eXtended Reality (XR)

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Abstract

This article discusses eXtended Reality (XR) and aspects necessary for incorporating XR in fifth-generation (5G) new radio (NR) radio access network (RAN) as well as areas for potential enhancements for the commercial viability and scalability of XR supported by 5G networks.

I. Introduction

eXtended Reality (XR) is an umbrella term that encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), and it is one of the most important fifth-generation (5G) media applications under consideration in the industry that shifts the way people interact with media.

Virtual reality (VR): VR is a computer technology that uses headsets to fully immerse users in a computer-simulated reality by generating realistic images and sounds to replicate a real world and to create an imaginary world that engages senses (such as taste, sight, smell, touch, sound).

Augmented reality (AR): AR merges, seamlessly, the real and the virtual worlds by overlaying virtual objects into the real world. Unlike VR which replaces the real world with a computer-simulated virtual world, AR alters one's ongoing perception of the real world. Pokémon Go and Snapchat filters are two examples of AR.

Mixed reality (MR): MR is a hybrid of VR and AR technologies. Sometimes referred to as hybrid reality, MR merges the real world with the virtual world, where real and digital objects can co-exist and interact with each other in real-time. Similar to AR, MR superimposes virtual objects on top of the real world. Similar to VR, these overlaid virtual objects are interactive and enable users to manipulate the virtual objects. A good example of MR is Microsoft HoloLens.

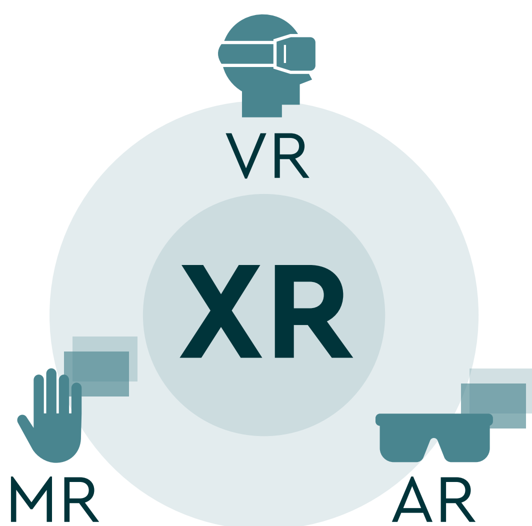

FIG. 1 Extended Reality [1]

These three technologies are compared in FIG. 2.

II. Use Cases for XR

The use cases of XR have been discussed in detail in [3]. Below, we provide a few use cases:

- **Streaming:** XR brings immersive experiences and enhances media streaming experience with the capability of 6 Degrees of Freedom (6DoF). This allows users to move within and interact with their virtual reality environments or sports events or concerts.
- **Gaming:** As VR technology initially took off in the gaming industry, it comes as no surprise that VR will have a huge impact on gaming. XR: i) provides players with appealing virtual objects that enrich the game environment, ii) allows remote players to play and interact in the same game environment in real-time, and iii) allows players to change their in-game position by body movements, and iv) allows games to move from a two-dimensional space to a three-dimensional space.
- **Real-Time 3D Communication:** XR removes barriers by supporting the blended representation of remote employees in a single virtual meeting room, where the participants (or avatars of the participants) can move and interact with one another using 6DoF.
- **Training and Education**
  Extended reality opens new avenues for training and education.
  - o People who work in high-risk conditions – like healthcare professionals, chemists, and pilots – can train in a safe and controlled environment and learn how to respond to life-threatening situations without putting their lives at risk. For example, medical students can get hands-on practice by performing surgeries and procedures on virtual patients, reducing the risk of making a mistake and inflicting harm while practicing on a real patient.
  - o Virtual field trips (for example, to museums in different parts of the world, to the solar system, and the 360-degree panoramic video on historical and natural topics), help students have a deeper understanding of the topics.

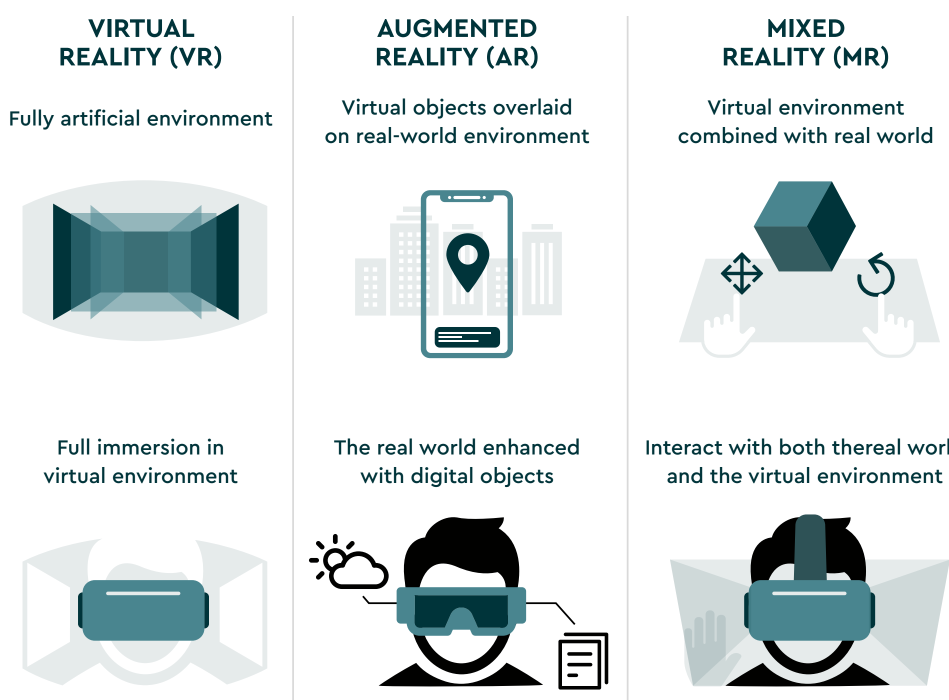

FIG. 2 Differences of VR, AR, and MR [2]

	Throughput	Reliability	Latency	Power consumption
eMBB	✓	✕	✕	✕
uRLLC	✕	✓	✓	✕
NR Light	✕	✕	✕	✓

FIG. 3 Requirements of 5G use cases

III. Challenges for XR

XR use cases have traffic requirements that are high in throughput as in Enhanced Mobile Broadband (eMBB), low in latency, and high in reliability as in Ultra-Reliable Low Latency Communications (uRLLC), and low in power consumption as in NR Light (e.g., smart wearables and sensing applications). As shown in FIG. 3, the current 5G new radio (NR) air interface is not particularly optimized for the specific requirements of XR applications.

Table I summarizes example XR use cases and initial performance requirements which have been discussed in [3, 4] in terms of downlink (DL) and uplink (UL) transmission data rates, transmission delay in terms of Packet delay budget (PDB) and round-trip time (RTT), and reliability in terms of Packet error rate (PER).

As seen in Table I, split rendering and cloud gaming applications require up to 100Mbps throughput. Note that higher traffic throughput is required if the XR service (e.g., cloud gaming) uses higher resolution and frame rate. Table II provides examples on DL data throughput in cloud gaming with respect to varying resolution and frame rates [5].

PDB in Table I denotes an upper limit of a time delay between the wireless device and the Policy and Charging Enforcement Function (PCEF), which limits the maximum packet transfer delay. Another important requirement on latency in addition to PDB is the RTT. The RTT has a great impact on the quality of experience (QoE). The latency requirement tightens as the dynamicity and complexity in an XR service increases. For example, for cloud gaming which wants to provide a feeling of "presence" to a gamer, the end-to-end PDB and RTT is 2.5ms and 5ms, respectively. This latency is required to ensure that users feel no lagging.

PER in Table I is a measure of reliability, which is denoted as the percentage of the end-to-end packet errors observed at the application layer within the

TABLE 1 Typical XR uses cases and requirements

XR Service	Data throughput		PDB		RTT	PER	
	DL	UL	DL	UL		DL	UL
Viewport dependent streaming	25 Mbps	More frequent HTTP requests every 100ms.	300ms	300ms	--	10e-6	10e-6
Split Rendering with pose correction	100 Mbps	500 kbit/s	20ms	10ms	50ms	10e-4*	10e-4*
XR Conversational	50Mbps	--	100 ms ~150 ms	--	--	10e-2 ~10e-3	--
Cloud Gaming	100 Mbps	1Mbps	2.5ms	2.5ms	5ms	10e-4	10e-4

TABLE 2 Example of DL data traffic of cloud gaming

	Resolution and frame rates	DL data throughput
High quality	4K with 120fps	100Mbps
Middle quality	1080p with 60-120fps	30-40Mbps
Low quality (for cat A and B in TR 26.995 only)	720p with 30 fps	10Mbps

PDB. PER with high reliability at 10e-6 is required for XR streaming services.

With the introduction of XR over 5G, some important aspects that are relevant from the radio access network (RAN) point of view are capacity, power, and mobility [6]. These aspects further depend on deployment scenarios (e.g., Urban Macro, Indoor Hotspot) and frequency ranges (e.g., FR1, FR2). For example, AR traffic is generated in both indoor and outdoor scenarios, whereas VR traffic is predominantly generated by indoor scenarios. Below we will review key performance indicators (KPIs) such as capacity, power, and mobility considerations for XR.

A. Power Considerations for XR

Power consumption and power-saving are very important factors for an XR experience as the XR applications are often run on portable/mobile devices, such as XR glasses and Head Mounted Displays (HMDs). These different portable/mobile devices have different power considerations from those of smartphones. For example, XR glasses are expected to: i) have a small form factor as the prescription glasses, ii) be lightweight, iii) have very limited space for battery, and iv) have long battery life for all-day use without any thermal complication. Therefore, the power consumption of the XR glasses should be significantly lower than that of a smartphone, which deserves a further study in RAN. Potential power-saving mechanisms must consider important features of XR, including: i) small form-factor, ii) limited battery space, iii) XR traffic pattern which requires the wireless device to exchange traffic very frequently for prolonged periods of time, and iv) split computation can be potential areas of study. XR applications are mainly not latency tolerant to make sure that users do not feel any lagging. Therefore, existing power saving mechanisms (for instance: Connected Mode Discontinuous Reception (CDRX), cross-slot scheduling, and maximum layer adaptation), which are tailored to latency-tolerant traffic need to be enhanced to efficiently support XR traffic patterns such as periodic arrival times.

Power consumption in XR applications mainly stems from edge cloud computing and modem power consumption through a 5G connectivity which carries the XR application traffic. For 5G connectivity, XR glasses are expected to either have an embedded 5G modem or be tethered to a smartphone via Universal Serial Bus (USB), Bluetooth, Wi-Fi, or a 5G sidelink. The viability of XR glasses is plausible if the increase in power consumption resulting from the 5G connectivity carrying the XR application traffic is not significant. Even though edge cloud computing can reduce the main power consumption on XR devices connected to a cloud server, modem power consumption may still occupy a large portion of the overall power consumption. Note that though RAN does not have any control over how much power can be saved in the edge cloud computing, it can still reduce the power consumption for the 5G connectivity.

Note-1: Compared to XR glasses, the power consumption issue may be less critical for VR HMDs due to their larger form factor which can accommodate a larger battery and more room for heat dissipation. However, for VR applications that have a long and intensive use time, the power consumption issue still deserves further study in RAN. Moreover, if the XR device is tethered, then the power consumption saving may not be crucial. Power saving is more crucial for standalone devices.

Note 2: If the target use case of the XR application is mainly indoor, then the need for the power saving may not be critical, where a convenient and easy charge is more important. On the other hand, if the target use case of the XR application is mainly outdoor or mobile scenarios, the need for power saving is more critical to improving user experience.

B. Capacity Considerations for XR

Capacity is an important factor for any mobile broadband system such as eMBB. As XR applications, such as real-time high-resolution videos mostly have higher Quality of service (QoS) requirements on throughput, latency, and reliability than eMBB applications, achieving a high capacity under low latency and high-reliability constraints could be one of the restricting factors that affect QoE for XR, especially for highly interactive XR applications. Therefore, the commercial viability and scalability of XR services over 5G networks heavily depends on the capacity of 5G connectivity to support XR applications. To that end, it is important to study capacity aspects for XR, including key performance indicators that represent the viability of XR over 5G.

While the performance evaluations of eMBB applications have focused on full-buffer throughput and user-perceived throughput, the performance evaluations of uRLLC applications have focused on outage performance under high reliability and low latency requirements for small packet traffic [6]. On the other hand, XR applications have a consistent and short-term high throughput requirement (e.g., for 99% of a 10 ms time window) under a delay budget, which is more challenging than meeting a similar requirement on a long-term average throughput as the short-term throughput can be significantly lower than the average throughput experienced by the device. Therefore, the performance evaluations of XR applications should focus on:

- the short-term throughput experienced by the device within the delay budget (e.g., full-buffer throughput achieved within the delay budget);
- the packet dropping rate under the delay budget for XR traffic patterns; and
- the outage probability under a target packed dropping rate within the delay budget.

Moreover, a typical characteristic of an XR traffic is burst arrival of traffic and burst interference as a divided frame may be received by the base station in a bursty manner. This creates a burst interference to neighboring cells and makes it hard to adapt to link dynamically.

Note that some XR services may need to serve multiple users simultaneously with limited resources. The performance evaluations of XR applications should also focus on the number of users that can be served simultaneously for an XR service under given traffic requirements and a deployment scenario (e.g., indoor, outdoor, Urban Macro, etc.). In this case, the viability of the XR service can be determined based on assessing the throughput, delay, and reliability with the increased number of users in the service. Moreover, smart scheduling mechanisms need to be developed to serve multiple users simultaneously.

C. Mobility Considerations for XR

XR headsets that are tethered (for example, AR glasses tethered to a smartphone, or a VR headset tethered to a computer), limit freedom of movement, and thus it impacts the usability of tethered XR headsets by users on the move. Therefore, mobility is an important factor for XR services such as: mobile office, navigation, gaming, and XR applications running on smartphones that people will be carrying all day long on trains and automobiles. In such scenarios, users expect to receive continuous and uninterrupted XR service with guaranteed throughput and latency, even when the users move across cells with mid-to-high speed. Providing a seamless XR experience for high-mobility wireless devices under high data rate, high reliability, and tight latency requirements is challenging.

Release 16 of the Mobile Broadband Standard, of the 3rd Generation Partnership Project (3GPP) supports "zero ms interruption" via dual-active protocol stack (DAPS) based handover which can minimize degradation of user experience in XR services during high-mobility scenarios. However, the DAPS based handover does not ensure zero service interruption as it requires the wireless device to reduce its user equipment (UE) capabilities for data transmission and reception with the source and/or target cells while the handover is ongoing. Due to the reduction in UE capabilities, the resource allocation at the source and/or target cells may not support the XR services during the high-mobility scenarios. Moreover, DAPS-based handover is not applicable when source and target cells are both in frequency range 2 (FR2) that includes frequency bands from 24.25 GHz to 52.6 GHz. Therefore, it is important to study and minimize the degradation of user QoE by high mobility events in order to achieve mass adoption of XR services.

IV. Edge Computing

As discussed above, creating XR experiences brings its own technical challenges. Combining and synchronizing the motions of the user in the real and digital worlds needs a huge amount of graphic rendering processing. To that end, edge computing which enables cloud computing capabilities such as rendering processing and graphic power to be deployed in the vicinity of cellular networks has been considered in the industry as a network architecture to enable XR [7]. Edge computing has been considered as it offers lower latency, higher bandwidth, reduced backhaul traffic, and higher security compared to cloud computing. As creating a fully immersive experience requires a massive amount of rendering workload, on-device processing is augmented by distributing the XR workload across the XR device and the edge cloud, for example, by pushing the compute-intensive calculations onto the edge cloud while allowing the lighter and latency-sensitive calculations to remain on the device [8]. In particular, efficient and high-quality graphical rendering processing performed on the edge cloud augment latency-sensitive XR applications running on the XR device such as head/hand/motion tracking [9]. When the graphic rendering is performed on the edge cloud, a service link with low latency, high capacity, and high quality is required to deliver the final immersive experience to the XR device, where 5G can meet these requirements. Distributing the processing loads across the XR device and the edge cloud over 5G links offers an optimized solution to make the XR experience truly immersive and provides momentum towards the expansion of the XR market.

The RTT delay shown in Table I can be divided into three parts: i) cloud processing time at the edge server, ii) DL/UL transmission delay via an air interface (e.g., 5G NR), and iii) on-device processing time (e.g., video frames decoding, display) at the XR device [10]. The cloud processing time at the edge server side and the on-device processing time at the XR device depend on capabilities of the edge cloud server and the XR device, which may vary from XR device to XR device and/or edge cloud to edge cloud. Therefore, the delay budget left for the 5G NR air transmission is uncertain. For example, as shown in Table I, the RTT requirement for split rendering with pose correction is 50ms. If the total processing time including the cloud processing time and the on-device processing time is 20ms, then the RTT delay budget left for 5G NR air transmission is 30ms. If the total processing time including the cloud processing time and the on-device processing time is 25ms, then the RTT delay budget left for 5G NR air transmission is 25ms.

Note that an edge server required for XR can be owned by 5G telecom operators. Thus, massive storage and computing capability requirements of XR services can be addressed via the deployment of edge cloud technologies within 5G operator networks.

FIG. 4 is an example of edge computing. For example, when the user changes the position of his head, the XR device determines the current head pose by the on-device processing and then transmits it to the XR edge cloud through a fast and reliable 5G connection.

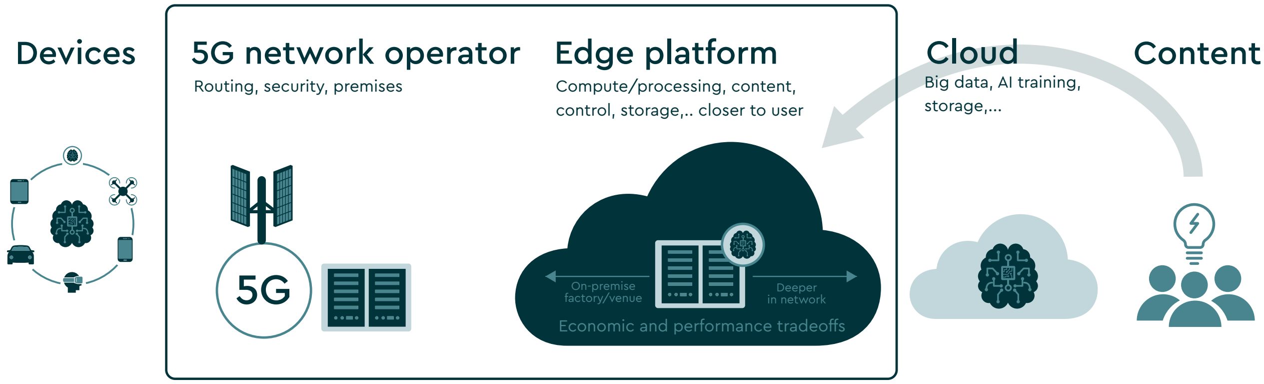

FIG. 4 Edge Computing (From Figure 4.3.5-1 in [3])

The XR edge cloud uses the head pose information received from the XR device to generate the next frame and/or XR viewport, which is later encoded, for example, with 2D/3D media encoders. The encoded data is sent back to the XR device, which decodes and performs further on-device rendering to minimize the motion-to-photon latency. The motion-to-photon latency is defined as a time duration between an input movement such as head movement and the screen on the XR device being updated [11].

In the context of Release-17 of the Mobile Broadband Standard, 3GPP work is ongoing in order to identify the integration of edge processing in 5G systems. Necessary modifications to the 5G system architecture to enhance edge computing have been defined in [12]. This work is currently in the study phase, defining key issues and scope for Release-17.

V. Conclusion

This article discusses XR and aspects, such as distributed computing over 5G connectivity and edge cloud processing, necessary to deliver the XR experience. Moreover, areas for potential enhancements to realize the commercial viability of XR such as power, capacity, and mobility considerations have been presented.

Acronym List

3GPP	3rd Generation Partnership Project
5G	Fifth Generation
6DoF	6 Degrees of Freedom
2D	Two Dimensional
3D	Three Dimensional
AR	Augmented Reality
CDRX	Connected Mode Discontinuous Reception
DAPS	Dual-Active Protocol Stack
DL	Downlink
FR1	Frequency Range 1
FR2	Frequency Range 2
eMBB	Enhanced Mobile Broadband
HMD	Head Mounted Display
KPI	Key performance Indicator
MR	Mixed Reality
NR	New Radio
QoS	Quality of Service
QoE	Quality of Experience
PCEF	Policy and Charging Enforcement Function
PDB	Packet Delay Budget
PER	Packet Error Rate
RAN	Radio Access Network
RTT	Round-Trip-Time
UL	Uplink
URLLC	Ultra-Reliable Low-Latency Communication
USB	Universal Serial Bus
UE	User Equipment
VR	Virtual Reality
Wi-Fi	Wireless Fidelity
XR	Extended Reality

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Ali received his B.S. and M.S. degrees in telecommunications and electronics engineering from Sabanci University, Istanbul, Turkey, in 2007 and 2009, respectively, and a Ph.D. degree in electrical engineering from the University of California, Riverside in 2014. During his Ph.D. studies, he interned with Mitsubishi Electric Research Labs, MA, and Broadcom Corporation, CA. He worked as an industrial postdoctoral researcher at the University of British Columbia, Vancouver, Canada, and Sierra Wireless, Richmond, Canada, between November 2015 and October 2017. He is an inventor in over 250 pending and granted patent applications and has authored more than 50 IEEE publications. He is currently working at Ofinno Technologies, Reston, Virginia, as a wireless technology specialist. His primary research interest is 5G NR beam management.

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