EXTENDED REALITY

and 3GPP Evolution

A 5G Americas White Paper

November 2022

Contents

Executive Summary

Extended Reality (XR) enhances our lived experiences with Augmented Reality (AR), Virtual Reality (VR) and Mixed Reality (MR). It creates either fully virtual, immersive environments or blends those virtual landscapes and features with the "real" world. Its use cases are not limited to consumer applications like gaming, but also include enterprise, institutions, and manufacturing. XR will influence the way people play, work, learn, and interact with each another. VR, but particularly AR, requires significant development in multiple areas including but not limited to multi-media, artificial intelligence, computing, display systems, and communication to provide experiences that incorporate XR into our daily lives.

Low latency, high reliability, lower power consumption and high capacity are key service requirements for the success of XR. 5G New Radio (NR) developed by 3rd Generation Partnership Project (3GPP) is designed to support emerging XR uses cases that require such Key Performance Indicators (KPI). While 5G NR benefits XR, potential enhancements for 5G and balanced KPIs require further end-to-end optimizations.

This white paper describes potential use cases with service delivery requirements. It also details how 5G can enable an end-to-end XR system, including how split computation architecture across various system components provides benefits for lower latency, higher reliability, higher rates, and less device computation. Rel-15/Rel-16 offers a decent foundation for XR but has not been specifically designed or optimized for XR support. The paper examines the evolution of 5G systems from Rel-15 and 16 that can be leveraged for XR, before describing potential enhancements recognized by 3GPP in Rel-17 through Rel-18 that are expected to optimize XR support including XR awareness, power optimizations, and capacity enhancements. The paper concludes by describing anticipated studies of localized mobile metaverse services in Rel-19.

1. Introduction

Extended Reality (XR) is an umbrella term for Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), as shown in Figure 1. XR will be the next-generation computing platform dictating our future relationship with the digital world by creating virtual experiences that are indistinguishable from reality. XR will majorly influence the way people play, work, learn, and connect.

VR is a digital render designed to mimic visual and audio sensory stimuli of the real world as naturally as possible to an observer or user as they move within the limits defined by the application. With VR, a user usually wears a head-mounted display (HMD) which completely replaces the user's Field of View (FoV) with a simulated visual component. The VR user may also wear headphones for accompanying audio. In addition, head and motion tracking of the user in VR allows the simulated visual and audio components to be updated to ensure that items and sound sources remain synced with the user's movements.[2]

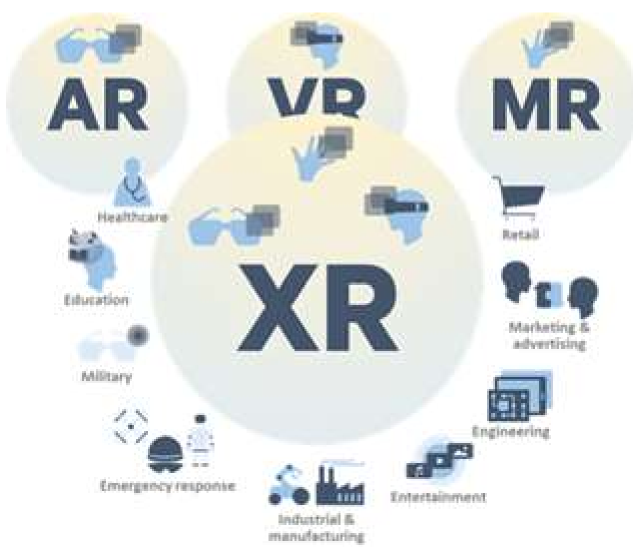
VR is gathering momentum, but much research is still needed to enhance the user's immersive experience. Advances include but are not limited to higher resolution, wider FoV, depth, haptic gloves, and audio propagation. With AR, artificially generated visual and audio content are overlaid on the user's current environment. Their observation of their current environment may be direct with no intermediate sensing, processing, rendering, or indirect, where their perception of their environment is relayed using sensors. With MR, virtual elements are inserted into the physical environment to provide the illusion that these elements exist in the real scene.

VR, and especially AR, remains in its early stages and needs immense research, innovation, and development before they are implemented practically in daily lives. These technologies include optics, projectors, display systems, graphics, audio, hand tracking, eye tracking, face tracking, body tracking, world mapping and reconstruction, and Artificial Intelligence (AI).

VR headsets provide visual input contained to the HMD, whereas AR glasses allow users to observe and use virtual objects overlayed in reality to annotate our world and interact with others. AR glasses and VR headsets operate within tight power and thermal budgets. AR glasses generally have small form factors and must operate within narrow budgets (lightweight, low power) to enable long sessions or all-day usage.

Cloud gaming (CG) is a closely related XR application that utilizes the edge server to render graphics on mobile devices. Game controller information is transmitted on the uplink, and the graphics rendered do not change on user movement and are generally with lower resolution compared to other XR systems. XR and CG[3] are currently one of the industry's most important 5G media applications under consideration.

Figure 1: Different types of XR services[1]



2. Evolution of XR

XR application enhancements need greater consideration as we move toward 6G. 5G technology improved access to high-quality video, but 5G-Advanced will offer more immersive user experiences, and 6G development is working to provide more holographic experiences. Digital twins, localization, and sensing are also being enhanced as these technologies move towards 6G.

Factors like ecosystem support and strong communication between device and network manufacturers cannot be overlooked. Communication and collaboration are necessary to enhance variables such as battery life, optics, power savings, and congestion control. Immersive media, 3D mapping, sensing, and content development drive the development of XR which needs lower latency and higher bandwidths. The journey to 6G is steadily progressing. Between now and 2030, consumers will continue to see optical improvements, more vivid images, and enhanced VR headset features like tracking for hands, full body, and facial expressions (see Figures 2 and 3).

Figure 2: XR is a long journey, consumer XR Devices Timeline[4]

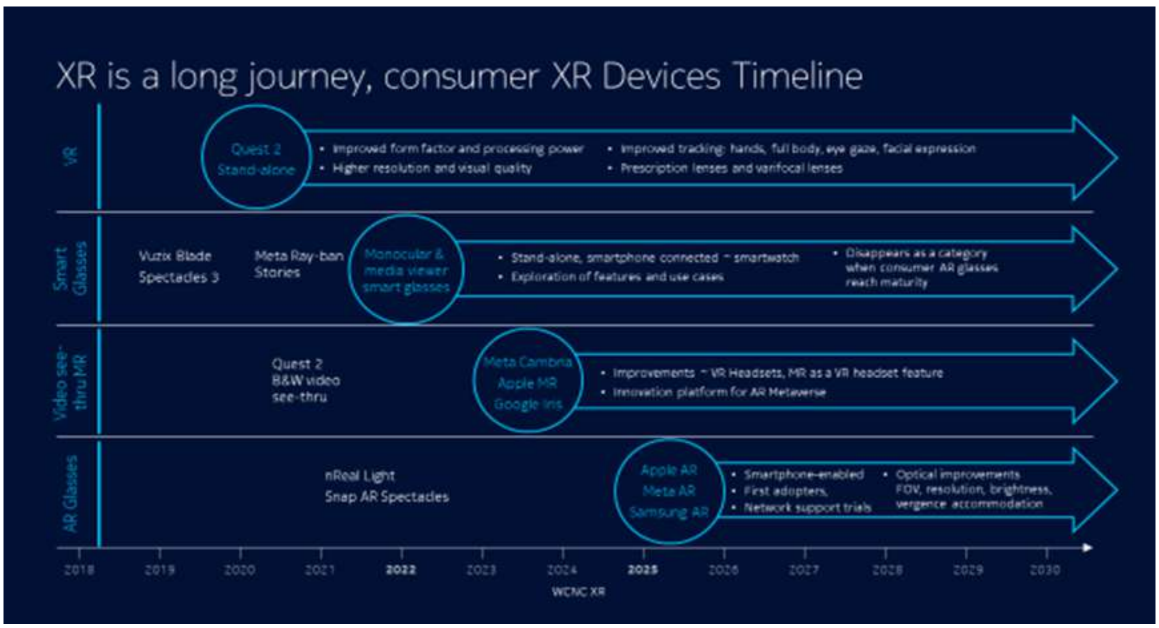


Figure 3: XR evolution on the networks level

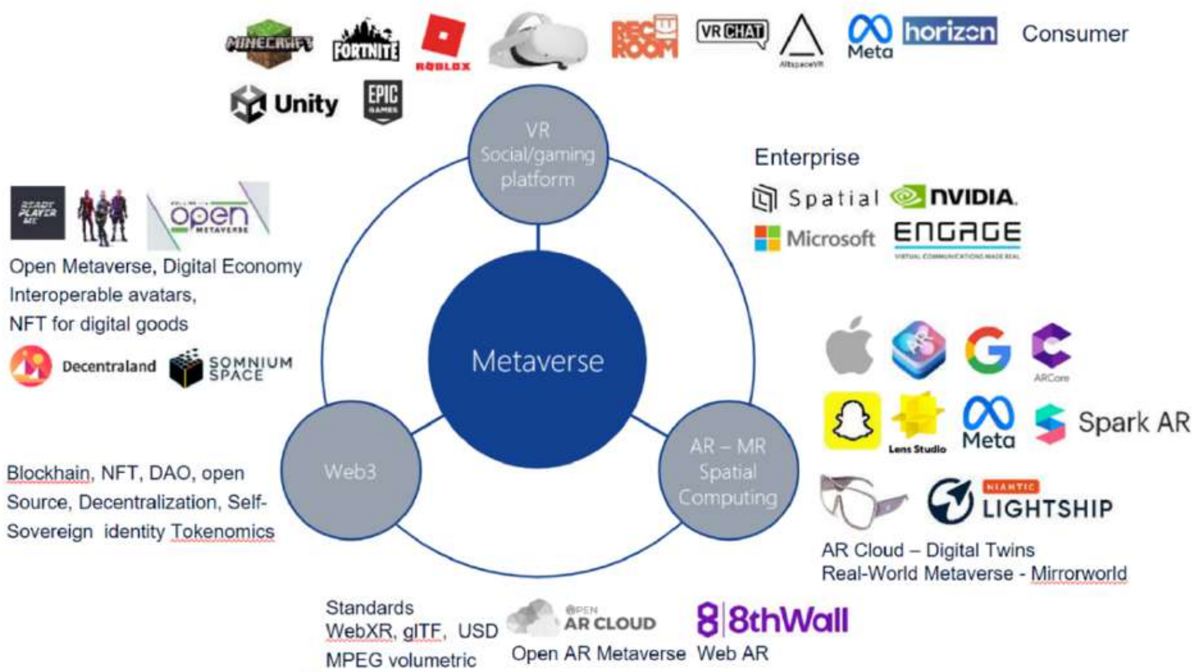
3. XR Key Facilitators and Use Cases

XR services are complex and mandate many novel functionalities. While complex, XR services will transform the way we communicate, learn, and play. XR services will be the cornerstone of enterprise applications, consumer applications, and everything in between. The metaverse and digital twins can successfully enable the deployment of future multi-sensory XR.

3.1 XR Key Facilitators

The Metaverse blends physical and digital worlds into one where XR users, content, and digital entities interact. The metaverse will bring XR to consumer homes, enterprise, and industrial realms. Users can see their physical actions reflected in the digital world and their virtual actions reflected in the physical world[56]. In essence, the metaverse can be a fictious world (e.g., video game realm) that mimics day-to-day life in a virtual and digital domain (e.g., a virtual replica of a power plant area).

Figure 4: Metaverse landscape



The metaverse could potentially usher in some form of blockchain technologies, crypto currencies or Non-Fungible Token (NFT) over a new iteration of the world wide web, i.e., decentralized web. This could be a fundamental pillar enabling the world of distributed applications (dApps) as it reinvents how data moves through the overall network backbone. Essentially, it is an infrastructure layer that can transform the flexibility of dynamic data. This new modus-operandi presents challenges with operational and energy efficiencies, but also provides new opportunities to make users a central part of this new internet and economy.

Digital Twins: Digital twins constitute the fundamental link between the real world and the metaverse, and have been made possible largely by the Industrial Internet of Things (IIoT). Digital twins guarantee end-to-end digitization of complex physical assets, and consist of a physical and cyber twin. Tuneable, corresponding XR content for complex physical assets necessitates a digital twin.

Artificial Intelligence (AI), Machine Learning (ML), and Autonomy: AI and ML have influenced almost every industry by reshaping the limits of high-tech. Service and operational intelligence are necessary to guaranteeing the successful and efficient performance of XR services and for providing XR via wireless access. Service intelligence is used within the application itself like ML pertaining to rendering, actions related to the VR scene, and coordination of multiple holograms. Operational intelligence provides the network with intelligent mechanisms to perform optimization and self-sustainability in complex services like XR[7]. Ensuring end-to-end digitization of complex physical assets necessitates utilizing Internet of Things (IoT) devices and sensors. IoT devices with limited compute power are seeing developments that promise to unleash their true potential with edge compute capabilities that enable decision making, pre-emptive maintenance, and more. Enterprises can also benefit from smarter IoT ecosystems with advanced building management systems that encourage sustainability.

Ultimately, successful deployment of the metaverse and digital twins guarantees successful emergence of XR services that are expected to penetrate versatile sectors and verticals, as shown in Table 1.

Table 1: XR Use Case Types

Use Case Types Industry Verticals	Cloud Gaming/ Sports	Virtual Events/ Collaboration	Education	Public Safety/ Healthcare	AI/IOT
Consumer	X	X	X	X	
Public Institutions		X	X	X	
Enterprise		X			X
Manufacturing		X			
FMCG		X			
Simulations	X				

3.2 VR Use Cases

VR was first renowned for the way it transforms screen-limited video games into fully immersive experiences. As a result, VR has catalysed significant evolution in the gaming industry leading to a paradigm shift in various industry verticals.

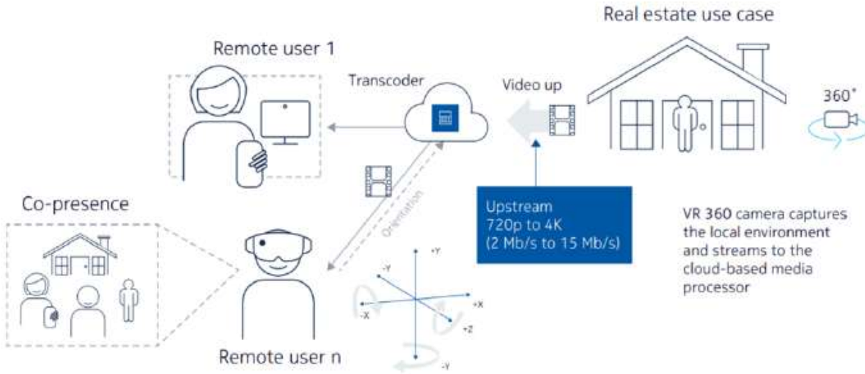
3.2.1 Online Immersive Gaming

Users can teleport from their living room to places like sporting stadiums, fantasy realms, or simulated battlefields to experience seamless multi-player gaming experiences. Cloud-native applications and cloud gaming have opened the door for this new avenue of game engagement. While this concept is still developing, VR gaming will propel a novel gaming metaverse and online ecosystems. For instance, games like Roblox and Minecraft have 10x in-app usage vs. Twitter and Facebook; its influence is undeniable[8].

3.2.2 Virtual Event Participation

It was not so long ago that the idea of instantly teleporting to another place seemed like science fiction. However, with the available VR technology, maturity of the metaverse, and robust network, participating in highly immersive virtual events in near real-time is becoming a reality. Virtual events are vastly inclusive, encompassing a wide spectrum from concerts and fashion shows to team collaboration. Users can attend virtual concerts or host their own virtual events for customers, friends and family across states and countries, e.g., a virtual open house. Enterprises also have opportunities to collaborate globally. For instance, a user could attend an immersive, virtual town hall meeting and after, “walk out” and order a pizza within the same virtual environment and pay with cryptocurrency. The user could consume the pizza virtually, but also once delivered to their physical location.

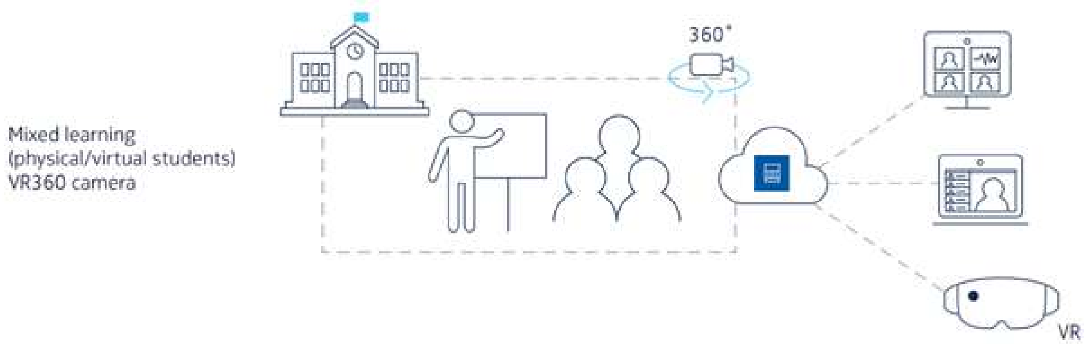
Figure 5: Virtual open house use case



3.2.3 Educational Experiences

The COVID-19 pandemic made it evident that educational resources and mediums backbone should not be limited to classrooms and in-person settings. Education must be accessible remotely from anywhere, at anytime. Throughout the pandemic, many users were inhibited by connectivity constraints and the inability to solicit their physical senses to understand learning modules and seamlessly engage in classroom discussions. A VR classroom experience enables users to erase the boundaries between in-person and remote boundaries. The "360 camera" allows remote students to experience the classroom setting in a more immersive manner[9]. In addition, the virtual world can usher in access to remote areas that go beyond online classes through virtual museum visits, virtual lab or company visits, and more hands-on approaches to learning. Research by Stanford University suggests that XR-enabled methods can lead to a 76% increase in learning efficiencies[10]. Access to customized study plans and learning material significantly benefits not only students, but also teachers.

Figure 6: Mixed physical and virtual classes use case



While mission-critical services have a larger reach with AR services (described in Section 3.3.2), VR can further revolutionize public safety response education through voice-driven training, and re-imagined, low-cost, remote Advanced Cardiac Life Support (ACLS) training for first responders. It also allows for early testing and calibration in simulated scenarios that can reduce the possibilities of error in actual emergencies.[11] [12]

3.3 AR Use Cases

VR and AR share common denominators and use cases, but with varying methods of delivery. AR supplements our day-to-day life with virtual components rather than immersing the user in a virtual world.

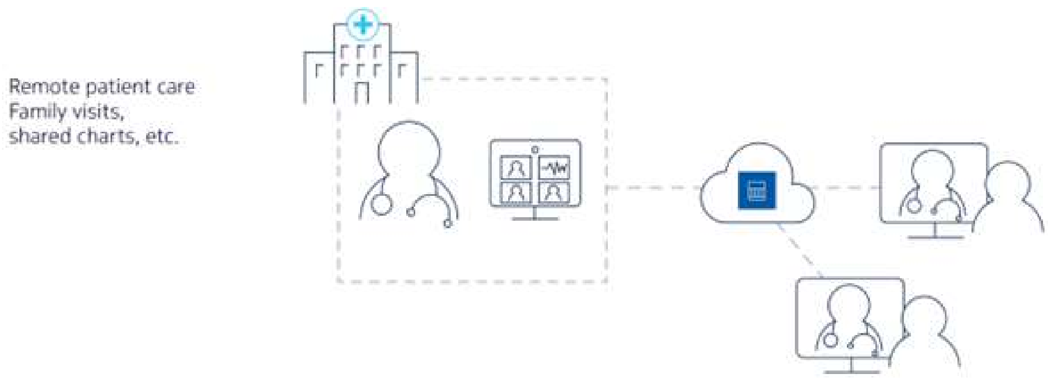
3.3.1 Mobile AR Video Gaming

Like immersive gaming experiences in VR, AR can leverage mobile phones, wearables, and AR glasses to supplement AR content in our daily lives (e.g., Pokémon Go). Ensuring the smooth flow of AR contents and their synchronization with the real world is ensured with the advancement of wireless networks that deliver reliable low latency while guaranteeing an extremely high rate. One facilitating approach is the migration of cloudification of versatile interfaces and edge-enabled access[13].

3.3.2 Mission Critical Services

AR services are expected to exert major influence over multiple mission-critical services, from public safety applications to healthcare and industrial manufacturing. AR is a portal to a new avenue of tunability, engineering, and intervention. A medical doctor can perform remote surgery on teleported patients, and engineers can fine-tune machinery cyber-twins. The navy can execute missions with overlaid AR content. XR enables transcending mission-critical tasks to be operated in the metaverse. That said, it is necessary to ensure that the goal of each service is attained within adequate safety measures. To do so, the end-to-end latency needs to be minimal to mitigate any risks and ensure a seamless execution of the task. Ultimately, this kind of feature promises access to healthcare from remote places without needing emergency transport.

Figure 7: Remote healthcare



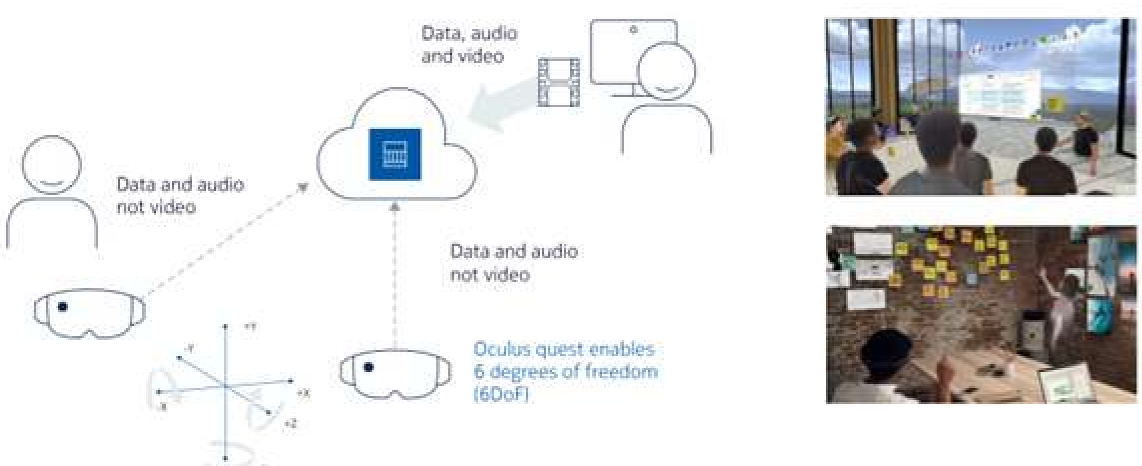
3.3.3 Online Shopping

The COVID-19 pandemic impacted many businesses and owners, leading to the closure of many shops, particularly small businesses. During that time, stores with online shopping venues faced less economic backlash, but the online shopping sphere still lacks some crucial features, like feeling the material, trying clothing on, and examining the size of the objects. AR can provide users with an immersive browsing experience in their favourite stores, and examine the texture, size, and real color of their purchase from the comfort of their home.

3.3.4 Spatial-Audio Multiparty Calls/Conferences

Conference and multiparty calls have always lacked the human-centric component when relying solely on a screen, camera, and microphone. However, AR can remedy users' device limitations with holograms that solicit their senses to communicate and converse with each other. Here, the role of body language, gestures, and facial expressions will ensure a smoother human interaction that mimics real-time face-to-face experiences.

Figure 8: Avatar virtual collaboration spaces



3.3.5 Digital Co-design

Co-design systems are designed to aid in creating innovative products and incorporating them into a virtual-real environment. This process allows designers to focus on the practical design and its relationship with the external environment by integrating context awareness. Spatial computing may be emphasized by capturing data using spatial mapping and imaging technology. Capturing movement, emotions, and facial expressions are vital with co-design, so using new forms of man-machine interactions is just as vital to measurements of the human body. Coupling the creativity of co-design with advanced user equipment and wearables will transform the next generation of Industrial IoT, because designers and practitioners require real-time shared platforms to work on projects simultaneously and make progress. Many enterprises, not limited to manufacturing, are experimenting with this concept. While the benefits of Co-design vary by project and vertical, early indications show substantial benefits.

4. XR Service Characteristics and Delivery Requirements

5G services consists of three main thrusts: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable and low latency communications (URLLC). eMBB is designed to cater to the additional capacity needed to accommodate higher peak data rates for big crowds and mobile user equipment. Examples include high resolution multi-media services and 3D content. mMTC services are characterized by a massive number of sensors or connected devices, typically necessitating a considerably low volume of non-delay sensitive data (e.g., smart grids, smart cities, etc.). URLLC services refer to services that are expected to have exceptionally low latency and extreme high reliability. Such services are predominantly seen in mission-critical services like IoT devices used in surgeries or traffic safety.

XR traffic characteristics include quasi-periodic traffic in large chunks, irregular intervals and variable size, high data rate including uplink (UL) for AR services, simultaneous transmission of 3D video stream, and control data over the same e2e connection. In addition, other key characteristics include low power consumption to extend battery life and minimize heat dissipation for user comfort, and tight delay and reliability constraints to meet user Quality of Experience (QoE).

XR services do not easily fall exclusively under any of the three main thrusts of 5G because they simultaneously necessitate the delivery requirements of eMBB and URLLC. The next sections delve into details of wireless delivery requirements of VR, AR, MR, and beyond XR, delivery limitations of current 5G systems, and network aspects that require a major overhaul to fulfill the requirements of future XR services.

5G-Advanced is set to evolve 5G Systems to its fullest capabilities from 3GPP Rel-18 onwards. The innovations from a large number of 3GPP 5G-Advanced items will offer improvements to: daily experiences for people and machines, extensions for new services, and expansions to offer new functionalities. In addition, these technological innovations will provide operational excellence. Among others, it will continue to improve coverage and capacity, enhance end-user experience, and expand 5G capabilities beyond connectivity.[14]

4.1 VR Wireless Requirements

VR's ultimate goal is metaverse immersion: a state of deep involvement, absorption or engagement. Simulating an experience of "actually being there" can be achieved if the network satisfies the application-level metrics such as display (or content) resolution, FoV angles, and application "lag". Consequently, VR services must first immerse the user in a high-fidelity visual component. Guaranteeing the successful delivery of this visual component requires the wireless network to deliver extremely high data rates.

Second, VR services must immerse the user in a multi-sensory experience predominantly through the haptic component. Guaranteeing the successful transmission of the haptic component requires taming the reliability and the latency of the end-to-end system. Here, it is important to note that for early generations of VR, a multi-sensory experience was not necessary. Additionally, the fidelity of the visual component was not as significant as in current and future XR generations.

Wireless service requirements are therefore dependent on the current VR generation. Early deployments of VR only consisted of 360 videos or 360 videos with simple haptic feedback. This simple generation of VR services, categorized as "Advanced VR" [15], requires a video resolution of full-view 12K video, and transmission data in the range of 796 Mb/s-11.94 Gb/s. The data rate range varies based on the compression technique performed on VR content. A lossy compression would require a less stringent data rate but would lead to a generation loss. Meanwhile, lossless data compression is more efficient but would impede the wireless network with a more stringent data rate. Here, given that 5G downlink and uplink targets could possibly be more than 50 Mb/s almost everywhere, it will be hard to implement this on a large scale (wide area network) via a 5G network. The maximum downlink data rates can be

Figure 9: 5G services thrusts

up to 1 Gb/s, and one can roughly use 5G to satisfy advanced VR requirements. However, such VR experiences would not be multi-sensory and would suffer from a lossy data compression process. Here, such VR services would benefit from eMBB's high data rate capability.

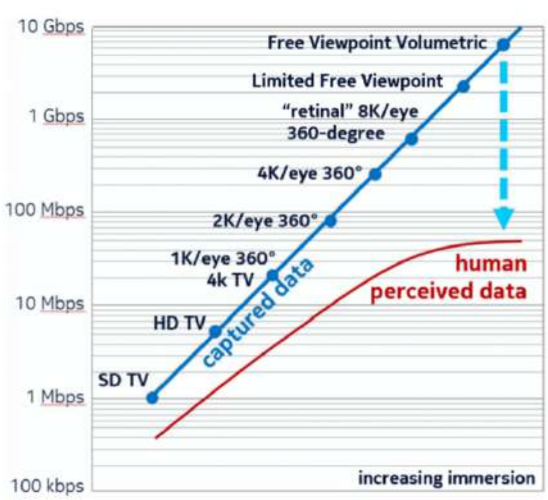
Figure 10: Quality of Service (QoS) requirements for VR phases

Requirement		Pre-VR	Entry-level VR	Advanced VR	Human perception	Ultimate VR
Experience duration		Less than 20 minutes	Less than 20 minutes	Less than an hour	/	More than an hour
Video resolution		3840 × s1920 (full-view 4K video)	7680 × 3840 (full-view 8K video)	11,520 × 5760 (full-view 12K video)	21,600 × 10,800 (full-view video)	23040 × 11520 (full view 24K video)
Single-eye resolution		1080 × 1080	1920 × 1920	3840 × 3840	9000 × 8100	9600 × 9600
Field of view (single-eye)		100 × 100	110 × 110	120 × 120	150 × 135	150 × 150
Bit per color (RGB)		8	8	10	/	12
Refresh rate		60	90	120	120	200
Pixel per degree		10	17	32	60	64
Service Requirement	Uncompressed bit rate (progressive 1:1)*	10.62 Gb/s	63.70 Gb/s	238.89 Gb/s	1007.77 Gb/s	1911.03 Gb/s
	Transmitting bit rate (low-latency compression 20:1)	530 Mb/s	3.18 Gb/s (Full-view) 796 Mb/s (FoV)	11.94 Gb/s (Full-view) 5.31 Gb/s (FoV)	50.39 Gb/s (Full-view) 31.49 Gb/s (FoV)	95.55 Gb/s (Full-view) 66.36 Gb/s (FoV)
	Transmitting bit rate (lossy compression 300:1)	35 Mb/s	210 Mb/s (Full-view) 53 Mb/s (FoV)	796 Mb/s (Full-view) 354 Mb/s (FoV)	3.36 Gb/s (Full-View) 2.10 Gb/s	6.37 Gb/s (Full-view) 4.42 Gb/s (FoV)
	Typical eound-trip time (RTT)	10 ms	10 ms	5 ms	10 ms	5 ms
	Typical packet loss	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}

* Progressive data rate = (3 × bit per color) × (pixel per degree × field of view (full-view or single-eye)) × refresh rate/compression ratio

The 'captured data' curve in Figure 11 depicts the rising data rate at the acquisition side for various established and emerging video formats on a logarithmic scale. The 'human perceived data' curve in Figure 11 shows the amount of data for various video formats that is perceived by a viewer at a particular moment in time, taking into account the natural limitations of the human eye.[16]

Figure 11: Human perceived data rate while streaming video versus captured data rate.



Current 5G systems fall short in supporting tactile intensive VR experience. In essence, multi-sensory VR services require high data rates, high reliability, and low latency simultaneously. Here, this experience mandates what eMBB and URLLC can deliver simultaneously. Pertaining to the latency requirements, VR poses an instantaneous requirement on the wireless network compared to the traditional average latency KPI.[17] This showcases that 5G falls short in delivering an "Ultimate VR" experience where data rates in the range of 6.37 -95.5 Gb/s (the range varies based on the compression technique) need to be attained and a maximum end-to-end latency of 5 ms needs to be achieved.

The end-to-end latency KPI stems from motion-to-photon (MTP) latency. In essence, reducing the motion-to-photon latency is a key metric for reducing motion sickness when immersed in a VR experience. It is the delay between the action and reaction of a VR user depicted by the movement of the user's head and the changes in the VR content observed. Another key metric regarding motion sickness that needs maintenance is jitter, or the difference in the latency perceived by the user over time.

Enabling high data rates, high-reliability, and low latency simultaneously for VR can be achieved by resorting to versatile avenues, but the tradeoff between diversity and multiplexing is inevitable. For instance, the data rate issue can be resolved by resorting to more abundant bandwidth at higher millimeter wave (mmWave) bands. The sub-THz range can indeed fulfill the rate needs, but such bands are highly susceptible to factors like blockage and molecular absorption, and lack robusticity for mobility, significant communication range, and beam misalignment. Relying on ultra-massive multiple-input-multiple-output (MIMO) base stations can enhance data rates, and Reconfigurable Intelligent Surfaces (RIS) can improve the reliability of line-of-sight (LoS) links. However, such bands and techniques are inherently unreliable and cannot guarantee consistent dependability.

Tiling scheme-based streaming strategies exist for the generations older than entry-level VR that limit the size of transmitted content and reduce data rates and delay requirements imposed on the wireless network. Such tiling schemes implement a useful trade-off between bandwidth consumption and coding efficiency and can be utilized in settings where bandwidth is limited to more evolved VR generations. However, such tiling-based streaming strategies limit the 360° quality of VR video perceived. While such streaming schemes are useful, they are limited in their applicability to more evolved VR generations.

AI and ML mechanisms that can enable enhanced real-time network optimization must be considered to tame high reliability an achieve low end-to-end latency.[18] Processes occurring at multiple layers, ranging from beam-tracking to resource block allocation and VR field-of-view optimization, need to be governed by low-latency aware AI mechanisms. Nonetheless, current ML and AI mechanisms face multiple challenges with delivering stringent wireless requirements. Their predictive capability provides the network with more awareness and robustness towards processes occurring at various layers; however, their performance relies on large datasets and requires lengthy training times or exploration periods. Evidently, this nascent, open problem is fundamentally important to guarantee a robust network performance when delivering XR services.

VR services predominantly occur in indoor areas, and this key advantage can benefit from fixed wireless access using higher frequency bands. Here, the reliability and low latency of the overall performance can be better controlled in an indoor environment.

4.2 AR Wireless Requirements

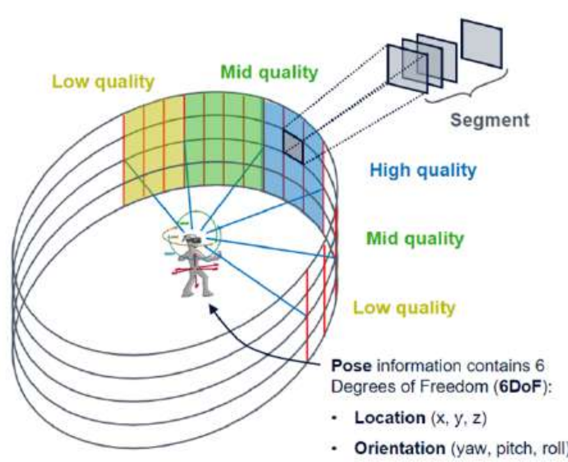
AR's goal seeks to overlay the user's reality with virtual components that are up and running in the metaverse, or with cyber twins of a physically complex asset in real-time. Like VR, AR mandates a high data rate, reliability, and low latency simultaneously when granted in a multi-sensory setting. AR requires less immersion for a supplementation of objects in users' daily lives compared to full immersion into the metaverse, so rate requirements can be slightly lower than VR.

AR mainly depends on the user's interaction with the AR components in real time, so such components must actively update and accompany the correct spatial-temporal constraints of the user's daily life. In addition to minimizing the end-to-end latency, outdated information in an AR network can potentially lead to tremendous risks when deployed in mission-critical services. The freshness of information can be quantified by the concept of Age of Information (AoI).[19] AoI depends on generating and transmitting AR content while capturing the freshness of receiver information. Given that AR depends on the user's input more than VR, AR necessitates a high-rate bidirectional (downlink and uplink). Therefore, it is important to propose novel, AI-oriented network optimization frameworks that can guarantee a wireless AR service with high-rate, reliable, and low-latency bidirectional links.

4.3 MR and Beyond Wireless Requirements

The concept of MR is not concretely defined by academia or industry. Nevertheless, MR's main objective is to combine the capabilities of AR and VR in the same device. MR uses

Figure 12: Example of view-port dependent virtual reality streaming



pose information with up to six degrees of freedom (6DoF)[20] (position [x, y, z], and rotation [yaw, pitch, roll]) to minimize data rates by only sending the visible field of view, known as “view-port dependent VR streaming”.

MR is evolving alongside 3D imaging technology to create the highly coveted holographic teleportation application domain. Holographic teleportation is the evolution of ultimate extended reality, whereby the user needs to solicit their senses. In addition to stringent XR wireless requirements, holographic teleportation requires massive data rates in the range of 5 Tbps.[19] Immersing the user in the metaverse requires tight synchronization between the holographic flows when considering user sense solicitation. Therefore, the risk of putting the user in a motion-sickness state grows substantially as the requirements for delivering this service are more stringent than in previous XR generations.

On top of connectivity requirements, different types of sensing modalities are necessary to deploy multi-sensory XR over wireless networks. Effectively, high-precision and high-resolution tracking feedback are necessary to provide information about the 6DoF of each user’s head and body with a cognizant situational awareness of the XR user’s surroundings. Empowering a wireless network with such capabilities can also be done by leveraging higher frequency bands (similarly to the high data rate requirement).[19] These bands can provide a high-resolution sensing capability with their large bandwidth if properly deployed. Fully multi-sensory XR and holographic teleportation has not been realized yet and requires a lot of technological advancements on the device, network, and technology level.

5. XR Key Enablers

5.1 Split Computing/Rendering Architecture

While the long-term vision to the metaverse is 5G powered AR glasses (Figure 13.1) that connect directly to the cloud, a near-time solution are Wi-Fi-powered AR glasses that communicate to the cloud via a 5G enabled phone or laptop (Figure 13.2). In the future, a 5G AR glass may utilize either 5G or Wi-Fi as available (Figure 13.3), and a seamless experience between Radio Access Technologies (RATs) is preferred for the best user experience. One option to realize low power consumption modem is through the Release 17 Reduced Capability (RedCap) features by limiting the bandwidth to 20MHz and the number of antennas to two, again, as an option.

In the Edge-to-Phone-to-Glass AR system of Figure 13.2, the glasses communicate with the phone over Wi-Fi, and the phone communicates with the server over 5G. In split XR architecture the user's pose and video information flow from the glasses to the phone to the server. The server processes the data and sends the encoded graphics back via the phone to be displayed onto the glasses. The split XR system leverages computing power from the edge compute server for graphics rendering. The Round-Trip Time (RTT) for this entire process is called Motion to Render to Photon latency (M2R2P), as illustrated in Figure 14. The Wi-Fi and 5G RTT are key components of this M2R2P. This 5G round-trip includes the time required to transport a complete video frame and the pose information between the server to the device along with scheduling, queuing delay, and propagation delay in core networks.

Figure 13.1: Direct Connect

Figure 13.2: Phone-to-Glass

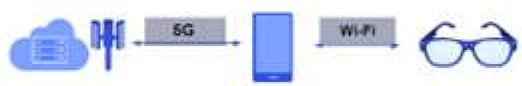
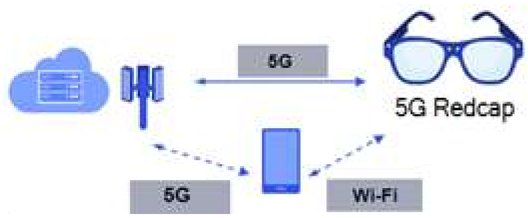


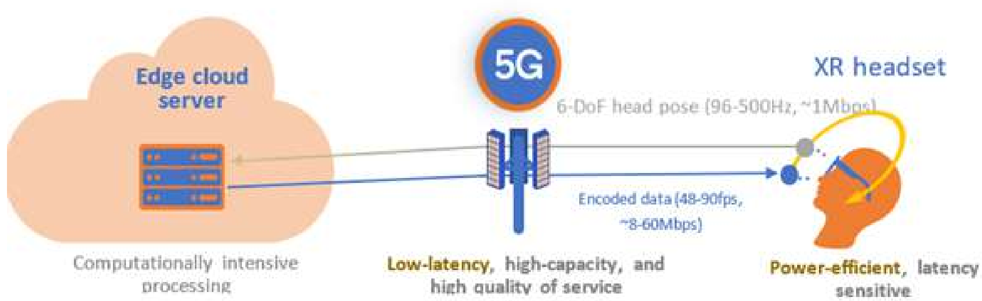
Figure 13.3: 5G AR glass utilizing 5G or Wi-Fi



Different XR devices may differ in tethering between the device carrying the 5G Uu modem and the XR device, the placement of the 5G Uu modem, the XR engine and localization support, the power supply, and the typical maximum available power. Sensors are placed on all device types. The XR engine can be broadly divided into:[21]

- **External:** The device only supports display. Any scene recognition, if applicable, is not on the device.
- **Split:** The device performs viewport pre-rendering and post-rendering. With split rendering, the computation between the server and the device may deliver truly immersive and enhanced experiences. Varying types of architectural splits differ by the functional split of main tasks between the XR servers and XR devices. With split compute/rendering, network functions run an XR engine to support processing and pre-rendering of immersive scenes, and the delivery is split into more than one connection, e.g., Split rendering, Edge Computing, etc. The latency and interaction requirements depend on the use case and the architecture implementation.
- **XR device:** A device that does full rendering of the viewport in the device.

Figure 14: Split XR architecture with M2R2P latency = 5G RTT + Device processing + Server Processing



5.2 Edge Computing

5G NR multi-access edge computing (MEC) brings applications, storage, switching, and control functions closer to the location where they are needed, which improves data processing and reduces latency. Moving on-device processing to the cloud allows for faster response times and lower battery usage, potentially transforming industries such as manufacturing, transportation, entertainment, and more. With edge computing, User Equipment (UE) can access services hosted close to the serving Base Station (BS). Lower latencies can improve end-user experience, while reduced backhaul transport requirements can improve network efficiency. Hosting services close to the serving BS means that there is User Plane Function (UPF) and DN (Data Network) of Local Area Data Network (LADN) at a location which is geographically close to the serving BS. The UPF and the DN/LADN could be co-located with the base station, or they could be co-located with a router within the transport network.

Figure 15: Cloud and edge processing[22]

The role of edge computing as a network architecture is an important consideration for enablement of XR and CG. For example, a museum could use AR to provide visitors with additional information as they tour the venue. The edge computing application could run on a local server which recognizes and tracks the visitor's location and provides relevant location information. As such, edge computing may provide several benefits, such as lower latency, higher bandwidth, and reduced backhaul traffic.

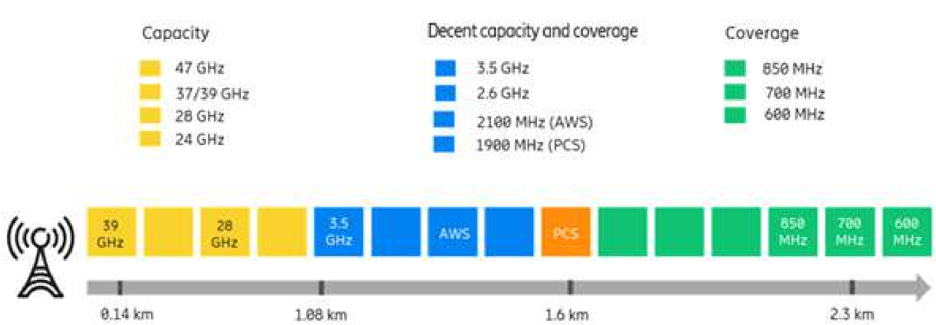
The SA6 Study on application architecture enabling Edge Applications[23] defines the necessary modifications to 5G System architecture to enhance edge computing. XR edge applications are expected to take advantage of the low latencies enabled by 5G and the Edge network architecture to reduce the end-to-end Application-level latencies.

In addition, 3GPP TR 23.758 and 3GPP TS 23.558 identify a new set of application layer interfaces for edge computing that are potentially useful for the integration of edge computing. Specifically, the interfaces will enable application-layer discovery of Edge Application Servers, capability exposure towards the Edge Application Server, and procedures for onboarding, registration, and lifecycle management of Edge Applications.

5.3 Spectrum Considerations

A good XR user experience requires high data rates, high-reliability, and low/ultra-low latency simultaneously. Although reliable and ideal for mobility, FR1 has capacity restrictions due to limited bandwidth. The mmWave and sub-THz bands can fulfill data rates and latency requirements but have limited range and mobility. Overcoming the spectrum challenges utilizing AI and ML technology to bring in high reliability and data rates will be crucial to the overall consumer experience [24].

Figure 16: Showcasing spectrum capacity vs. coverage considerations



6. XR in 3GPP Standards

XR is a service between URLLC and eMBB requiring a balance among KPIs which include high reliability, low latency, low power consumption and high capacity. 3GPP introduced 5G NR in Rel-15, which is mainly for eMBB with some support for URLLC. XR can leverage 5G NR as a basis with further XR specific enhancements. The following sections outline XR in 3GPP releases.

6.1 XR in Rel-15/Rel-16

Rel-15/Rel-16 introduced features for URLLC and power savings that provide higher reliability, lower latency, and larger power savings, but these features have not been specifically designed and optimized for XR. For example, these features do not account for XR's periodic traffic that comes in larger burst sizes. Moreover, some features may trade reliability and latency for throughput. Consequently, this decreases network capacity and the number of XR users that can be reliably served. Rel-17 XR Study Item (SI) and current Rel-18 targets XR-specific enhancements, but some Rel-15 and Rel-16 features that support low latency and/or power savings could be baseline features for XR. Rel-15 enhancements such as mini-slot transmissions, downlink preemption, grant-free transmissions, and frontloaded DMRS (Demodulation Reference Signals) enable low latency and are useful for XR applications.

At the physical layer, enhancements for providing higher reliability and lower latency included the support of new Downlink Control Information (DCI) formats: DCI format 0_2, DCI format 1_2, and DCI format 2_4. Additionally, the legacy DCI formats include new fields. Priority Indicator is a one-bit indicator that signals High Priority or Low Priority to facilitate the intra-UE prioritization to resolve traffic conflicts. XR applications can potentially benefit from these features given the tight latency requirement and the need to prioritize low latency XR traffic to meet delay budgets.

With dynamic power boosting introduced in Rel-16, a UE with enhanced power control may be boosted over eMBB, i.e., transmitting a low latency traffic transmission power. Rel-16 also introduced uplink cancellation that allows a UE to get uplink resources for latency-sensitive services which may be previously assigned to another UE. All these features benefit XR services requiring low latency.

XR devices have a small form factor and may benefit from lower power consumption to save battery life. Rel-16 introduced enhancements to save UE power that may be considered baseline schemes for XR devices. The key features include a Physical Downlink Control Channel (PDCCH) wake–up signal (PDCCH-WUS), which indicates to the UE whether PDCCH is to be transmitted in the Connected Mode Discontinuous Reception (CDRX) OnDuration. If no indication is present, the UE can continue to sleep through CDRX OnDuration and save battery power.

Some features that are useful for XR scheduling could be the use of uplink configured grant (ULCG) for the UL XR video data transmission. When compared to a dynamic grant (DG), ULCG reduces the overhead of a scheduling DCI. Moreover, the UE does not need to transmit Scheduling Request (SR), monitor PDCCH for UL grant, transmit a Buffer Status Report (BSR) and then finally transmit UL data. This reduces latency and allows UL packet transmission to meet the PDB. However, the configuration of resource allocation of ULCG is semi-static, and enhancements might need to be adapted to the variable packet size.

The UE may use the UE Assistance Information (UAI) to indicate its preferred power savings parameters, such as providing preference on the parameters of the CDRX configuration. This allows a UE to adapt to different applications and bandwidth, thus saving more power. Furthermore, the maximum number of multiple input multiple output (MIMO) layers, maximum aggregate bandwidth, and the maximum number of component carriers may also be adapted based on UAI.

Specific work for XR was initiated in Rel-16[25], where the SA4 Work Group (WG) introduced XR by providing definitions, core technology enablers, and a summary of device form factors. It further identified the relevant client and network architectures, application programming interface (API) s, and media processing functions that support XR use cases. In addition, the media formats, including audio and video, accessibility features, and interfaces between client and network are required to offer such an experience were identified. Also considered were key performance indicators and QoE metrics for relevant XR services.

While XR services can build on 5G NR, there are key issues that have been recognized in 3GPP as part of the "Study on XR enhancements for NR" in Rel- 17, and the 5G system is expected to evolve to address the issue through Rel-18 and beyond. The next sections provide a system level overview of the 5G evolution to better support XR.

6.2 XR in Rel-17

This section provides an overview of the XR Study in Rel-17, “Study on XR enhancements for NR”. Table 2 summarizes relevant 3GPP Rel-17 efforts in the context of XR.

The Rel-17 SI in RAN1 was coordinated with SA4, and the adopted statistical traffic model for CG/AR/VR traffic for downlink and uplink is shown in Table 3 and Table 4. The video frame size is assumed to be generated from Truncated Gaussian Distribution with [standard deviation, min, max] of [10.5%, 50%,150%] of mean data rate. Jitter for frame arrivals into 5G systems is also assumed to be Truncated Gaussian with [standard deviation, min, max] of [2, -4, 4] msec. On the uplink, all XR services contain the uplink flow that carries frequent small control packets such as from UL pose/control of the HMD. The delay bound for this type of flow is small (10 msec). The SI considered the evaluation methodology for capacity, power, coverage, and mobility. Performance evaluations were presented, as such, for these aspects. The study resulted in the Technical Report (TR) 38.838.

The SI TR 38.838 includes the potential enhancements with the evaluation results for increasing XR capacity and decreasing power consumption. The evaluations were based on multi-cell system level simulation. The evaluation methodology includes the XR traffic model, deployment scenarios, UE configurations, BS configurations, TDD UL-DL slot format pattern, etc. In addition, it was agreed that UE power and capacity are jointly evaluated to avoid adopting any power enhancement that can cause a decrease. The most major issues and design challenges for XR are discussed in the following sections.

Power Savings Enhancement: The power study aims to understand the NR UE power consumption performance for XR applications, and identify any issues and performance gaps which could be useful for understanding the limitation of current NR systems in supporting XR applications, and the potential directions for necessary future enhancements to improve power efficiency. The main power savings issues are:

- **Mismatch between the CDRX cycle and XR traffic periodicity:** A tempo mismatch exists between the Rel-15 and Rel-16 CDRX cycle values and the XR DL frame arrival periodicity. The typical XR DL frame rates are 60, 120 frames per seconds (fps), of which frame periodicities are 16.67ms, 8.33ms while the configurable Rel-15/ Rel-16 CDRX long cycle values are 10, 20, 32, 40ms, etc. and short cycle values are 2, 3, 5, 6, 7, 8, 10, 14, 16, 20, 30, 32, 35ms, etc. Since CDRX cycle values support only integer multiples of 1ms, no matter which cycle periodicity is chosen from currently available values from 38.331, it cannot be exactly aligned with DL frame arrival timing. The following figure illustrates the mismatch between 60fps and CDRX cycles of 16ms and 17ms. This mismatch would lead to XR capacity loss due to larger latency and/or larger UE power consumption to keep the same latency performance.

Figure 17: Mismatch between XR DL traffic (60fps) and R15/16 CDRX periodicity

Table 2: XR Rel-17 Study Items and Work Items

WG	SI/WI TR
SA1	XR (and Cloud Gaming) use cases are outlined in SA1 study item on Network Controlled Interactive Services (TR 22.842)
SA2	Work item on 5G System Enhancement for Advanced Interactive Services (SP-190564) proposes to introduce new 5Q1s to identify the requirements on traffic from SA1 NCIS
SA4	Feability Study on Traffic Models and Quality Evaluation Method for Media and XR Services in 5G Systems (TR 26.926)
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 Application (TR 23.758)
RAN1	Study on XR Enhancements for NR (TR 38.838)

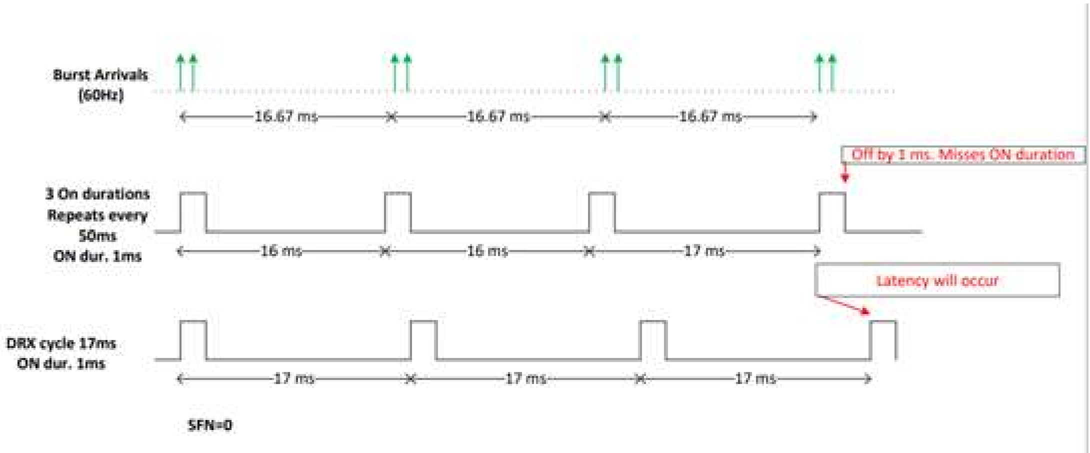
Table 3: Traffic models and QoS constraints used to evaluate XR applications in DL direction

Application	CG	VR	AR
Traffic model	Video single-stream	Video single-stream	Video single-stream
Bitrate	30 Mbps	30 Mbps	30 Mbps
Packet rate	60 fps	60 fps	60 fps
Packet Delay Budget (PDB)	15 ms	10 ms	10 ms
Packet Error Rate (PER)	1%	1%	1%
Number of streams	1	1	1

Table 4: Traffic models and QoS constraints used to evaluate XR applications in UL direction

Parameters	VR/AR/CG (UL pose or controller)	AR (scene + video)	Audio + Data (all use cases)
Periodicity (ms)	4	1/60 * 1000 (= 60fps)	10
Success %	99 (90, 95 optional)	99	99
Packet size (bytes)	100	Derived from data rate & distribution	Derived from data rate & distribution
Delay Bound (ms)	10	30 (10, 15, 60 optional)	30
Data rate (Mbps)	Derived from packet size & periodicity	10 (20 optional)	~1

Handling the mismatch is currently being discussed in Rel-18. Possible solutions may include allowing multiple CDRX



configurations, non-integer periodicity, configuring cycle pattern, and dynamic indication for adjusting the start offset.

- **Mismatch between the PDCCH monitoring periodicity and XR traffic periodicity**: Similar to the CDRX issue above, the misalignment in time causes capacity loss or consumes additional power due to frequent PDCCH monitoring.
- **Jitter handling**: The XR DL traffic arrival has jitter, which makes exact frame arrival timing random even after the tempo mismatch problem is solved. For example, if the DL burst arrives later than the expected time of arrival (where potentially CDRX On duration start is configured), as shown in Figure 18, the UE should wait for the DL burst arrival while performing unnecessary PDCCH monitoring. This unnecessary PDCCH monitoring increases UE power consumption. The variable XR frame size also results in high power consumption since the configuration is inefficient and usually based on the maximum packet size.

Capacity Savings Enhancements: Similar to power savings enhancements, the purpose of the capacity study is to understand the performance of NR systems for XR applications and identify any issues and performance gaps that limit the current NR systems in supporting XR applications. In addition, such a study provides potential directions for necessary future enhancements to better support XR.

- Enhancement to semi-persistent scheduling: As the traffic generated by the XR application is quasi-periodic, it is suitable to use ULCG for the UL XR video data transmission. Compared to dynamic grant (DG), ULCG reduces the overhead of a scheduling DCI. Moreover, the UE does not need to transmit SR, monitor PDCCH for UL grant, transmit a BSR and then finally transmit UL data. This reduces latency and allows UL packet transmission to meet the PDB. The configuration of resource allocation of CG is semi-static. Therefore, the ULCG configuration cannot adapt to the XR traffic packet sizes. Moreover, A tempo mismatch exists between the Rel-16/ Rel-17 Semi-Persistent Scheduling (SPS)/ULCG cycle values and the XR UL/DL frame arrival periodicity. The typical XR traffic periodicities are 60, 120 frames per second (fps) or Hz; frame periodicities are 16.67ms and 8.33ms. Since ULCG/SPS periodicity values support only integer multiples of slot, no matter which periodicity is chosen from currently available values from TS 38.331, it cannot be exactly aligned with UL/DL traffic arrival timing. Figure 19 illustrates the XR periodicity mismatch between 60fps XR traffic and ULCG/SPS periodicity of 16 slots and 17 slots in 15kHz SCS. This would lead to XR capacity loss due to the packet delay caused by the timing difference between ULCG/SPS resources and actual XR traffic. Current discussions in Rel-18 include considerations for SPS/ULCG enhancements using either semi-static or dynamic approaches.

Figure 18: Late DL packet (burst) arrival with positive jitter with respect to the expected arrival time

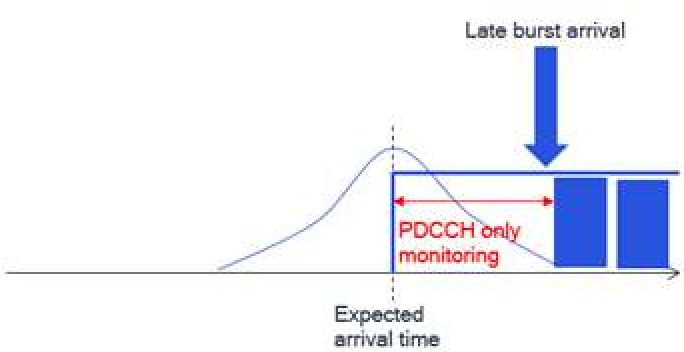
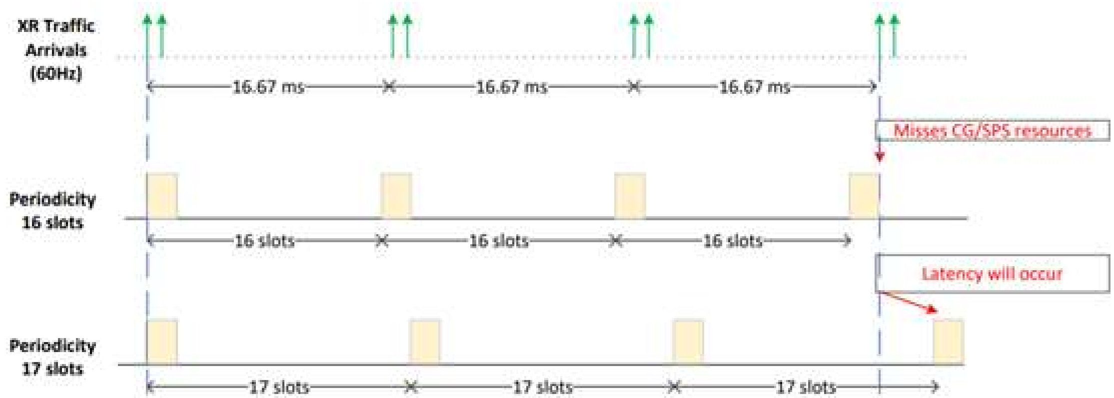


Figure 19: Mismatch between XR UL/DL traffic (60fps) and Rel-16/ Rel-17 ULCG/SPS periodicity (16 slots or 17 slots)

Other enhancements useful for XR capacity include (and are not limited to): delay-aware scheduling, enhancements to



multi-PDSCH/PUSCHs scheduling using single DCI, WUS, Hybrid Automatic Repeat Request (HARQ-ACK) enhancements, and enhancements to measurement gaps. Moreover, given the large transport block sizes and the PDB that allows for a couple of HARQ retransmissions, Code Block Group (CBG)-based HARQ can be beneficial for XR use cases as current link adaptation mechanisms and the corresponding UE CQI feedback designs are suboptimal for CBG-based transmissions.

XR Awareness at RAN: The latency and reliability QoS parameters in 5G systems are specified for traffic in terms of "packets" (e.g., PDB, PER). On the downlink, the packets correspond to the packet data unit on the N6 interface inbound towards the UPF. These packet data units are typically (Internet Protocol) IP packets, so the packets correspond to the IP payload.

XR (and CG) application traffic, however, on the downlink typically consists of encoded video or scene information. Typically, the applications require a certain minimum granularity of application data to be available on the client side before the next level of processing can start. For example, in certain configurations, application client processing can start only if all bits or a certain percentage of bits of a video frame are available. Although this information is packetized into IP payloads, the minimum granularity of traffic consumption on the application client side will require a certain minimum set of IP packets available before the next level of processing can start. We refer to this minimum granularity of information that a given application requires as a Packet Data Unit Set "PDU Set".

XR (and CG) traffic consists of bursts of traffic that can carry one or more PDU Sets, where the PDU set is composed of one or more PDUs carrying the payload of one unit of information generated at the application level (e.g., a frame or video slice)[26].

The QoS parameters specified in packets do not adequately capture the application requirements, typically in terms of PDU Sets. First, applications can have a certain PDU Set error rate PS-ER requirement, where PS-ER is the percentage of PDU Sets in error in a specified measurement window. Specifying the PER does not adequately specify the PS-ER. If multiple IP packets in a PDU Set are in error, then the system can operate at a point where PER is met, but PS-ER is not satisfied. Therefore, it is observed that specifying PS-ER to the 5G system as a QoS parameter can be beneficial.

Second, applications can have a certain delay requirement on a PDU Set that cannot be adequately translated into packet delay budget requirements. For example, if the PDU Set delay budget (PSDB) is 10ms, then PDB can be set to 10ms only if all packets of the PDU Set arrive at the 5G system simultaneously. If the packets are spread out, then PDU Set delay budget is measured either in terms of the arrival of the first packet of the PDU Set or the last packet of the PDU Set. In either case, a given PSDB will result in different PDB requirements on different packets of the PDU Set. It is observed that specifying the PSDB to the 5G system can be beneficial. As such, signalling new 5G QoS Identifier (5QI) attributes (delay budget, error rates, etc.) based on the PDU Set on the control plane is useful. On the user plane, the application server may mark the IP packets to differentiate packets which belong to the same set and/or bursts.

Third, not all bits within a PDU Set are equally significant.

For example, if the application implements an application-level error correction, then the application client only consumes a certain fraction of the bits of a PDU Set, and the remaining bits need not be transmitted to improve capacity. If an application implements error concealment techniques, it can tolerate a certain percentage of bits of a PDU Set in error. Certain video encoder configurations can consume all bits of a PDU Set up to the first bit in error. All subsequent bits after the first bit in error can be discarded since the corresponding decoder cannot consume it. The treatment of bits within a PDU Set can be specified via a QoS parameter called PDU Set content policy. Specifying this content policy to the 5G system as a QoS parameter can be beneficial.

In addition to PDU set awareness, the 5G system can benefit from an awareness of the bursts that can constitute multiple PDU Sets. For example, if the 5G system is aware of the end of the burst, then it can ensure that UE can be sent to sleep without having to implement inactivity timers, resulting in additional power savings.

Other useful attributes that may be useful to the 5G system and currently being discussed as part of the Rel-18 SI may include (and may not be limited to): PDU set periodicity, priority, size, or number of PDUs in a PDU set, jitter characteristics, etc.

6.3 XR in Rel-18

5G-Advanced standardization is currently in the early stage, with Release 18 work started in RAN in Spring 2022[27] and further evolving[28] in 3GPP Rel-19 and Rel-20. The 3GPP related XR SI and Work Items (WI) in Rel-18 are summarized in Table 5.

Table 5: XR Rel-17 SI/WIs

WG	SI/WI TR
SA2	Study on architecture enhancement for XR and media services (SP-211646)
RAN1/RAN2	Study on XR enhancements for NR (RP-213587)

In December 2021, a new Study Item, "Study on XR Enhancements for NR," was approved [29]. The agreed timeline discussed in RAN1 #109-e is shown in Figure 20. From the RAN perspective, the two important milestones are the provision of the TR for information at RAN#97 in September 2022 and the provision of the TR for approval at RAN#98 in December 2022. The task is for RAN1 and RAN2 to complete the work in November 2022. The study in Rel-18 is to be based on Rel-17 TR 38.838, on corresponding Rel-17 work from SA4[30], and on Rel-18 work from SA2[31]. The objectives are summarized into XR-awareness, XR-specific Power Saving, and XR-specific capacity improvements[32]. The main enhancements include the ones described in Section 5.2.

Figure 20: XR TU across working groups for Rel-18[33]

6.4 XR in Rel-19

To support the XR KPIs requirements, prediction of, or fast adaptation to, RF conditions changes is critical. This is especially true in mmWave and higher frequencies systems which experience higher propagation losses and are more susceptible to blockage. These channel conditions are exacerbated by use cases that require high speed of rotation and motion. Perception assisted beam selection is useful for such scenarios/use cases.

SA1 approved a study on Localized Mobile Metaverse Services in Study Item Description (SID)[34]. These metaverse services would involve coordinating input perception/sensing data from different user devices (such as sensors and cameras) and coordinating output data to different devices at different destinations to support the same application.

This study will investigate specific use cases and service requirements for 5GS support of enhanced XR-based services. XR-based services are an essential part of "Metaverse" services considered in this study, and potentially other functionality to offer shared and interactive user experience of local content and services, accessed either by users in the proximity or remotely. In particular, the following areas will be studied:

- Support of interactive XR media shared among multiple users in a single location, including:
- Performance aspects; e.g., latency, throughput, connection density
- Efficiency and scalability aspects for large numbers of users in a single location.
- Identification of users and other digital representations of entities interacting within the metaverse service.
- Acquisition, use, and exposure of local (physical and digital) information to enable metaverse services, including:
- Acquiring local spatial/environmental information and user/UE(s) information (including viewing angle, position, and direction);
- Exposing local acquired spatial, environmental, and user/UE information to 3rd parties to enable metaverse services.

Conclusion

Extended Reality (XR) will be the next-generation computing platform to determine our relationship with the digital world today and in the coming years. XR will influence how people play, work, and connect. XR will impact all aspects of consumer life, industrial and manufacturing verticals, education, emergency response, and healthcare.

Digital Twins, AI/ML, IoT, are integral to the evolution and implementation of XR. Digital twins link reality and the metaverse by guaranteeing end-to-end digitization of complex physical assets. Artificial Intelligence and Machine Learning connect almost every industry with XR services, and provide the necessary service via wireless access. Furthermore, using IoT devices and sensors with edge computing capabilities will enable pre-emptive decision-making maintenance. Verticals can benefit from a smarter ecosystem of IoTs while encouraging sustainability. Verticals include, but are not limited to, Enterprise, Public Safety, NFTs, Consumers Verticals, and Manufacturing.

VR is renowned for its capacity to transform screen-limited video games into fully immersive experiences. Even though AR and VR share common virtual components in our daily lives, AR supplements our day-to-day life with virtual components rather than immersing the user in a virtual world.

XR service characteristics and delivery requirements incorporate 5G services like eMBB, mMTC, and URLLC. 5G NR MEC brings applications, storage, switching, and control functions closer to where they are needed, improving data processing, and reducing latency. Increased efficiency allows for faster response times and lower battery usage, potentially transforming industries such as manufacturing, transportation, entertainment, and more. Certain aspects of edge computing help improve the end-user experience and network efficiency. The paper also discusses the role of split rendering/architecture for the phone to glass topology.

3GPP is considering various enhancements for the support of XR including enhancements for power savings, capacity and XR awareness in Rel-17 and Rel-18. Finally, the paper discusses some future directions 3GPP is targeting XR- specific enhancements in Rel-19.

Aside from advancements in technologies not limited to optics, projectors, display systems, graphics, audio, tracking and AI; from communications perspective, the standards enhancements and design aspects that are discussed and recommended in this paper together with the split rendering/computation architecture make it more likely to realize the promised benefits of XR, for example, low power, low latency high reliability with a small form factor device that provides XR services in a wide area. In the future, advances in beam perception, machine learning and artificial intelligence can further bring benefits and make the XR dream a reality. 3GPP and the growing 5G mobile wireless industry ecosystem are entering a new era of 5G innovation and should continue to collaborate to focus on the key areas as described in this white paper to progress XR to reach its full potential as it affects the way we live, play and work.

Acronyms

5QI: 5G QoS Identifier

6DOF: Six Degrees of Freedom

ACLS: Advanced Cardiac Life Support

AI: Artificial Intelligence

API: Application Programming Interface

AR: Augmented Reality

BS: Base Station

BSR: Buffer Status Report

CBG: Code Block Group

CDRX: Connected Mode Discontinuous Reception

CG: Cloud gaming

DCI: Downlink Control Information

DL: Downlink

DMRS: Demodulation Reference Signals

DN: Data Network

FoV: Field of View

HARQ: Hybrid Automatic Repeat Request

HMD: Head-mounted display

IIoT: Industrial Internet of Things

IoT: Internet of Things

IP: Internet Protocol

KPI: Key Performance Indicator

LADN: Local Area Data Network

LoS: Line-of-sight

M2R2P: Motion to Render to Photon

MEC: Multi-access edge computing

MIMO: Multiple-input-multiple-output

ML: Machine Learning

mmWave: Millimeter wave

MR: Mixed Reality

MTP: Motion-to-Photon

NFT: Non-Fungible Token

Acronyms

NR: New Radio

PDB: Packet Delay Budget

PDCCH: Physical Downlink Control Channel

PDU: Packet Data Unit

PER: Packet Error Rate

PSDB: PDU Set delay budget

PUSCH: Physical Uplink Shared Channel

QoE: Quality of Experience

QoS: Quality of Service

RAN: Radio Access Network

RAT: Radio Access Technologies

Rel: Release

RIS: Reconfigurable Intelligent Surfaces

RTT: Round-Trip Time

SA: System Architecture

SCS: Sub-Carrier Spacing

SI: Study Item

SID: Study Item Description

SPS: Semi-Persistent Scheduling

SR: Scheduling Request

TR: Technical Report

UAI: UE Assistance Information

UE: User Equipment

UL: Uplink

ULCG: Uplink configured grant

UPF: User Plane Function

URLLC: Ultra-reliable and low latency communications

VR: Virtual Reality

WG: Work Group

WI: Work Item

XR: Extended Reality

Acknowledgments

5G Americas' Mission Statement: 5G Americas facilitates and advocates for the advancement and transformation of LTE, 5G and beyond throughout the Americas.

5G Americas' Board of Governors members include Airspan Networks, Antel, AT&T, Ciena, Cisco, Crown Castle, Ericsson, Intel, Liberty Latin America, Mavenir, Nokia, Qualcomm Incorporated, Samsung, Shaw Communications Inc., T-Mobile USA, Inc., Telefónica, VMware and WOM.

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Endnotes

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