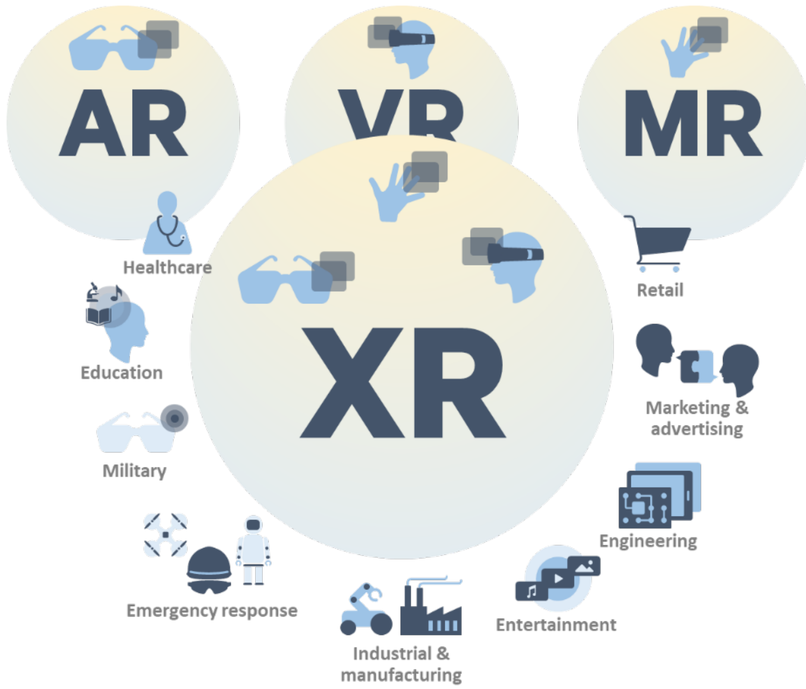

Figure 6.1. Different Types of Realities and Some Applications.

6.1 INTRODUCTION TO AR & VR

The increasing availability of products with network connectivity is expected to create an abundance of multi-dimensional data. Assimilation of such massive amounts of data by users will be a huge challenge, and AR is expected to be a key enabler.[52] Specifically, AR is expected to improve how users visualize and therefore access all the new monitoring data, how they receive and follow instructions and guidance on product operations, and even how they interact with and control the products themselves.

VR use cases were previously investigated in 3GPP TR 26.918 for the relevance of VR in the context of 3GPP. By collecting comprehensive information on VR use cases, existing technologies and subjective quality, the TR attempts to identify potential gaps and relevant interoperability points that may require further work and potential standardization in 3GPP. The TR primarily focuses on 360 degrees video and associated audio, which support 3 Degrees of Freedom (3DoF).

[52] *Why Every Organization Needs an Augmented Reality Strategy*, Harvard Business Review. November-December 2017.

XR use cases including AR are further discussed in detail in the 3GPP SA4 study item Extended Reality (XR) in 5G (TR 26.928). The following classification of use cases is identified in the document.

- **Offline Sharing of 3D Objects:** Offline sharing is used for sharing 3D models/objects and 3D Mixed Reality scenes among users
- **Real-time XR Sharing:** Video chats are captured using 3D models of people's heads, which can be rotated by the receiving party. Multiparty VR conferences support the blended representation of the participants into a single 360-degree video with a pre-recorded office background. Some of the conference participants may also be overlaid on an AR display. Shared presence using depth cameras is one of the features of this use case. In one instance, a virtual meeting space could be created, and the participants' avatars could move and interact with other avatars using 6DoF. Remote participants use an HMD and audio is binaural or spatially rendered.
- **XR Multimedia Streaming:** The typical media streaming experience is enhanced with the capability of 6DoF within a scene. 6DoF motion and interaction are allowed by changing the viewer's angle within the scene, and by head movements with a Head-Mounted Display (HMD). The stream display may occur over VR HMDs or AR glasses on a chosen augmented wall within the home, after the spatial room configuration has been analyzed. Synchronized playback and interaction with multiple co-located viewers are possible. This category covers live and on-demand streaming of XR multimedia streams, which include 2D or Volumetric video (therefore, Constrained 6DoF) streams that are rendered in XR with binaural audio as well as 3DOF and 3DOF+ immersive A/V streams
- **Online XR Gaming:** Multiplayer VR games will allow remote people to play and interact on the same game space. Users can change their in-game position by using controllers and body movements. It is possible for a game spectator to take two possible views: player's view and spectator's view. Interaction between a spectator and the players is also envisioned
- **Industrial Services:** One of the use cases considered by 3GPP in this area covers an AR guided assistant at a remote location for augmented instructions/collaboration. It requires AR glasses. A remote assistant is guiding a local person to perform maintenance on an industrial machine. The remote assistant can see in real-time, through the local person's AR glasses, the local environment and the machine to be repaired. Part of the repairing instructions are sent as overlays to the AR glasses
- **XR Mission Critical**: In this use case a team in an indoor space is equipped with mission gear that is connected to a centralized control center. There may be more than one device included in the mission gear, such as AR glasses, a 360-degree helmet-mounted camera, a microphone, binaural audio headphones and other sensors. A control center/conference server performs the role of mission support by providing XR graphics such as maps, text, location pointers of other team members or other objects/people in the surrounding, and etcetera. The mixed audio of the team members as well as audio from control center is also delivered to the team members to aid team communication and coordination. One or more drone-mounted cameras may also be used, which can be controlled by the control center or one of the members of the mission team
- **XR Conference**: This use case envisions an XR conference with multiple physically co-located and remote participants using XR to create telepresence. The shared conference space can be: 1) a physical space that is shared by local participants and sent as an immersive stream to the remote participants; 2) a virtual space that has the same layout as the physical space so that the physically

present (local) and remote participants have a similar experience while moving in the space (for example, captured via a 360-degree camera); and 3) a virtual space that is retrieved from an application server. In any of the three options the conference space might be extended with other Media Objects (for example a presentation video) retrieved from an application server

- **Spatial Audio Multiparty Call**: This use case envisions an AR multiparty call. Each party can see the other parties using 2D video streams captured by the front facing camera of a mobile phone. Alternatively, they can be displayed as avatars, for instance, when a pair of AR glasses are used at each party. Each party hears spatial audio with the audio of the other parties originating from where their avatar/video is placed on the display. Motion such as head turns are tracked to create a realistic impression that the audio is originating from that virtual direction

Worldwide shipments of XR headsets are forecast to reach 8.9 million units in 2019, up 54.1 percent from the prior year according to the International Data Corporation (IDC).[53] Global shipments are expected to reach 68.6 million in 2023 with a Compound Annual Growth Rate (CAGR) of 66.7 percent over the 2019-2023 forecast period. IDC forecasts for shipments of virtual reality headsets is 36.7 million units in 2023 with a five-year CAGR of 46.7 percent. Standalone headsets are expected to account for 59 percent of all VR headsets shipped in 2023, followed by Tethered Head-Mounted Displays (HMDs) with 37.4 percent share of shipments and Screenless Viewers accounting for the remainder. 5G is expected to provide renewed momentum towards expansion[54] of the XR market.

In the AR headset market, IDC indicates that total shipments are expected to reach 31.9 million units in 2023 with a 140.9 percent CAGR. Like VR, standalone headsets will lead the market with 17.6 million units shipped and 55.3 percent share in 2023 followed by Tethered HMDs with 44.3 percent share.

6.2 ARCHITECTURE

XR services can be delivered over 5G via a few different architectural options. In this section, device architecture and end-to-end architecture are the two XR aspects that are relevant from a 5G point of view and discussed in this section.

6.2.1 XR DEVICE ARCHITECTURE

Figure 6.2 shows a high-level view of some of the architectural options on the device side. When XR applications are enabled on the smartphone, or in the case of HMD, tethered to the smartphone, the connection to the network is via the cellular connection of the smartphone.

[53] *Augmented Reality and Virtual Reality Headsets Poised for Significant Growth, According to IDC*. March 2019.
[54] *VR Market Stall Drags on as Focus Shifts to 5G as Likely Game Changer*, Screen Plays Magazine. July 2019.

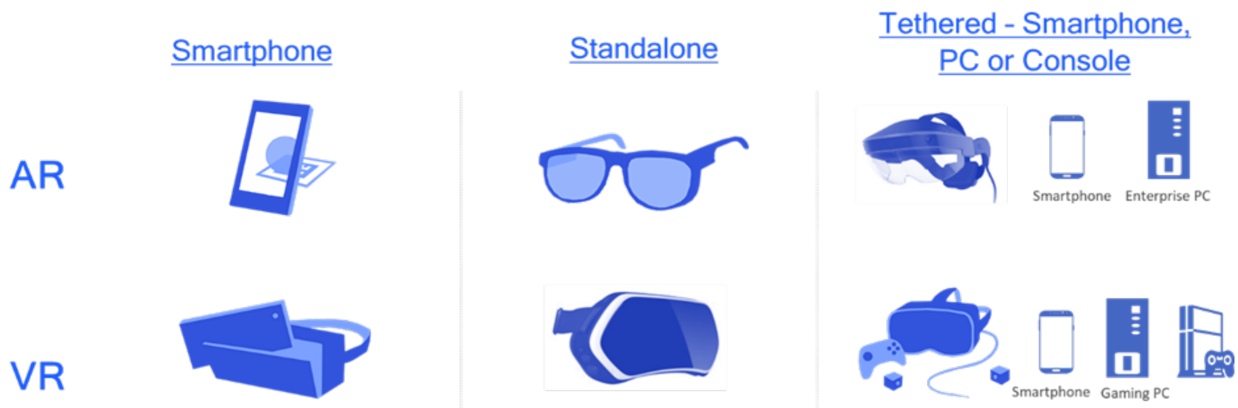

Figure 6.2. XR Device Architecture.[55]

Many smartphone-based XR applications are available as of July 2019. Smartphone VR headsets such as the Google Daydream View and the Samsung gear VR are on the lower end of the price spectrum with limited 3DOF tracking. Tethered XR headsets (for example, AR glasses tethered to a smartphone, or a VR headset tethered to a PC) can have access to higher computation processing capabilities, allowing them to deliver better user experiences in media quality, but with the inconvenience of tethering wires (for example, Universal Serial Bus (USB). Wireless tethering options include Bluetooth, Wi-Fi and 5G Sidelink. Standalone XR headsets offer the convenience of no dependency on another device, and this is the future direction of the XR device market.

Power and connection data throughputs are key considerations for both standalone and tethered XR headsets. USB tethering offers high data throughputs (for example, USB3.1 can support up to 10 Gbps[56]) and can power the tethered XR headset albeit with the inconvenience of the wires. Bluetooth offers a low power wireless connection, but data throughputs are limited (for example, maximum data rate of Bluetooth 2.0 can be limited to 2.1 Mbps[57]). Wi-Fi and 5G Sidelink are expected to provide other trade-off options in terms of data throughput and power. The wireless connection options are even more important in enabling standalone XR headsets where the power and connection data throughputs are even more challenging due to the longer range over which the wireless links must communicate.

6.2.2 XR END-TO-END ARCHITECTURE

There are several end-to-end architectural options for XR across various aspects of XR. One significant impact on the 5G connection is from the choice of the rendering architectures outlined in TR 26.928.

[55] TR 26.928.
[56] *USB 3.0*, Wikipedia. July 2019.
[57] *Bluetooth 2.0*, Wikipedia. July 2019.

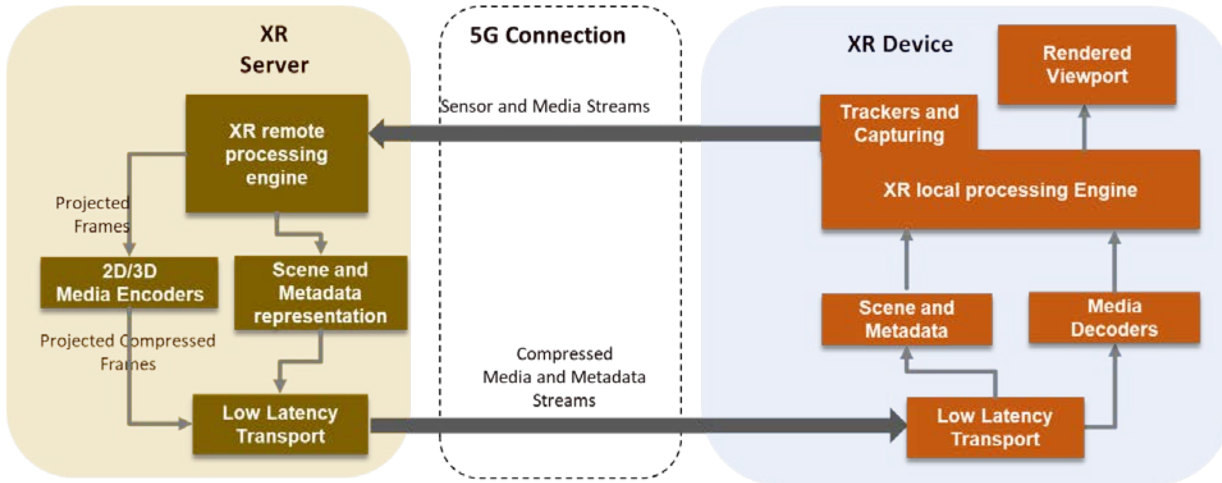

Figure 6.3. Generalized XR Architecture.[58]

Figure 6.3 shows a generalized XR architecture from TR26.928, where the 5G connection is a critical component of the architecture. The XR device collects sensory information from sensors and processes that information (for example, pose estimation or AR tracking). The collected information or processed information (for example, a current pose) is sent to the XR (Edge) Server. The XR (Edge) Server uses the information to generate/compose the XR viewport. For example, the XR device takes the captured images from a camera and sends the captured image stream to the XR (Edge) server. The XR (Edge) server performs the AR tracking and composes the AR viewport based on tracked information. The viewport, or 3D media components for the viewport, are encoded with 2D/3D media encoders and the additional metadata (including the scene description for the XR viewport) is generated. The compressed media or metadata is sent to the XR client. The XR device decodes the media or metadata stream(s) into the decoded signals and rendering metadata. The presentation engine generates the XR viewport presentation by using the decoded signals and rendering metadata and possibly other information. With the pose, a user viewport is determined by determining horizontal/vertical field of view of the screen of a Head-Mounted Display or any other display device. The appropriate part of video and audio signals for a current pose is generated by synchronizing and spatially aligning the rendered video and audio.

Other architectures (for example, device-based) impose less stringent requirements on the 5G connection compared to the generalized XR architecture described but do not take advantage of the low latency 5G connection and the availability of server-side processing for computation functions.

6.2.3 EDGE NETWORK FOR XR

The generalized XR architecture from TR26.928 assumes Edge Computing as a network architecture, and XR services driven by such architectures are some of the most important Edge applications under consideration in the industry. Edge Computing is a concept that enables cloud computing capabilities and service environments to be deployed close to the cellular network. It promises several benefits such as lower latency, higher bandwidth, reduced backhaul traffic and prospects for several new services as indicated in the 3GPP SA6 Study on application architecture for enabling Edge Applications (TR 23.758). Edge Applications are expected to take advantage of the low latencies enabled by 5G and the Edge network

[58] TR 26.928.

architecture to reduce the end-to-end application level latencies. Edge Computing is a valuable enabler that should be considered to help 5G systems achieve the required performance to enable XR.

6.3 REQUIREMENTS AND KPIS ON 5G

The communication link is one component in the end-to-end system that delivers the immersive experience in an XR system. Depending upon the XR architecture choice, the computation on the device and computation on the edge server are other key components that contribute towards the overall immersive experience. The end-to-end system design and the architecture choice will then determine a set of key performance requirements on the XR traffic on the communication link.

6.3.1 XR END-TO-END REQUIREMENTS

In XR and immersive streaming, the objective is the full immersion of the user to create a presence for the user in the mixed reality world. Immersion and presence are subjective observations, but technical factors are known to be essential for best performance. Figure 7.4 provides a decomposition of immersion into three different main pillars: (i) visual quality, (ii) sound quality, and (iii) natural interaction. For each of those aspects, another set of technical aspects are relevant, and are also addressed in Figure 6.4.

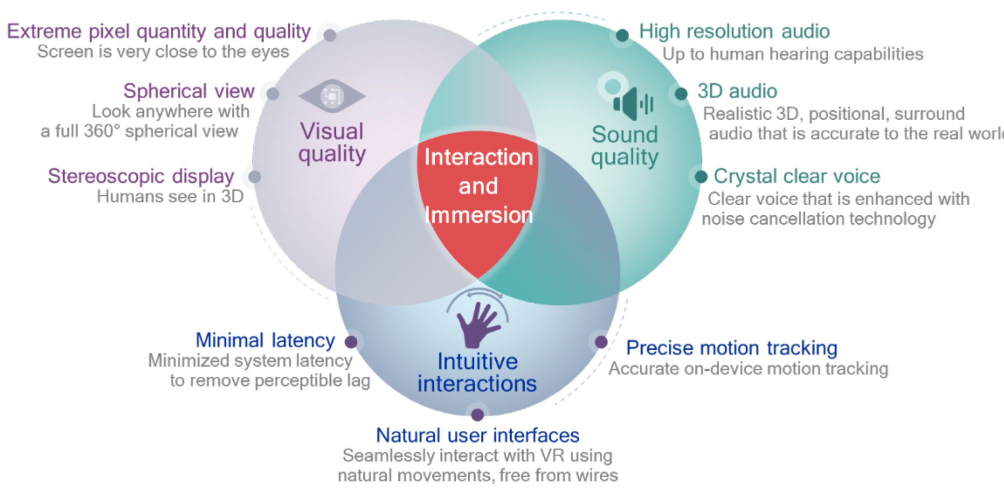

Figure 6.4. Three Pillars of Immersion Experience.[59]

6.3.2 XR REQUIREMENTS ON 5G

The end-to-end traffic requirements from an XR end-to-end architecture can be broken down into requirements on the traffic between the XR Edge server and the 5G system (backhaul), and the requirements of the traffic on the 5G system. The Edge server for XR can be owned by the 5G operator or a 3rd party and hosted by the operator or a 3rd party. If the Edge server is owned and hosted by the operator, then the requirements of the traffic between the Edge server and the 5G system is well-understood, and consequently the definition of the requirements of the XR traffic on the 5G system is easily accomplished. If the Edge server is owned and/or hosted by a 3rd party, it is anticipated that a Service Level Agreement (SLA) between the 3rd party and the 5G operator can define the terms based on which the requirements for the traffic between the Edge server and the 5G system can be defined.

[59] Making immersive virtual reality possible in mobile, Qualcomm. March 2016.

Table 6.1. Examples of XR Traffic Requirements.

XR Use Case and Architecture		XR gaming with generalized XR architecture	360º XR streaming with Device-based architecture
Uplink requirements	**Bitrate**	Flow 1: 640 Kbps Flow 2: 16 Mbps	<<640 Kbps
	Packet format	UDP	TCP
	Packet Error Rate (PER)	Flow 1: 1e-3, 1.25 ms Flow 2: 1e-3, 100 ms	1e-6
	Packet Delay Budget (PDB)	Flow 1: 1.25 ms Flow 2: 100 ms	300 ms
Downlink requirements	**Bitrate**	100-150 Mbps	10-25 Mbps
	Packet format	RTP-UDP	TCP
	Packet Error Rate (PER)	1e-3	1e-6
	Packet Delay Budget (PDB)	10 ms	300 ms

An example set of requirements on XR traffic is shown in Table 6.1. The requirements depend on the XR use cases and the end-to-end architecture option. Two examples are described in the table:

- XR streaming use case with a device-based architecture
- XR gaming use case with generalized XR architecture

As described in the table, the XR streaming use case with a device-based architecture is expected to be carried as Transmission Control Protocol (TCP) traffic in both uplink and downlink. The uplink traffic can be an http request, or optionally, updates to the user's pose at a slow time scale (for example, once every 500 ms). The downlink traffic is XR streaming traffic, which can be in one high resolution for all 360º or in a high resolution in the direction of the last known pose, and at a lower resolution in all other directions. The throughput requirement can be reduced by sending the high-resolution views only in the direction of the known pose, and sending the low-resolution views in all other directions.

The XR gaming use case with generalized XR architecture imposes more stringent traffic requirements on the 5G system. In this example, on the uplink, the pose and sensor information are sent as "Flow 1" over User Datagram Protocol (UDP) transport and a media stream (for example, camera capture stream) is sent as "Flow 2" again over UDP transport with a different more relaxed PDB requirement. These two flows can represent traffic corresponding to two different computation loops in the generalized XR architecture framework. On the downlink, a single traffic flow carrying the rendered view frames that correspond to the user pose is shown with high throughout, low latency, and high reliability requirements.

6.3.3 TRANSPORT PROTOCOLS FOR XR

Streaming services typically use Dynamic Adaptive Streaming over HTTP (DASH) over Transmission Control Protocol (TCP) as described in 3GPP TS 26.247. At the low latencies required by the generalized XR architecture, the latencies from TCP can be prohibitive, and User Datagram Protocol (UDP) is a more preferred option. The lack of reliability in the UDP transport protocol can be partially compensated by the higher reliability requirements on the 5G traffic. However, high reliability and low latency requirements on the 5G traffic can limit the throughput that can be a realized over a 5G system, and alternative protocols like WebRTC[60] can be considered for such XR traffic.

The bit-rate for the XR use cases is discussed in 3GPP TS 26.925 and depends upon various factors including the resolution, number of frames per second, the codec used in the compression (for example, Advanced Video Coding (AVC)/H.264 or High-Efficiency Video Coding (HEVC)/H.265), and on content type and latency allowed in encoding (for example, whether it is live or on-demand). Bitrates are expected to be reduced with expected encoder implementation enhancements and new codecs. The bitrates for basic 360º VR is 2.5 – 25 Mbps, for High Definition (HD) 360º VR is 10 – 80 Mbps, and for Retinal VR is 15-150 Mbps.

6.3.4 5G QOS FOR XR

The traffic on the 5G link can be treated with Quality of Service (QoS) parameters which can be specified in terms of

- Guaranteed Bitrate (GBR)
- Packet Delay Budget (PDB)
- Packet Error Rate (PER)

Traffic flow in the 5G system is associated with these QoS parameters as specified in 3GPP TS 23.501. Traffic flow can be of resource-type “GBR”, or “Non-GBR” or “Delay Critical GBR”. A best effort traffic flow has the lowest priority, with no specified minimum data rate for the packets of that flow that need to meet the associated PDB and PER. A “GBR” traffic flow will be served by the 5G system up to the associated GBR, with the fraction of packets dropped not exceeding the associated PER, and 98 percent of the served packets meeting the associated PDB. A “Delay Critical GBR” traffic flow will be served by the 5G system up to the specified GBR, with the fraction of traffic packets not meeting the associated PDB or dropped not exceeding the associated PER. For the XR traffic examples provided, the traffic from XR streaming use cases with device-based architecture can be mapped to a Non-GBR 5G traffic flow, and the traffic from the XR gaming use cases with generalized architecture can be mapped to a GBR 5G traffic flow.

Release 15 of the 5G system has been designed to provide PDB values as low as 5 ms, and PER values as low as 10^{-6}. However, defining a traffic flow with very low PDB and very low PER can severely restrict the bitrate of the traffic that can be served, or equivalently the number of simultaneous users that can be served at a given GBR.

[60] *Overview: Real Time Protocols for Browser-based Applications,* draft-ietf-rtcweb-overview-19, IETF. November 2017.

6.3.5 5G SCENARIOS FOR XR

3GPP recognizes 5G cellular operation in different radio Frequency Ranges (FR), with FR1 representing carrier frequencies in the range of 410 MHz to 7125 MHz, and FR2 representing carrier frequencies in the range 24250 MHz to 52600 MHz. 3GPP also recognizes cellular layouts in a variety of scenarios: Indoor Hotspot models (for example, open office, mixed office) for FR1 and FR2, Urban Micro for FR1 and FR2, and Urban Macro for FR1. All these are applicable deployment scenarios for XR services. Mobility-wise, the XR user can have 6DOF mobility either limited to a room, a pedestrian, or in a car,[61] train, or an airplane. "Absolute high but relative low speed" is a scenario in 3GPP TR 22.842, where the XR user is in a train or an airplane with the 5G infrastructure within the train or airplane, resulting in the relative low speed.

6.4 DEPLOYMENT STATUS

Although 3GPP has developed considerable work on standardization for XR as a 5G use case, there are other standards, open source solutions and operator efforts that are briefly explained in this section.

6.4.1 3GPP STANDARDIZATION STATUS

3GPP has considered XR as a key use case for 5G since its inception. TR 22.891 on "Feasibility Study on New Services and Markets Technology" contains around 70 use cases that led to the definition of the 5G system. Many of these use cases envisioned Virtual Reality or Augmented Reality. Subsequently, Release 15 of 5G has been standardized incorporating XR as one of the use cases. 3GPP specifies several standardized 5G QoS Identifiers (5QIs) in TS 23.501 for services that are assumed to be frequently used and thus benefit from optimized signaling by using standardized QoS characteristics. Many of these 5QIs can support XR traffic that does not require low latencies. Specifically, traffic from XR streaming applications in a device-based architecture can tolerate higher latencies, and can be supported by 5QIs 4, 6,8,9, all of which can support non-conversational video (buffered streaming) at a Packet Delay Budget (PDB) of 300 ms. Traffic from the real-time 3D communication use case of XR requires lower latencies and can be supported by 5QI of two with a PDB of 150 ms. Traffic from generalized XR architecture will require lower latencies and can be supported by 5QI of 80 with a PDB of 10 ms but without a guarantee on the bitrates (Non-GBR). Additional sets of standardized 5QIs for guaranteed bit-rate operation at low latencies can be expected in future 5G releases as the generalized XR architectures mature.

There are several ongoing XR activities in 3GPP at various SA working groups:

- **3GPP SA1**: XR (and Cloud Gaming) use cases are outlined in the SA1 study item on Network Controlled Interactive Services: NCIS (TR 22.842)
- **3GPP SA2**: work item on 5G System Enhancement for Advanced Interactive Services (SP-190564) proposes to introduce new 5QIs to identify the requirements on traffic from SA1 NCIS
- **3GPP SA4**: XR use cases are discussed in detail in the SA4 study item Extended Reality (XR) in 5G (TR 26.928)
  3GPP SA6: Edge Computing is a network architecture to enable XR and Cloud Gaming and is under study in the SA6 Study on application architecture for enabling Edge Applications (TR 23.758)

In addition, XR and Cloud Gaming has been proposed as a Rel-17 study item in RAN1 and is under email discussion.[62]

[61] *Audi puts VR in the backseat*, Engadget. January 2019.
[62] *Email: [Rel-17 items] XR & 5G,* 3GPP_TSG_RAN_DRAFTS Archives @LIST.ETSI.ORG. July 2019.

6.4.2 OTHER STANDARDS AND OPEN-SOURCE EFFORTS

The GSMA 5G Cloud XR[63] effort aims to "bring together Cloud based technologies and XR to deliver superior experiences that revolutionize the consumption of content in both the consumer and the enterprise sectors." The initiative focuses on the following topics, in order to help Operators tackle the challenges of this new service:

- Identify the key use cases in Cloud XR
- Investigate value chain, stakeholders and business models
- Share case studies and best implementation practices
- Define a recommended service architecture to accommodate 5G Cloud based services

The ETSI Augmented Reality Framework (ARF)[64] effort is working to define a framework for the interoperability of Augmented Reality (AR) applications and services. The AR framework will define an overall high-level architecture, identify key components and interfaces.

The Akraino Edge stack[65] is a project under Linux Foundation, and at least two XR related blueprints (defined[66] as a declarative configuration of the Edge stack) have been approved. One blueprint is the AI/ML and AR/VR applications at Edge,[67] and the other is the AR/VR oriented Edge Stack for Integrated Edge Cloud (IEC) Blueprint Family.[68]

6.4.3 XR OPERATOR STATUS

AT&T has been supporting[69] the Akraino Edge stack. AT&T has also been showcasing[70] the XR experience with Edge servers and has announced its intention to bring Network Edge Compute (NEC) capabilities into the AT&T 5G network with Microsoft Azure.[71] AT&T also has a collaboration[72] with Magic Leap to introduce their devices and services on its network.

Verizon has been building technologies that will exploit the latency and bandwidth advances of 5G networks through its XR arm Envrmnt.[73] Verizon's immersive content studio RYOT has an "innovation studio" to foster development of VR, AR and even holographic content[74] that will be able to leverage the delivery technologies over 5G. Verizon has announced partnership[75] with the Mixed Reality (MR) hardware company ThirdEye Gen to bring MR glasses to Verizon's 5G network.

Sprint, together with Open Networking Foundation[76] (ONF), has launched Open Evolved Mobile Core[77] (OMEC) as an Open-Source project under the CORD®[78] umbrella project. OMEC provides a high performance, lightweight, and cost-effective data plane solution to support a variety of applications targeted

[63] *5G Cloud XR*. July 2019.
[64] *Augmented Reality Framework,* ETSI. July 2019.
[65] *Akraino Edge Stack*, 20 November 2018.
[66] *Akraino Edge Stack Integration Projects (Blueprints).* 20 November 2018.
[67] *AI/ML and AR/VR applications at Edge,* Akraino Wiki. 25 April 2019 .
[68] *AR/VR oriented Edge Stack for Integrated Edge Cloud (IEC) Blueprint Family,* Wiki. 21 August 2019.
[69] *AT&T Boosts Akraino with Code Summit,* LightReading. 23 August 2018.
[70] *Designing New XR and Gaming Experiences with the Rise of Edge,* ATT Innovation Blog. April 2019.
[71] *AT&T and Microsoft Test Network Edge Compute to Enhance 5G for Business*, ATT news. February 2019.
[72] *AT&T Brings Connectivity and Content to Magic Leap to Create the Future of Entertainment*, ATT news. October 2018.
[73] *Envrmnt,* Verizon. August 2019.
[74] *Verizon's immersive media company RYOT to launch the Innovation Studio of the future with 5G technology in Los Angeles*. Verizon news. September 2018.
[75] *5G and mixed reality glasses help change how we see the world,* Verizon. April 2019.
[76] *ONF*. August 2019.
[77] *OMEC*, August 2019.
[78] *CORD,* August 2019.

for hosting at the network edge, be it in a market, or at single or multiple sites. Edge network infrastructure deployments will offer ideal hosting opportunities for XR application providers who will likely demand unprecedented 5G performance for a new paradigm of XR related end user experiences.

6.5 KEY CHALLENGES TO 5G EXTENDED REALITY

As XR use cases evolve to take advantage of the high throughput and low latencies offered by the 5G system, 3GPP is expected to continue evolving 5G to better support XR services. Device power consumption, 5G system capacity to handle XR traffic, and maintaining XR service continuity through mobility are some of the key issues 3GPP is expected to continue to address.

Power consumption on XR devices is an important consideration for XR use cases. There are some unique aspects to be studied:

- Battery size and heat dissipation depend on the form-factor of the device (AR and VR Head Mounted Displays (HMDs)), and on whether the HMD is standalone or tethered to another device
- XR traffic patterns may require the device to be exchanging traffic very frequently for prolonged periods of time
- Existing 3GPP power savings mechanisms are tailored to latency-tolerant traffic. XR is sensitive to latency, and this must be accounted for
- Architecture for XR may be based on computation split between a device and an edge server. The choice of computation split must account for the device power consumption

For XR traffic with high throughput, low latency and high reliability requirements, it is important to consider the commercial viability of these services over Rel-16 based 5G networks. One way to represent the viability of the XR services is via the number of users who can simultaneously consume the service (capacity) under given traffic requirements and for a given deployment scenario (for example, Urban Macro, Indoor Hotspot) with some density of 5G cells. When the latency is low and the reliability requirements are high, two effects come into play:

1. The burst throughput of XR traffic can be high. For example, the average throughput requirement of an XR traffic can be 100 Mbps, but its burst throughput requirement over short measurement windows can be 300 Mbps while also requiring high reliability
2. The short-term 5G link throughput experienced by a UE can be significantly lower than the average throughput experienced by that UE

These two effects can significantly impact the commercial viability of XR services over a 5G network. Therefore, it is important to study capacity aspects of XR services over 5G.

Mobility is an important aspect for wide area use cases of XR. It is important to maintain a certain level of user experience through mobility events. 3GPP Rel-16 supports “zero ms interruption” that ensures continuity in packet flows through mobility events. However, “zero ms interruption” does not ensure zero service interruption. Further, it is anticipated that the “zero ms interruption” in 3GPP Rel-16 can require the UE to reduce its UE capabilities for data transmission and reception with the source or the target while hand-over is in progress. The reduction in UE capabilities can potentially mean that the resource allocation at the source or target cell might not be able to handle the XR service requirements during mobility events. As such, it is important to address XR service degradation under mobility events.

In addition to 5G aspects, the Edge network can benefit from improvement of several aspects that the study in 3GPP TR 23.758 has identified. Some of those key issues are listed below:

- In order to avail Edge computing services deployed in the Edge Data Network, a UE should be able to connect with the Edge Data Network
- The deployment of Edge Data Network may not be available at all the locations due to operational constraints. For certain applications, before attempting to avail Edge computing services the UE needs to determine the availability of an Edge Data Network at the UE's location
- Several application providers can use the Edge Data Network to provide their applications as Edge Application Servers. To enable such Edge Application Servers on the Edge Hosting Environment, the application providers may need to supply Edge Application Servers related information
- The deployment of Edge Application Servers may not be uniform across the Edge Data Networks due to operational constraints. For certain applications, before attempting to avail services from an Edge Application Servers, the UE needs to determine the availability of the Edge Application Server
- When a UE hands off to a new location, different Edge Application Servers may be more suitable for serving the Application Clients in the UE. There needs to be a way for Application Clients in the UE to continue their service while replacing the serving Edge Application Server with a target Edge Application Server
- Availability of Edge Data Network and the Edge Application Servers can change dynamically due to multiple reasons such as change in deployments, mobility of the UE and etcetera. Such changes should be provided to the UE to fine tune the services provided accordingly

7. USE CASE: CLOUD GAMING

Gaming has transformed significantly over the years through three major waves that have been strongly influenced by technology advancements. The first catalyst to transform the gaming industry was the development of console gaming systems that made gaming an accessible mass market household activity. The console gaming wars of the 1980's, 1990's, and 2000's saw heavy competition between Nintendo, Sony, and Microsoft, among others. The technical capabilities of console systems greatly increased over these years fueled by improvements in consumer electronics from better, smaller, and more efficient computer processors, memory, and storage. These same computer hardware improvements also spurred a development in PC gaming that offered additional competition for the consoles.

The development of the Internet and vast improvements in home broadband connectivity brought a second wave of change to the gaming industry. Network gaming allowed for the expansion of gaming from single player experiences to multiplayer experiences that connected players in different homes. The Internet infrastructure that developed also enabled an important change in the distribution of video games and interaction with the consumer. A more robust Internet infrastructure opened a new avenue for directly distributing video games to the consumer besides traditional retail stores. This direct relationship with consumers allowed game companies to offer more frequent updates, new types of content, and even in-game purchases.

The third major wave that has propelled the gaming industry to new levels has been the revolution in mobile devices. Handheld electronics had been around for a while, even in gaming, with early devices like the Nintendo Game Boy, but the portable computing power of smartphones was a catalyst for mass adoption. In that sense, smartphones and tablets acted to enable mobile gaming on a larger scale, moving gaming beyond the confines of the home, while at the same time connecting people on an unprecedented scale. Today, with smartphone penetration approaching saturation in many markets, gaming is more accessible than ever before. The technical capabilities of smartphones have developed rapidly and they now offer rich graphics and high-speed processing that make increasingly complex games playable and enjoyable on pocket-sized devices. The growth in mobile gaming has driven the global games market to be valued at an estimated $138 billion in 2018, with mobile games accounting for 51 percent of that total or $70 billion, as shown in Figure 8.1. The global games market is expected to grow to $180 billion in 2021, led by mobile games increasing their share to 59 percent of that total to be valued at $106 billion as reported by Newzoo in April 2018 and also shown in Figure 7.1.

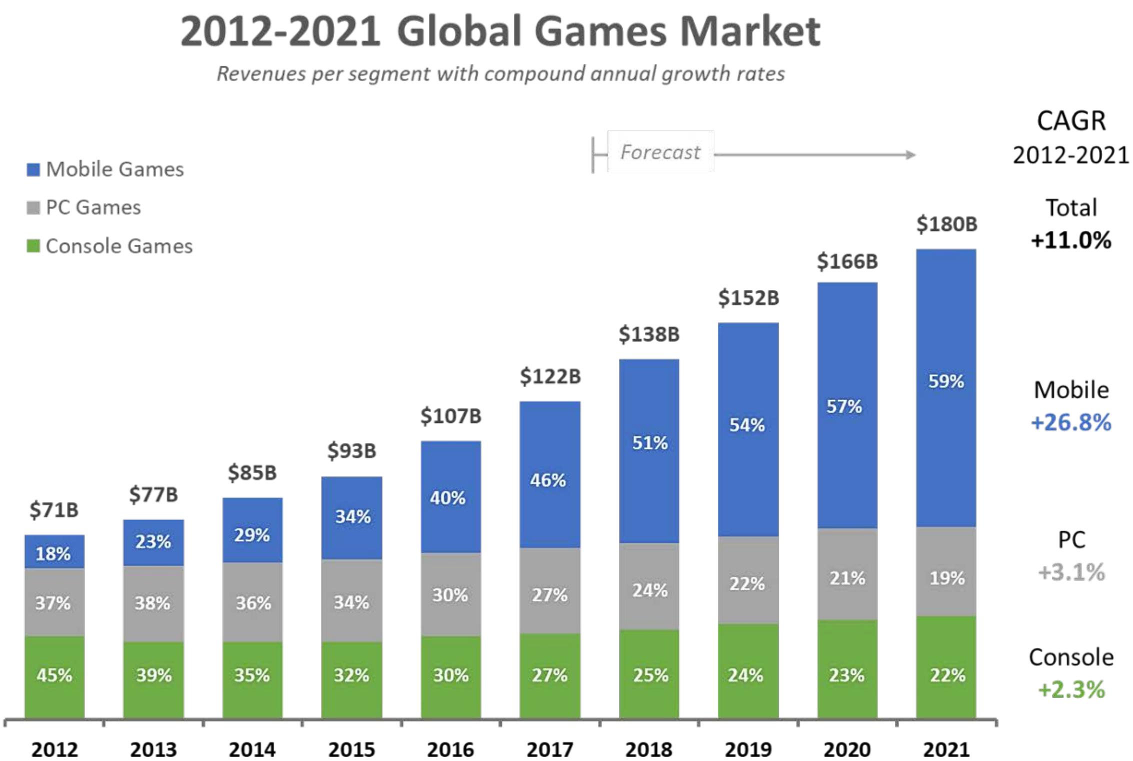

Figure 7.1. Global Games Market Revenues by Segment from 2012-2021. Data for 2012-2017 Represents Actual Numbers, 2018-2021 Represents Forecasted Data.[79]

With these three waves in context, cloud gaming is believed to be the next major development that will have substantial impact on the gaming industry.

7.1 INTRODUCTION TO CLOUD GAMING

Cloud gaming represents a fundamental change in gaming in that it shifts the computationally intensive graphics rendering and processing from the user's device to network servers. This concept has been made possible by further advancements in Internet connectivity and infrastructure that have reduced latency and increased throughput to enable more responsive experiences. A simplified process flow for cloud gaming, or streaming gaming, is shown in Figure 7.2 with the game's video frames being delivered to the user's device in a manner similar to streaming video.

[79] *2018 Global Games Market Report,* Newzoo. 30 April 2018.

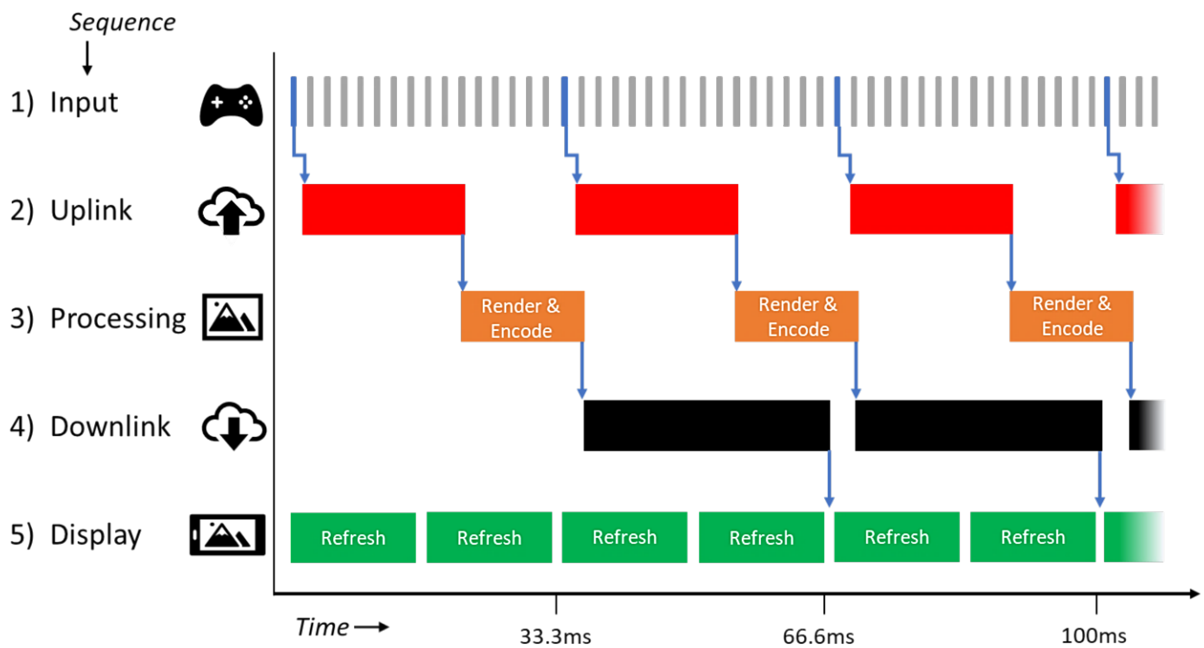

Figure 7.2. Simplified "Round Trip" Process Flow for Cloud Gaming Showing the Involvement of Network Connectivity to Deliver a 30-Video-Frames-Per-Second Streaming Gaming Experience to a 60-Frames-Per-Second Display Screen.[80]

The cloud gaming process begins with collecting the player's control inputs from the device (step 1) whether it be touchscreen controls on a mobile device, or an external controller connected to the device via Bluetooth or other means. The inputs, gaming coordinates, and other relevant information are then uploaded to the cloud gaming server via a cellular, Wi-Fi, or wired internet connection (step 2). The cloud gaming server, wherever it may be located, contains powerful hardware to quickly perform the necessary computer processing and graphics rendering needed to create the video frames and audio that correspond to the player's control inputs (step 3). The rendered video frames and audio are then sent to the player's device over the network connection (step 4). The video frames are displayed on the device, based on the refresh rate of the display hardware, usually at 60 Hz or 60 times per second, as is shown in Figure 7.2. This sequence is then repeated with the next set of inputs to comprise the gameplay experience.

As Figure 7.2 shows, network connectivity plays an integral role in cloud gaming because after allotting time for processing on the cloud game server, there is limited time available for the uplink and downlink segments of the process flow. Cloud gaming can operate at a range of video frames per second (fps), such as 30 fps or 60 fps. The figure shows cloud gaming operating at 30 fps meaning that a new video frame is displayed every other display refresh. Typically, a higher number of frames per second will result in smoother gameplay and a more responsive user experience as with 60 fps there is a new video frame available for every single display panel refresh. Thus, while cloud gaming may be possible to some extent over 4G LTE, it is expected that 5G connectivity, with its lower latency, will be required to deliver enhanced cloud gaming services on mobile devices.

Cloud gaming has drawn interest from major players in the gaming industry who are motivated by the potential business advantages. A key focus of cloud gaming is to expand the addressable market by removing the dependence on owning expensive gaming consoles or high-end PCs and allowing people to experience games on a broader range of devices than would otherwise be possible due to hardware

[80] *Based on information from "How Many FPS Do You Need?"* TechSpot. 27 December 2018.

limitations. Gaming companies also hope that predictable subscription revenue from cloud gaming services will increase as more users embrace playing games across new types of devices. Lastly, the effects of a larger gaming market and more time spent gaming will combine to improve user engagement, lead to more in-game purchases, and drive new monetization opportunities.

7.2 ARCHITECTURE

The network architecture that will be needed to support streaming cloud gaming will likely depend on the latency and throughput requirements dictated by the video quality and gameplay experience. Latency is a critical component for enabling cloud gaming and understanding the contributions to latency from network architecture is important. In terms of end-to-end latency, in a typical network architecture, data packets travel across multiple hops between a client (therefore, UE) and an application located on an Internet server, as shown for a 5G network architecture in Figure 7.3.

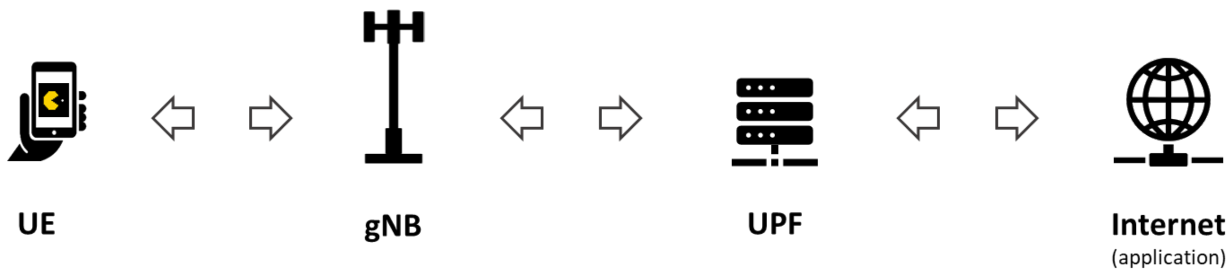

Figure 7.3. Pathway of Data Packets across Various Points in a 5G Cellular Network Architecture.

The RAN) – the hop between the UE and the eNB in an LTE network – is typically the most significant contributor to latency and its variation, compared to the other hops – therefore, eNB to the Internet (via the core network). In this regard, 5G networks can play a critical role, as they can deliver significantly lower latencies than LTE. The target user plane latency for URLLC (for 5G IMT-2020 submission) should be 0.5 ms for UL, and 0.5 ms for DL. For eMBB, the target for user plane latency should be 4 ms for UL, and 4 ms for DL.[81] Furthermore, 5G frame structure offers additional enhancements which can further reduce air-interface latency, for example mini-slots where uplink and downlink data are transmitted in a single timeslot, reducing time for Acknowledgements/Negative Acknowledgements (ACKs/NACKs) and overall latency.

Edge computing may offer another method for reducing the end-to-end latency to meet high performance cloud gaming requirements. There are many ways that edge computing could be implemented by a Mobile Network Operator, or other telecommunications company. Figure 7.4 shows the different layers of edge computing, which begin beyond a centralized cloud data center, considering first the core edge, then radio edge, and finally moving to the most distributed – the user edge. The scale, or the number of edge computing presence points, increases exponentially as it becomes more distributed; from only a few main data centers in the cloud the scale ramps dramatically to millions of points of presence at the user edge. This implies a much greater deployment cost as the edge reach becomes more distributed and closer to the end user. Therefore, the reductions in latency and other benefits that occur by locating the edge closer the user must justify these higher costs.

[81] *Study on Scenarios and Requirements for Next Generation Access Technologies,* Rel-14, 3GPP TR 38.913. 2016.

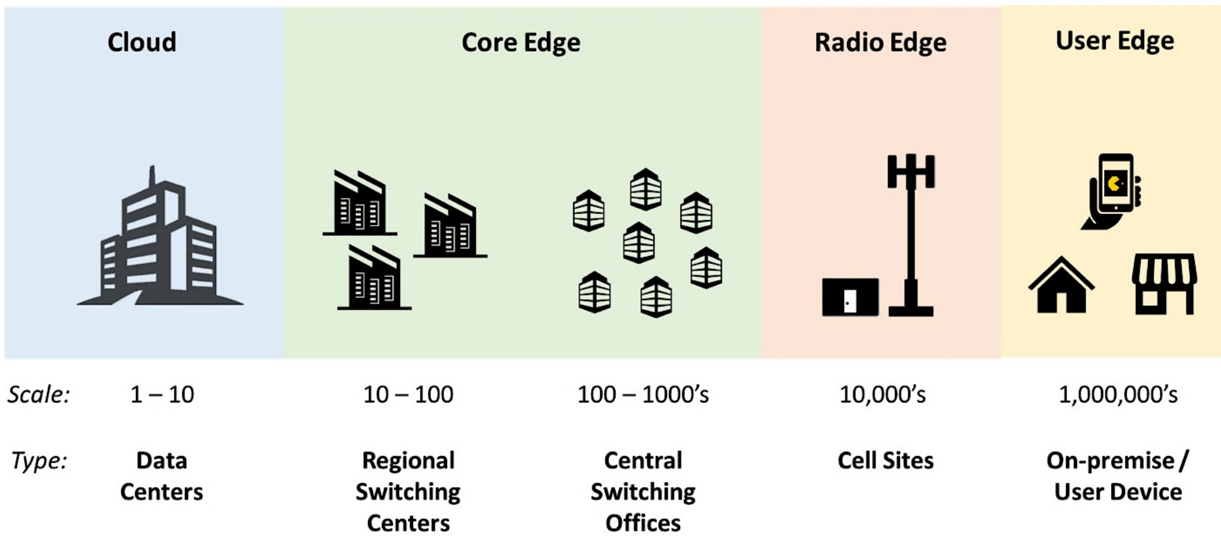

Figure 7.4. Different Layers of Edge Computing Moving Beyond the Cloud to the Core Edge, Radio Edge and User Edge.

Note: Possible points of presence for network operators. Each layer provides unique benefits but is implemented at a different scale and cost.

Initial cloud gaming launches by Google's Stadia and Microsoft's xCloud appear to be focusing on the cloud, leveraging those companies' existing data center assets at that scale. This may provide satisfactory performance for some users under certain conditions in locations easily served by these few data centers. However, network peering between a user's broadband or mobile provider and the cloud gaming companies' servers will add latency. Thus, network operators are well positioned to offer significant latency improvements by bringing computing resources closer to the user with their existing network assets at the core edge and radio edge. For cloud gaming it is possible that the optimal balance between scale, cost, and proximity to the user would lie somewhere in the core edge.

7.3 REQUIREMENTS AND KPIS ON 5G

The network requirements for streaming cloud gaming depend largely on the desired quality of the video and gameplay experience. Latency, especially consistent latency with low jitter, plays a large role in the gameplay experience in two ways. Since the user input is sent from the device to the game server, this means that uplink latency must be as low and consistent as the downlink latency. Second, smoother gameplay for the user requires more video frames per second (fps). This necessitates lower latency in order to respond to the user's control input and then render and deliver a unique frame of video in that smaller time window. For example, 30 fps requires a unique video frame every 33.3 ms, whereas 60 fps requires a unique video frame every 16.7 ms. To reach this level of performance the round-trip latency, including the uplink, processing and rendering, and downlink, needs to be less than or equal to the twice the time duration of each video frame, so 66.6 ms for 30 fps or 33.3 ms for 60 fps. Figure 7.2 illustrates this full round-trip process for a 30-fps gaming experience, with the uplink and processing and rendering of one video frame occurring while the previously rendered frame is transmitted over downlink to the device. The uplink will likely be a shorter process than the downlink because less data needs to be sent from the device compared to the video, audio, and other data sent on the downlink.

Throughput is another key parameter, especially in the downlink, because a richer gaming experience requires higher resolution video frames, better fidelity audio, haptic feedback, and other data demands. Granted, the smaller screens on today's mobile devices may not require the same 4K UHD resolution that is required on the large televisions in people's homes. However, in the future, foldable phones and tablets are expected to have increasingly larger screens where higher resolutions have a noticeable benefit to the user. Continuous developments in video encoding and compression technology have resulted in more efficient data delivery and have reduced the burden of delivering higher resolution video. Advanced Video Coding (AVC), also known as H.264 or MPEG-4, a standard that was completed in 2003, is often used to deliver streaming video and gaming content today. The next iteration of codecs includes VP9 and High Efficiency Video Coding (HEVC or H.265), with both standards initially proposed in 2013 offering even better performance. Research from Netflix shows that VP9 can deliver the same quality of video at a 20-35 percent reduction in the data rate.[82] In the future, there are promising new video compression standards like AV1, developed by a consortium of video-on-demand providers, which offers an additional 30-35 percent data rate reduction on top of VP9 at a similar level of quality.[83]

While these new codecs offer improved efficiency and reduce the payload requirements, there is one key disadvantage. For applications sensitive to latency, such as streaming gaming, the downside to more efficient video compression is that it often requires more compute resources and time to execute. With a tight latency budget for streaming gaming, there is limited time available for perform complex video encoding and compression. This creates a delicate balance between delivering higher quality video within the throughput constraints of a mobile network versus achieving the low latency for a more responsive gaming experience at a higher rate of frames per second.

In summary, the key performance indicators for streaming gaming consist of latency and throughput. Table 7.1 shows a range of these KPIs that might be expected for certain gaming conditions. Note that there is a large range of throughput values because even for a given resolution there are various levels of quality based on the type of video encoding and compression that is used. Thus, with a limited amount of bandwidth, tradeoffs will always exist between delivering a higher resolution at a lower quality versus a lower resolution at a higher quality.

Table 7.1. KPIs for Cloud Gaming with Latency and Throughput Based on Video Frames Per Second for a Range of Display Resolutions.[84]

Frames per second	Round-Trip Latency	Throughput		
		HD 720p	**HD 1080p**	**UHD 4K**
30	≤66.6 ms	2 – 6 mbps	3 – 12 mbps	17 – 24 mbps
60	≤33.3 ms	3 – 10 mbps	5 – 20 mbps	26 – 35 mbps

[82] *More Efficient Mobile Encodes for Netflix Downloads,* Netflix Tech Blog. 1 December 2016.
[83] *AV1 beats x264 and libvpx0vp9 in practical use case,* Facebook. 10 April 2018.
[84] *Throughput ranges based on internal T-Mobile testing of mobile gaming and video streaming and stated requirements from Google,* Stadia Founder's Edition. 24 June 2019.

7.4 DEPLOYMENT STATUS

Many of the major gaming companies have announced their intent to launch streaming gaming services or expressed interest in such services. These services are expected to target indoor users on consoles, PCs and TVs and indoor and outdoor mobile users via smartphones and tablets. Microsoft announced Project xCloud in October 2018 and has explained that the streaming gaming service would run off Microsoft's Azure data centers in key regions like North America, Asia, and Europe.[85] Microsoft hopes to be able to offer the service over 4G and 5G networks, as well as Wi-Fi, with public trials expected in 2019.

Sony currently offers its PlayStation Now service with game streaming to PlayStation consoles and PCs.[86] In May 2019, Sony announced a partnership with Microsoft to collaborate on the development of future streaming gaming solutions using Azure data centers.[87] Rounding out the major gaming companies, Nintendo has been testing cloud gaming in Japan[88] and there are rumors that the company may be working with Microsoft as well for the data center infrastructure necessary to expand this effort beyond Japan.[89]

Google is another company that has significant interest in cloud gaming. Google unveiled Stadia, its cloud gaming platform, at the 2019 Game Developers Conference and showcased seamless streaming gameplay over Wi-Fi across laptops, mobile phones, TVs, and PCs.[90] However, Google has not stated any plans for supporting cellular connectivity, but it is likely that this remains a goal. Google has announced that Stadia Pro, a premier tier of the service, would launch in November 2019 for $9.99 per month with a free version launching in 2020.[91]

Nvidia, with its strengths in graphics processing, is another company interested in the cloud gaming market. Their cloud gaming service, GeForce NOW, was first announced in 2015 and is now available in beta trials in North America and Europe that have over 300,000 active gamers and a waiting list of over one million users.[92] The service is currently available on Windows and Mac computers as well as Shield, Nvidia's streaming media player, which connects to TVs.

Several other game streaming services exist today. Companies such as Shadow and LiquidSky offer PC cloud gaming platforms that enable streaming gaming on an array of devices. Vortex provides another service that offer players the ability to stream games over 4G LTE wireless connections at varying rates of quality to any Internet-connected device with a Windows or Android operating system.[93]

Hatch, another streaming cloud gaming service, is currently available over 4G but has recently developed a 5G-optimized gaming application for use on 5G mobile phones.[94] Hatch's deployments around the world, include Vodafone in the UK, SK Telecom in Korea, NTT Docomo in Japan, along with Sprint in the U.S., and multiple countries throughout continental Europe.

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[85] *Project xCloud: Gaming with you at the center,* Microsoft. 8 October 2018.
[86] *"PlayStation Now",* Sony. June 2019.
[87] *Sony and Microsoft to explore strategic partnership,* Microsoft. 16 May 2019.
[88] *The Nintendo Switch in Japan offers a peek at the cloud gaming future,* The Verge. 4 April 2019.
[89] *Nintendo could be looking into offering its own game streaming service in some countries,* Games Radar. 22 May 2019.
[90] *Google Stadia hands-on: streaming analysis and controller impressions,* Eurogamer. 19 March 2019.
[91] *"Stadia Founder's Edition",* Google. 24 June 2019.
[92] *The Cloud Gaming Race is on and Nvidia GeForce NOW Already has a Big Head Start,* Forbes. 6 May 2019.
[93] Vortex.
[94] *Samsung tackles 5G gaming opportunity with cloud gaming service Hatch,* FierceWireless. 4 June 2019.

Among telecommunications companies, Verizon is reportedly testing a cloud gaming service called Verizon Gaming that runs on Nvidia's Shield, although support for cellular data connections has not been disclosed.[95]

7.5 KEY CHALLENGES TO 5G CLOUD GAMING

The key issue to address for streaming gaming is likely to be the level of involvement of mobile network operators in enabling a viable streaming gaming experience on mobile devices. Some of the companies interested in pursuing streaming gaming already have access to substantial portfolios of data centers and infrastructure assets. The question remains as to whether they will be able to provide their streaming gaming services as over the top (OTT) solutions or whether they will need the help and support of Mobile Network Operators (MNOs) to enable the desired levels of latency and throughput that will be needed. Within the unique infrastructure assets that MNOs possess for Edge computing and the broad set of tools available within 5G for delivering a differentiated connectivity experience, it is likely that MNOs will play a pivotal role in enabling streaming mobile gaming services.

8. USE CASE: SMART GRID

Smart grid refers to a two-way communication network for the electricity grid where devices that are connected wirelessly are able to remotely detect the status of electricity generation, transmission lines and substations, monitor consumption of user electricity usage, adjust the power consumption of household applications to conserve energy, and reduce energy losses.

Figure 8.1 depicts the logical model of legacy systems that are mapped onto conceptual domains for smart grid information networks.[96]

[95] *Verizon is quietly testing its own Netflix-style cloud gaming service,* The Verge. 11 January 2019.
[96] *Adoption of NextGeneration 5G Wireless Technology for "Smarter" Grid Design; An Overview by:* Alidu Abubakari

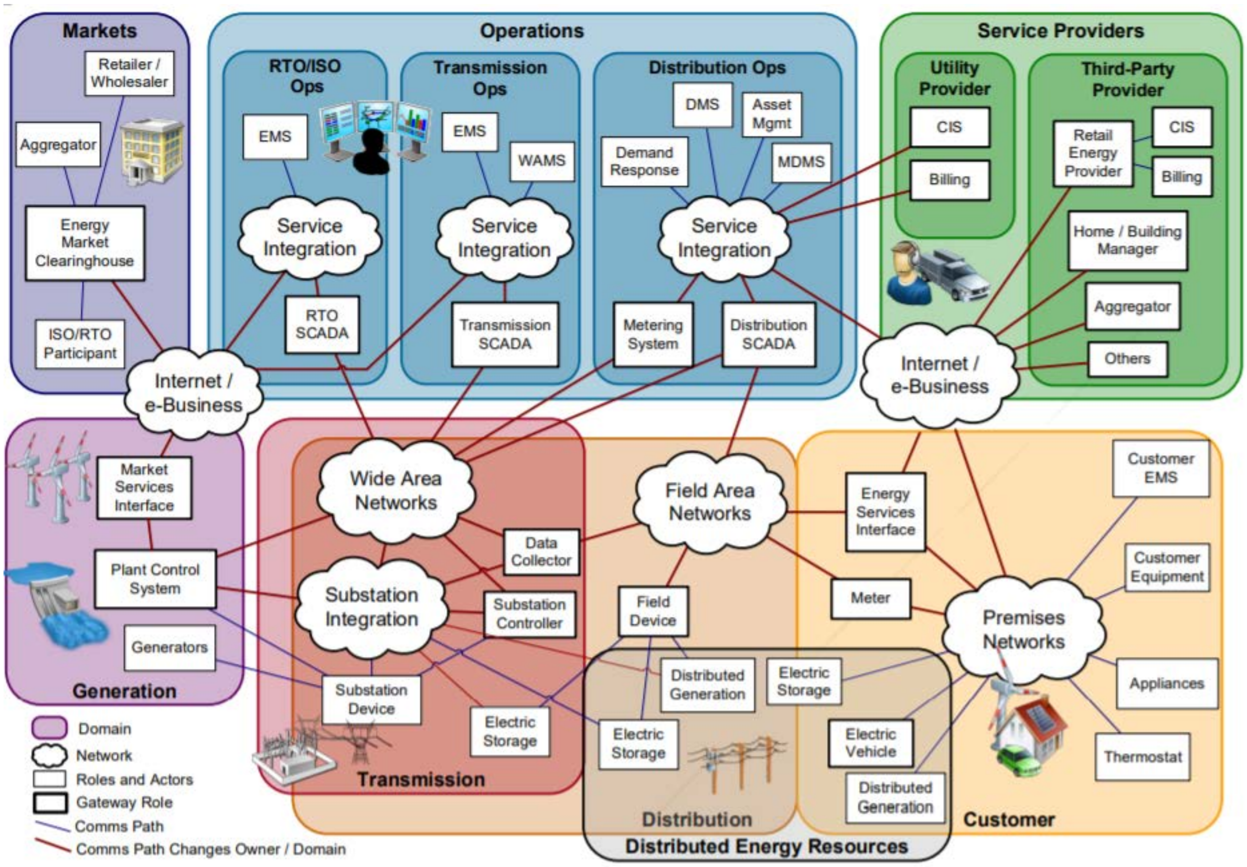

Figure 8.1. Logical Model of Legacy Systems Mapped onto Conceptual Domains for Smart Grid Information Networks.[97]

8.1 INTRODUCTION TO SMART GRID

Grid modernization is critical for economic growth along with environmental gains. 5G telecommunication networks will provide the required throughput and latencies that are essential for smart grid applications. 5G will be a catalyst for utility providers enabling improvements to the grid systems' communications. With continuous population growth, the demand for power is increasing, which leads to new business cases being developed to achieve more distributed power systems as a result of 5G networks.

Smart grids consist of smart meters, sensors, proper monitoring, and data management systems.[98] The incorporation of smart meters and smart grid technologies is happening across the utility industry today and can be significantly improved with 5G technologies. When dealing with utilities, there are also the inherent stringent security factors that need to be established and also improved with 5G technologies. 5G technologies also bring about security isolation through network slicing. Figure 8.2 depicts the energy use cases divided into Smart Grid use cases and Smart Assets use cases.

[97] *NIST Smart Grid Framework:* https://www.nist.gov/sites/default/files/documents/smartgrid/NIST-SP-1108r3.pdf
[98] *Future Generation 5GWireless Networks for Smart Grid: A Comprehensive Review,* Sofana Reka. S, Tomislav Dragiˇcevi´c, Pierluigi Siano,and S.R. Sahaya Prabaharan. 4 June 2019.

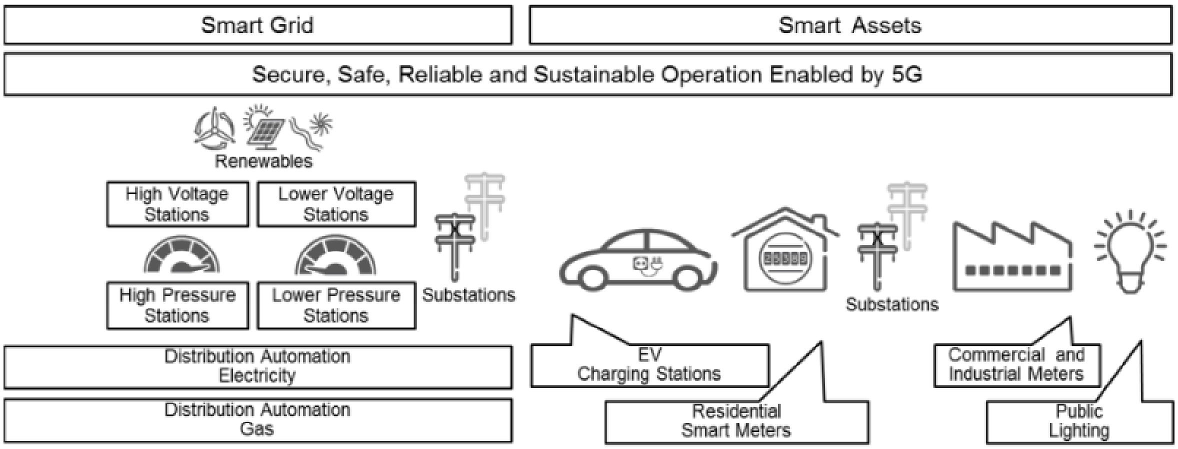

Figure 8.2. Energy Use Case Highlighting Smart Assets Use Case and Energy Distribution Use Case from Smart Grids.[99]

Smart grids are meant to be decentralized, reliable, self-healing and efficient. Characteristics of smart grids are:[100]

1. Consumer Participation including:
    - Real Time Monitoring of consumption
    - Control of smart appliances
    - Building automation
2. Real Time Pricing
3. Distributed Generation: Incorporation of renewable energy resources into the grid
4. Power System Efficiency
    - Power monitoring
    - Asset management and optimal utilizations
    - Distribution automation and protection
5. Power Quality
    - Self-healing
    - Frequency monitoring and control
    - Load forecasting
    - Anticipation of disturbances
6. New products in terms of Value-Added Services (VAS)

Characteristics of smart grids can be seen in Figure 8.3.

[99] *5G and Energy;* 5G Infrastructure Association; https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White_Paper-on-Energy-Vertical-Sector.pdf .
[100] *India Smart Utility Week:* http://www.indiasmartgrid.org/sgg2.php.

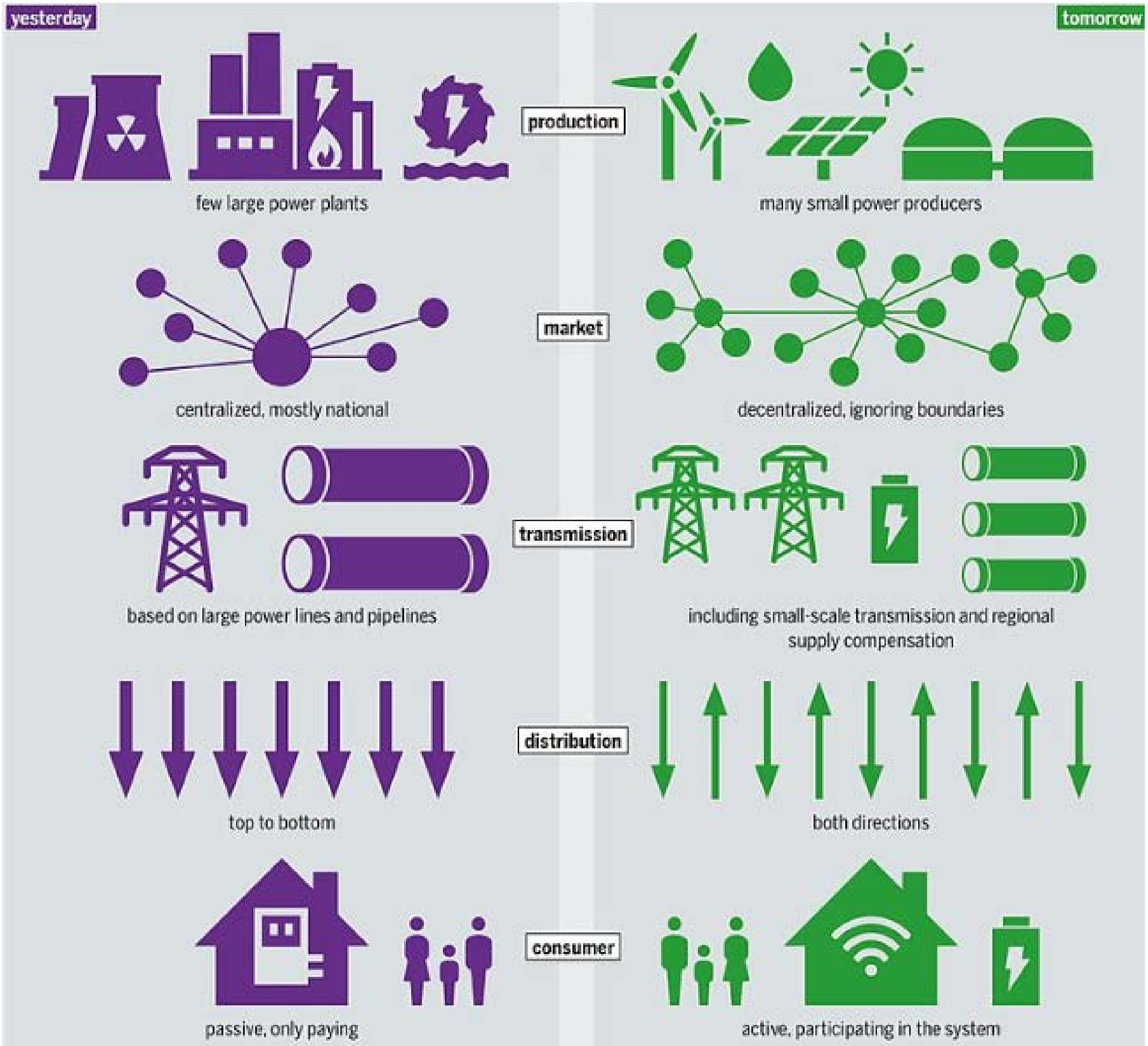

Figure 8.3. Characteristics of a Smart Grid. [101]

There is also significant work being implemented as part of 3GPP for smart grids. 3GPP TR 103 492, details the spectrum suitable for Resilient Machine-To-Machine (RM2M) supervision, control, and data acquisition (SCADA) systems, including Wide-area Multi-Point (WiMP), for electricity, gas and water Smart Grids. All electricity, gas and water grid systems are designated as critical national infrastructure.[102]

There is also the introduction of synchrophasor technology which essentially provides smart grid intelligence. Synchrophasor technology uses monitoring devices called Phasor Measurement Units (PMUs) that measure the instantaneous voltage, current, and frequency at specific locations in an electric power transmission system (or grid) in real time.[103]

[101] *Energy Atlas 2018:* https://gef.eu/publication/energy-atlas-2018/.
[102] 3GPP TR 103 492*.*
[103] *Sychrophasor Technologies and their Deployment in the Recovery Act Smart Grid Programs – August 2013 (PDF),* Department of Energy.

8.2 ARCHITECTURE

In the following sections, network slicing and the multiple domains of communications networks for smart grids are explained.

8.2.1 5G NETWORK SLICING AND SMART GRIDS

End-to-end network slicing is a key use case for 5G networks today and also a key enabler for smart grids. 5G network slicing is a logical network that is created with a customizable set of characteristics and uses a Mobile Network Operator (MNO) shared physical network. Smart grids are a particular vertical industry that benefits from 5G network slicing since network slicing provides the level of security isolation required for highly reliable applications such as smart grids. 5G also provides smart grids with the Ultra-Reliable Low Latency Communication (URLLC) requirements needed for transmission.

8.2.2 SMART GRID ARCHITECTURE

Smart grid communication networks consist of multiple domains. Each of these domains serves a specific area for example a distribution network or location like a secondary substation (transformation between medium and low voltage). It has to support individual requirements driven by the applications it has to serve. The communication network architecture, depicted in Figure 8.4, is derived from, and mapped to, the Power Network it serves.[104]

[104] *5G and Energy: 5G Infrastructure Association:* https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White_Paper-on-Energy-Vertical-Sector.pdf .

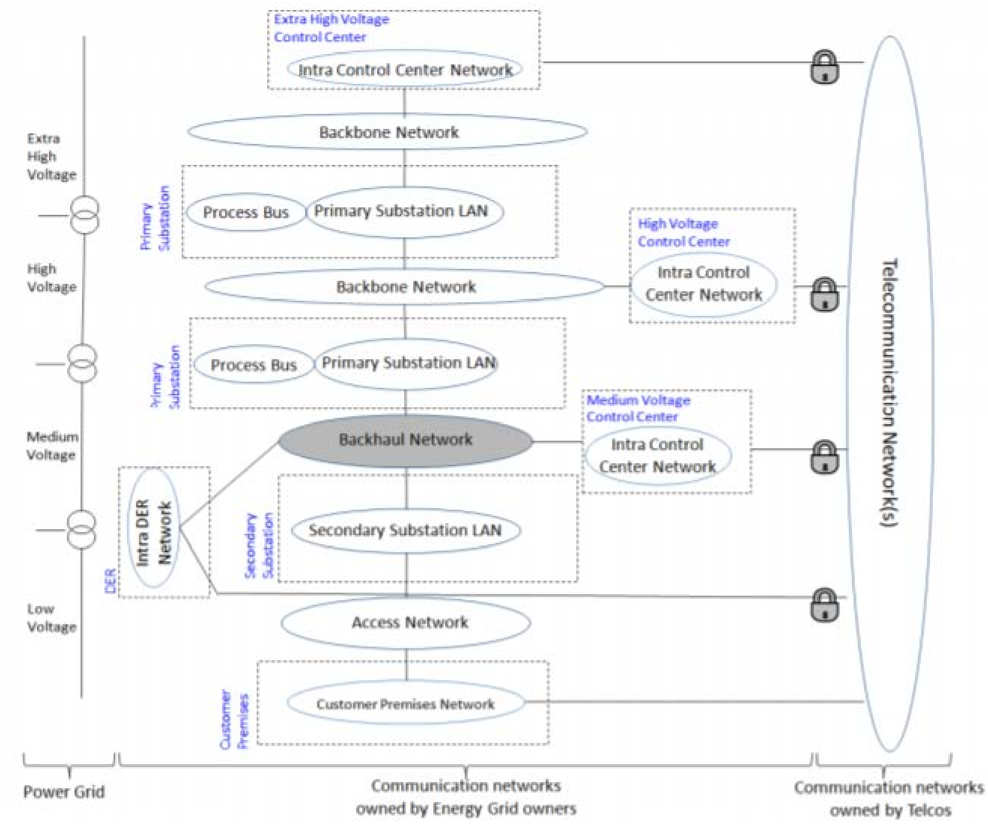

Figure 8.4. Communication Network Smart Grid Architecture.[105]

The border elements of the voltage levels are of major relevance for the smart grid communication domains as they have their own very specific requirements:

- **Primary Substation**: the medium voltage to high voltage transformation point, and the high voltage to extra high voltage transformation point
- **Secondary Substation**: low voltage to medium voltage transformation point[106]

There are several communication methods:

- **Grid Backbone Communication Network**: Interconnects the Primary Substation LANs together and connects them with the regional control centers (often co-located) and central control centers
- **Primary Substation LAN**: Requires its own communication infrastructure that distinguishes between a Process Bus and a Station Bus. It is mainly based on a Gigabit Ethernet infrastructure
- **Grid Backhaul Communication Network**: Connects the Secondary Substation LANs with each other and with a control center
- **Secondary Substation LAN**: Network inside the secondary substation (today this network is quite trivial and may consist of just one single Ethernet switch/ IP router)

[105] *5G and Energy: 5G Infrastructure Association:* https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White_Paper-on-Energy-Vertical-Sector.pdf .
[106] *5G and Energy: 5G Infrastructure Association:* https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White_Paper-on-Energy-Vertical-Sector.pdf

- **Grid Access Communication Network**: Connects the customer premises or for example low voltage sensors to a specific Secondary Substation
- **Customer Premises LAN**: In-building communication network where the customer is characterized by consumption and production of energy (Prosumer) and the customer can be residential, public or industrial Prosumer
- **Intra-Distributed Energy Resource (DER) Network**: For medium-sized DERs like wind/solar parks a dedicated LAN is required for control, management and supervision purposes **Intra-Control-Center Network**: LAN within a Distribution System Operator's or Transmission System Operator's control center
- **External Network**: Fixed or Mobile Network Operator owned communication network[107]

8.3 REQUIREMENTS AND KPIS ON 5G

Table 8.1 provides a list of the expected services that smart grids will be supporting along with the KPIs that are required by the 5G infrastructure.

Table 8.1. 5G Infrastructure Requirements.[108]

	5G Infrastructure Requirement			
Service	**Communication Latency**	**Reliability requirement**	**Bandwidth Requirement**	**Terminal Node Quantity**
Intelligent distributed feeder automation	High	High	Low	High
Millisecond Load Control	High	High	Medium/Low	Medium
Data acquisition for distributed Automation	Low	Medium	Medium	High
DER Monitoring and Control	High	High	Low	High
Distributed Energy Storage	High	High	Low	Low

Table 8.1. continued. 5G Infrastructure Requirements.[109]

5G Infrastructure Requirement

[107] *5G and Energy: 5G Infrastructure Association:* https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White_Paper-on-Energy-Vertical-Sector.pdf
[108] *Adoption of Next Generation 5G Wireless Technology for "Smarter" Grid Design; An Overview by: Alidu Abubakari.*
[109] *Adoption of Next Generation 5G Wireless Technology for "Smarter" Grid Design; An Overview by: Alidu Abubakari.*

	Communication Latency	Reliability requirement	Bandwidth Requirement	Terminal Node Quantity
Fault Localization and Self-Restoration	High	High	Low	High
Smart Metering (Data Acquisition)	Medium	High	Low	High
Microgrid Coordination	High	High	Medium	High
Electric Vehicles (V2X)	High	High	Medium	High

Smart grid requirements are very stringent. The specific requirements are:

1. Bandwidth: in the range of Mbps to Gbps between the primary substations and towards the control center
2. E2E Latency (upper bound): <5 ms between the primary substations and towards the control center
3. Packet loss: $< 10^{-9}$
4. Availability: >99.999% equal to 5 min downtime p.a.
5. Failure Convergence Time: Seamless failover required, therefore, no loss of information in case of a failure while keeping real-time delivery of the information (therefore, within a small number of milliseconds)
6. Handling of crisis situations (surviving long power downtimes on a large scale, assuring black start capability): mandatory[110]

[110] *5G and Energy: 5G Infrastructure Association:* https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White_Paper-on-Energy-Vertical-Sector.pdf.

Table 8.2. Summary of Essential Requirements for Smart Grids from a Radio Regulation Perspective.[111]

High availability	Mains power independence	Wide area coverage	Capable of supporting distributed control	Air-ground-air operation
High reliability	Low latency and guaranteed symmetry	Cost effective	Longevity of support for technology(ies)	Flexible payloads, but primarily uplink centric
Resilient architecture	Cyber security	9,6 kbits/s to 10 Mbits/s data rates/bandwidth	Graceful degradation	

Smart grids have strict requirements in terms of reliability, tolerating only short packet dropouts. Table 8.3 indicates the 5G performance requirements for low latency and high availability states based on 3GPP TS 22.262.

Table 8.3. 5G Performance Requirements for Low Latency and High Availability States.[112]

Scenario	End-to-End Latency	Communication Service Availability	Reliability	User Experience Data Rate	Connection Density	Service Area Dimension
Discreet Automation – motion control	1ms	99.9999%	99.9999%	1 Mbps to 10 Mbps	100 000/km2	100x100x30 meters
Process Automation – remote control	50ms	99.9999%	99.9999%	1 Mbps to 100 Mbps	1000/km2	300x300x50 meters
Process Automation – Monitoring	50ms	99.9%	99.9%	1 Mbps	10 000/km2	300x300x50 meters
Electricity Distribution – medium voltage	25ms	99.9%	99.9%	10 Mbps	1000/km2	100 Km along power Line
Electricity Distribution – medium voltage	5ms	99.9999%	99.9999%	10 Mbps	1000/km2	200 Km along power Line
Intelligent Transport – infrastructure backhaul	10 ms	99.9999%	99.9999%	10 Mbps	1000/km2	2 Km along a road

8.4 DEPLOYMENT STATUS

Smart grid investments increased by 10 percent in 2018 based on the International Energy Agency (IEA). However, this only represents a fraction of what is invested in network infrastructure. 5G will introduce real-time monitoring and control of smart grids through closed loop automation. This will enable predictive failures and facilitating maintenance. 5G network slicing also enables multiple deployments of power grids which can be monitored and controlled collectively and thus reduce overall CAPEX and OPEX.

[111] 3GPP TR 103 492.
[112] *Service requirements for next generation new services and markets,* 3GPP TS 22.261.

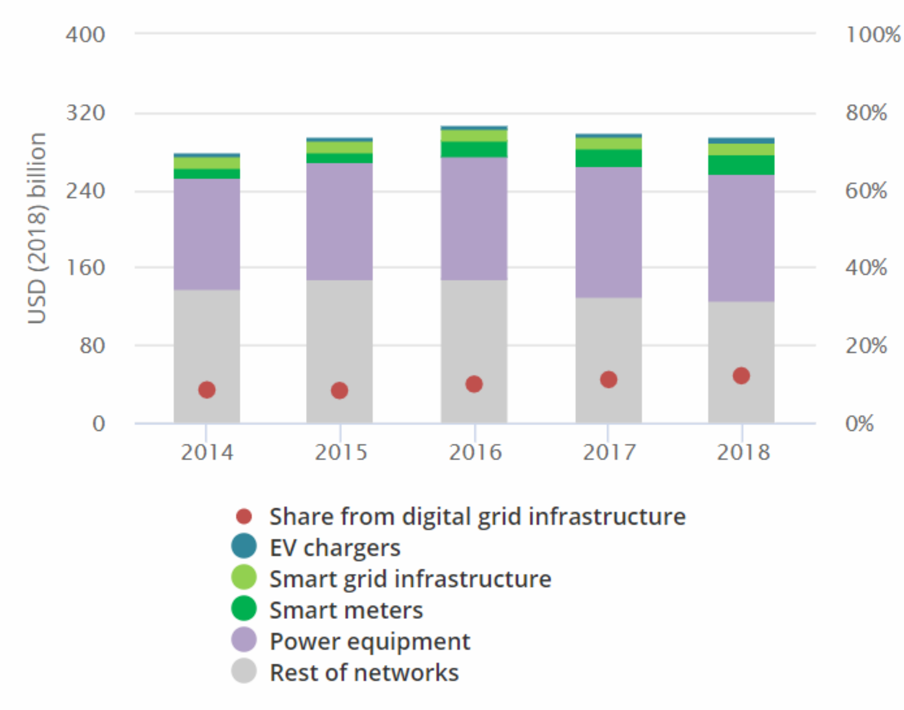

Figure 8.5. Investment in Smart Grid by Technology Area.[113]

8.5 KEY CHALLENGES TO 5G SMART GRID

Some concerns with using 5G as a communication technology in smart grids are:

1. Potential for the unpredictably large number of small generation stations and the fluctuating energy consumption at the end user level. This could result in difficulty in predicting demand
2. 5G networks will introduce an enormous number of connected devices leading to a significant rise in network power consumption. As a result, implementation of a sustainable network with renewable power sources, optimum utilization of power and minimal power leakage is required
3. Network authentication of devices and security
4. Survival of the power down circumstances and the black start capability is the main concern for any electric network, because unavailability of electric power for even a short duration of time is intolerable. This requires 5G technical solutions that enable switching between different communication technologies, thereby guaranteeing seamless and real-time delivery of information[114]

9. CONCLUSION

5G technology will expand the value of mobile networks to take on a much larger role than previous generations, empowering many new connected services across an array of world changing use cases.

[113] *IEA (International Energy Agency)* https://www.iea.org/tcep/energyintegration/smartgrids/.
[114] *Future Generation 5GWireless Networks for Smart Grid: A Comprehensive Review,* Sofana Reka. S, Tomislav Dragiˇcevi´c, Pierluigi Siano, and S.R. Sahaya Prabaharan. 4 June 2019.

As 5G technology matures, and 5G deployments ramp up, more 5G capabilities are set to be a reality in the next few years, helping transform industries and enrich people's lives.

10. APPENDIX

A. ACRONYMS

ACRONYM	DEFINITION
2G, 3G, 4G & 5G	2nd, 3rd, 4th & 5th Generation mobile architecture
3GPP	3rd Generation Partnership Project (3GPP) unites seven telecommunications standard development organizations and provides their members with a stable environment to produce the Reports and Specifications that define 3GPP technologies.
5QIs	5G Quality of Service Identifiers
ACK/NACK	Acknowledgement/Negative Acknoledgement
ACM	Ascent Control Module
ACS	Auto Configuration Server
AI	Artificial Intelligence
ANS	Access Network Serving
ARF	Augmented Reality
ARF	Augmented Reality Framework
ARFCN	Absolute Radio Frequency Channel
ATM	Air Traffic Management
ATRA	Asset Tracking
AV1	AO Media Video 1 is video coding format degined for video transmissions over the Internet.
AVC	Advanced Video Coding (also referred to as H.264 or MPEG-4)
AVPROD	Audio Visual Service Production
BH	Busy Hour
Bps/Hz	Bits per Second/Herz
BS	Base Station
BVLOS	Beyond-Visual-Line-of-Sight
C2	Command and Control
CA	Carrier Aggregation
CAF	Connected America Fund
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CBRS	Citizens Broadcast Radio Service
CMED	Critical Medical Application
CMNF	Communication Service Management Function
CN	Core Network
CPE	Customer Premises Equipment
CUC	Considered User Cases

DASH	Dynamic Adaptive Streaming over HTTP
dB	Decibel
dBi	Decibel relative to isotropic
dB/K	Decibel relative to reciprical temperature
dB/M	Decibel relative to one milliwatt
dB/W	Decibel relative to one watt
DER	Distributed Energy Resource
DL	Downlink
DMRS	Demodulation Reference Signal
DSL	Digital Subscriber Line
E2E	End-to-End
EAV	enchancements for UAVs
eCAV	enhancements for Contol Applications in Vertical Domains
EIRP	Equivalent Isotropically Radiated Power
eNB	evolved NodeB
eMBB	Enhanced Mobile Broadband
EMT	Emergency Medical Technician
eNB	Evolved NodeB
ePC	Option 3.x Enhanced PC
ETSI	European Telecommunications Standards Institute
FCC	Federal Communication Commission
FDD	Frequency Divison Duplex
fps	frames per second
FR	Frequency Range
FR1	Frequency Range 1- 410 MHz to 7125 MHz
FR2	Frequency Range 2 - 24250 MHz to 52600 MHz (mmWave)
FWA	Fixed Wireless Access
Gbps	Gigabits per second
GBR	Guaranteed Bit Rate
GDPR	General Data Protection Regulation
GE	Gigabit Ethernet
GEO	Geostationary Earth Orbit
gNB	Next Generation NodeB
GSMA	Global System for Mobile Communications Association
HAPS	High Altitude Platform Stations
HARQ	Hybrid Automatic Repeat Request
HD	High Definition
HEVC	High Efficiency Video Coding (also referred to as H.265)
HIPAA	Health Information Patient Accountability Act
HITECH	Health Information Technology for Economic and Clinical Health
HMD	Head Mounted Display
HPLMN	Home Public Land Mobile Network
IAB	Intergrated Access Backhaul

IAL	Inter-Aerial Links
IDC	International Data Corporation
IEA	International Energy Agency
IETF	Internet Engingeering Task Force
IMS	Internet Protocol Multimedia Subsytem
Intra-PLMN	Intra Public Land Mobile Network
IoT	Internet of Things
IIoT	Industrial Internet of Things
IPTV	Internet Protocol Television
ISL	Inter-Satellite Links
ITU	International Telecommunication Union
kbps	kilobits per second
KPI	Key Performance Indicator
LAN	Local Access Network
LCM	Life-Cycle Management
LEO	Low Earth Orbit
LoS	Line of Sight
LTE	Long Term Evolution
M2M	Machine-to-Machine
MAC	Medium Access Control
MBB	Mobile Broadband Network
MDU	Multi-Dwelling Unit
MEC	Multi-Access Edge Computing
MIMO	Multiple-Input Multiple-Output
MINT	Minimize Service Interuption in Emergency Events
MIOT	Massive Internet of Things
mmWave	Millimeter Wave
MNO	Mobile Network Operators
MPS2	Multi-media Priority Service - Phase 2
MR	Mixed Reality
ms	Millisecond
MSO	Multi-Service Operators or Multiple Systems Operator
MU-MIMO	Multi-User MIMO
MUSIM	Multi-UMTS Subscriber Identity Module Devices
NASA	National Aeronautics and Space Administration
NBP	National Broadband Plans
NCIS	Network Controlled Interactive Services
NEC	Network Edge Compute
NGC	Next Generation Controller
ng-eNB	Next Generation - evolved NodeB
NLOS	Non Line-of-Sight
NR	New Radio
NSMF	Network Slice Management Function

NSSI	Network Slice Subnet Instance
NSSMF	Network Slice Subnet Management Function
NTN	Non-Terrestrial Networks
OMEC	Open Mobile Evolved Core
ONF	Open Networking Foundation
OPEX	Operational Expediture
OTT	Over-the-top
PAPR	Peak to Average Power Ratio
PC	Packet Core
PCI	Physical Cell Identifier
PDB	Packet Delay Budget
PER	Packet Error Rate
PMU	Phasor Measurement Unit
PNF	Phyiscal Network Function
PRB	Physical Resource Block
PT-RS	Phase Tracking - Reference Signal
QCI	Quality of Service Class Identifiers
QoS	Quality of Service
RACH	Random Access Channel
RAN	Radio Access Network
RBS	Radio Base Station
Rel-	3GPP Release-#
REFEC	enhanced Relays for Energy Efficiency & Extended Coverage
RF	Radio Frequency
RGW	Residential Gateway
RLC	Radio Link Control
RM2M	Resilient Machine-to-Machine
RTT	Round Trip Time
Rx	Receive
SA1	SA Working Group 1 is responsible for Technical Specifications and Reports that form the basis for the work for the whole of 3GPP
SA6	SA Working Group 6 is responsible for the evolution and maintenance of Stage 2 technical specifications for application layer functional elements and interfaces supporting critical communications and other applications.
SCADA	Supervisory Control and Data Acquisition
SCS-CS	Sub-Carrier Spacing - Circuit Switched
SDTV	Standard Definition Television
SFU	Single Family Unit
SINR	Signal to Interference Noise Ratio
SLA	Service Level Agreement
SMA	Sub-Miniature Version A
SPID	Service Profile Identifier
TCP	Transmission Control Protocol
TDD	Time Division Duplex

TP	Transmission Point
TR	Technical Report
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicles (e.g., Drones)
UDP	User Datagram Protocol
UE	User Equipment
UGV	Unmanned Ground Vehicles
UHD	Ultra-High Definition
UL	Uplink
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communications
USB	Universal Serial Bus
UTM	Unmanned Aerial Vehicles Traffic Management System
UxNB	User Defined NodeB
VAS	Value-Added-Service
VNF	Virtualized Network Function
VoLTE	Voice over LTE
VoNR	Voice over New Radio
VP9	Video coding format developed by Google
VPN	Virtual Private Network
VR	Virtual Reality
WiMP	Wide-Area Multi-Point
XR	Extended Reality
V2X	Vehicle-to-Everything (communications)

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The mission of 5G Americas is to advocate for and foster the advancement of 5G and the transformation of LTE networks throughout the Americas region. 5G Americas is invested in developing a connected wireless community for the many economic and social benefits this will bring to all those living in the region.

5G Americas' Board of Governors members include AT&T, Cable & Wireless, Cisco, Ciena, CommScope, Ericsson, Intel, Kathrein, Mavenir, Nokia, Qualcomm Incorporated, Samsung, Shaw Communications Inc., Sprint, T-Mobile USA, Inc., Telefónica and WOM.

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