Extended Reality (XR) over 5G and 5G-Advanced New Radio: Standardization, Applications, and Trends
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Abstract—Extended Reality (XR) is one of the major innovations to be introduced in 5G/5G-Advanced communication systems. A combination of augmented reality, virtual reality, and mixed reality, supplemented by cloud gaming, revisits the way humans interact with computers, networks, and each other. However, efficient support of XR services imposes new challenges for existing and future wireless networks. This article presents a tutorial on integrating support for the XR into the 3GPP New Radio (NR), summarizing a range of activities handled within various 3GPP Services and Systems Aspects (SA) and Radio Access Networks (RAN) groups. The article also delivers a case study evaluating the performance of different XR services in state-of-the-art NR Release 17. The paper concludes with a vision of further enhancements to better support XR in future NR releases and outlines open problems in this area.

I. INTRODUCTION

Extended Reality (XR) has been one of the ambitious research topics under development for several decades already and today it is becoming mature enough to appear in the mass market. The suggested replacement of large-scale handheld smartphones with smaller wearable devices enables numerous novel attractive use cases in consumer, industrial, and medical areas, as well as is a foundation for Metaverse revolution [1], [2]. Meanwhile, the successful adoption of XR requires support from the underlying wireless networks. The latter imposes new challenges, as XR does not perfectly fit into the existing classification of fifth-generation (5G) applications and services, typically divided into enhanced mobile broadband (eMBB), ultra-reliable low latency communications (URLLC), and massive machine-type communications (mMTC).

By design, XR has a unique set of features. First is a new device form factor replacing or complementing carriable smartphones with wearable head-mounted helmets or smart glasses. New form factors lead to strict requirements on user equipment (UE) power consumption, performance, and heat dissipation. Consequently, XR devices cannot do all the computations themselves but require assistance from other nodes (i.e., split rendering on an edge computing server) [3]. Second, XR services feature specific traffic, typically with one or more video streams in downlink (DL) tightly synchronized with frequent motion/control updates in the uplink (UL). Finally, XR is characterized by both high data rate and strict packet delay budget (PDB), placing it in between 5G eMBB and URLLC [1]. As a result, further effort is required from the standardization bodies in supporting XR via cellular networks.

The standardization of XR support via New Radio (NR) started in the 3rd Generation Partnership Project (3GPP) back in 2016, with Service and System Aspect (SA) working group (WG) on “Services” (SA WG1 or SA1) specifying 5G service requirements for high-rate and low-latency XR applications [4]. The work continued in 2018 by SA4 (“Multimedia Codecs, Systems and Services”) documenting relevant traffic characteristics in [5] and providing a survey of XR applications in [6]. In parallel, SA2 (“System Architecture and Services”) standardized new 5G quality of service identifiers (5QI) to support interactive services including XR [7].

Recently, the SA effort was followed by 3GPP Radio Access Network (RAN) WG1 (“Physical layer”, RAN1). Particularly, RAN1 performed a Release 17 study on evaluating NR performance for the XR [8]. The normative work now continues in both SA and RAN for Release 18 (first 5G-Advanced release, tentatively, until 2023), aiming to provide necessary enhancements to better support XR services over NR. Further activities beyond 2023 are also envisioned and will be planned later with respect to the outcomes of the XR Release 18 items.

Following high market potential, XR will inevitably play an important role in 5G-Advanced and later 6G systems. Meanwhile, further research in this direction requires a better understanding of the main peculiarities when handling XR devices and services in real cellular networks. To facilitate this goal, following the latest 3GPP studies, the article provides an overview of the support for different XR use cases in state-of-the-art and future cellular networks employing NR.

To the best of authors’ knowledge, this is the first tutorial on the topic from the standardization point of view. We start by reviewing typical XR applications for future NR deployments. We then explain the main 3GPP-driven XR traffic models and key performance indicators (KPIs). We later present our simulation study evaluating the realistic performance of modern NR Release 17 when handling different XR services. We finally outline perspective enhancements and research directions for better support of XR in 5G-Advanced cellular systems.

II. SELECTED XR APPLICATIONS AND SERVICES

Decades of engineering led to the development of various XR applications and services, each characterized by own user setup, traffic flows, and quality of services (QoS) metrics [1], [2], [9]. Following 3GPP SA4 classification, over 20 XR use cases are identified [6]. For such an extensive set of setups, the performance evaluation of XR wireless solutions is challenging. Therefore, it was proposed in [8] to group the XR use cases into three meta-categories related to: virtual reality (VR), augmented reality (AR), and cloud gaming (CG). We briefly introduce them below and in Fig. 1 describing the essential features to be considered in modeling.
A. Virtual reality with viewport-dependent streaming

VR generates a virtual world where the user is fully immersed, thus creating a sense of physical presence that transcends the real world. Modern VR services are usually enabled by optimized viewport-dependent streaming (VDS). VDS is an adaptive streaming scheme that adjusts the bitrate of the 3D video using both network status and user pose information [3]. Specifically, the omnidirectional 3D scene with respect to the observer’s position is spatially divided into independent subpictures or tiles. The streaming server offers multiple representations of the same tile by storing tiles at different qualities (varying, i.e., video resolution, compression, and frame rate). Transmission of new XR content can be triggered by user movements, as well as the demand for the next portion of the 3D video. Once all tiles in the field of view (FOV) are downloaded, they are rendered, generating the 3D representation displayed to the user. The use of VDS implies that VR services feature high-rate video in DL complemented by frequent pose updates in UL.

B. Augmented reality with simultaneous localization and mapping

AR merges virtual objects with the live 3D view of the real world, thus creating a realistic personalized environment the user interacts with. Therefore, estimating the user location and FOV is important. However, modern AR solutions do not rely exclusively on expensive motion detection sensors but rather complement them with cameras mounted on AR glasses. Hence, AR is often featured by a video stream in UL. The video is continuously transmitted to the XR server that performs pose tracking to estimate the position and orientation of the user via simultaneous localization and mapping (SLAM) [10]. The estimated FOV is used to generate an augmented 3D scene where virtual objects are overlaid onto certain positions. Finally, the rendered 3D objects or video are encoded and streamed back to the UE. A medium-quality UL video that captures the major objects is already sufficient for SLAM. Therefore, aiming to reduce the UL bitrate, AR UL video stream is often downsampled compared to the DL one.

C. Cloud Gaming with 6 degrees of freedom

CG refers to an interactive gaming application executed at the cloud server. Hence, heavy computations are offloaded from the CG device, relaxing the user equipment requirements (UE). In a typical scenario, the server generates a sequence of 2D/3D scenes as a video stream in response to a control command sent by the UE. For XR CG, control signals include handheld controller inputs and 3 or 6 Degrees of Freedom (3DoF/6DoF) motion samples (see Fig. 1) [9]. Here, 3DoF refers to the rotation data (“roll”, “pitch”, and “yaw”), while 6DoF also adds the information on the UE displacement in X, Y, and Z dimensions. Multiple players may participate in the same gaming session. It is important to note that the resulting video stream in CG is dependent on the user actions. Hence, as for VR, frequent motion/control updates are needed in UL.

III. XR-SPECIFIC 3GPP TRAFFIC MODELS

The traffic model is one of the principal elements needed when simulating applications. In this section, we describe the 3GPP-employed traffic models for selected XR services. The models are based on a deep analysis of the data traces from the 3GPP SA4 trace generator and present a reasonable balance between accuracy and complexity [8]. Apart from discussed distinct features, VR, AR, and CG have some commonalities in the employed data streams. Therefore, the description is grouped based on the data semantic, as illustrated in Table I.

A. Traffic model for XR video stream

Video stream is the most important flow for all the considered XR use cases in DL, as well as for the AR UL. Following the traces by SA4, video is divided by a source generator into separate frames before transmission. To keep a reasonable complexity, a single data packet in the model represents multiple IP packets corresponding to the same video frame. The packet also includes the data for both left and right eyes. The packet size follows a Truncated Gaussian distribution and is determined by the average data rate in megabits per second (Mbit/s). The average inter-arrival time is an inverse of the frame rate in frames per second (fps, i.e., 60 fps leads to 16.6 ms). The actual inter-arrival time is random accounting for jitter that also follows a Truncated Gaussian distribution [6]. As jitter primarily affects DL traffic, it’s modeling for UL can be neglected. Main stream parameters are summarized in Table I.

Modern video codecs, such as H.264 and H.265, may encode video into different types of frames. Thus, the baseline single-stream model is complemented by an optional multi-stream model, assuming that a single video frame consists...
of one larger I (intra-coded picture) and several smaller P (predicted picture) frames. The multi-stream model is further divided into slice-based and Group of Picture (GOP)-based models depending on the employed encoding scheme. In the slice-based model, slices of I and P frames arrive at the same time, while in the GOP-based model, I and P frames arrive in a sequence. Optional multi-stream models are considerably more complex than the baseline single-stream one, therefore, should be used only when justified. Major parameters for multi-stream video can be found in Table 5 of [8]. For a greater level of precision, one can also optionally model separate streams for left and right eye video. In this case, the mean packet size is naturally reduced by 50% and the frame rate is increased two times, compared to the baseline single-model stream.

B. Traffic model for XR motion/control stream

The second important stream refers to motion/control updates sent by the XR device in UL, which is typically mapped to 5QI number 87 or 88. This stream aggregates: (i) UE pose information update received from 3DoF/6DoF tracking and device sensors; and (ii) control information including user input data, auxiliary information, and/or commands from the client to the server. Following [8], the packet size and inter-arrival time are constant, as detailed in Table I.

C. Traffic model for aggregated XR audio and data

In addition to the video stream in UL and DL, it is possible to model audio and extra data as a separate stream. Same as for motion/control, the packet size and inter-arrival time are constant and given in Table I. According to SA4 conclusions, modeling this stream is not mandatory, as it is relatively small compared to a video. On the other side, the frame rate is higher than the DL video, which may be important for modeling certain XR power saving schemes.

Summarizing, as illustrated in Table I, the recommended baseline setup for the VR includes a single-stream video in DL plus a single-stream motion/control update in UL. CG employs a similar set, while the data rates and PDBs for the DL video are different. The major feature of AR modeling here is the presence of UL video that complements or (for simplicity, in the baseline) replaces UL motion/control updates.

IV. MAJOR XR-SPECIFIC 3GPP KPIs

After defining the selected use cases and the associated traffic models, the final step is to define a simple yet credible set of KPIs that well characterize XR services. In this section, we summarize the extensive discussions on this in 3GPP RAN1 [8] and describe the approved set of metrics for two major XR KPIs: capacity and power consumption. We also provide our clarifications alongside the formal definitions.

First, a joint user-centric metric was defined for capacity and latency constraints. Selected XR use cases are delay-sensitive: receiving a packet late has almost the same effect as loosing this packet completely. Therefore, the metric considers all the late packets added to the packet error rate (PER):

**Metric 1: A satisfied XR UE.** An XR UE is declared satisfied if more than X% of packets are successfully transmitted within a given PDB, where the baseline X is 99%.

Once the user-centric satisfactory metric is defined, it is logical to extend it to the network level as:

**Metric 2: XR capacity.** XR capacity is defined as the maximum number of XR UEs per cell with at least Y% of these UEs being satisfied, where the baseline Y is set to 90%.

Besides XR capacity, the battery lifetime is another important criterion determining the market potential of cellular-connected XR devices. Due to their diversity, absolute UE power consumption values vary a lot and are not illustrative. Therefore, the following relative metric has been adopted:

**Metric 3: UE power saving gain versus “Always ON”.** This metric compares the average UE power when employing a certain power saving technique with the average UE power when the UE continuously monitors control channels and is always available for base station (BS) scheduling.

Reducing the XR UE power consumption does not come for granted. Most existing UE power saving techniques, including discontinuous reception (DRX) and physical control channel skipping (PDCCH skipping), suggest the XR UE to stay in a sleep mode as long and frequent as possible. However, due to strict PDBs of XR traffic, there is not always enough time to
wake up the UE, schedule the transmission, and successfully deliver the packet if it arrives during a UE sleep period. Therefore, the corresponding loss in XR capacity should be estimated in conjunction with the power saving gain.

V. XR EVALUATION IN NR RELEASE 17: A CASE STUDY

One of the principal research questions related to running XR over cellular networks is to clarify how well XR services can be supported today in a modern 5G system. The answer defines the state-of-the-art and can serve as an important baseline when assessing existing and future proposals for better XR support in 5G-Advanced and 6G networks. For this purpose, we present a case study below evaluating the performance of XR over 5G NR Release 17. Our study targets the two most critical XR KPIs: capacity and UE power consumption.

A. Simulation setup and framework

Our results are obtained via a 3GPP-calibrated Nokia simulator with symbol resolution in time and subcarrier resolution in frequency. The key assumptions are summarized in Table I inline with the XR features discussed above, as well as with relevant 3GPP RAN1 considerations [8]. Two 3GPP deployments are modeled: (i) Dense Urban (DU) with 21 macro cells and Indoor Hotspot (InH) with 12 indoor cells [11]. In DU, 20% of UEs are outdoor, the rest are distributed indoor across floors 1–8. We assume even-load random placement of XR UEs, where the UEs perform cell selection based on reference signal received power (RSRP). We study both NR frequency ranges (FRs): sub-6GHz FR1 and millimeter wave FR2.

![Table II: Case Study Simulation Parameters](Image)

| Deployment | FR1 | FR2 |
|------------|-----|-----|
| Channel model | UMa | InH |
| Inter-site distance | 200 m | 20 m |
| Base station (BS) height | 25 m | 3 m |
| Antenna downtilt | 12° | 90° |

| Radio | | |
|-------|-----|-----|
| Carrier frequency | 4 GHz | 30 GHz |
| Subcarrier spacing | 30 kHz | 120 kHz |
| System bandwidth | 100 MHz |
| BS noise figure | 5 dB | 7 dB |
| UE noise figure | 9 dB | 12 dB |
| BS antenna | 32 TxRU/s, 5 dBi gain | 2 TxRU/s with grid of beams, 5 dBi gain |
| UE antenna | 2T4R, 0 dBi gain | 3 panels (left, right, top), 5 dBi gain |
| BS Tx power | DU: 51 dBm | InH: 31 dBm |
| UE Tx power | 51 dBm | 24 dBm |

B. Capacity evaluation

Fig. 2 illustrates the XR network capacity (minimum of DL and UL) achievable for typical XR setups in InH and DU deployments with either FR1 or FR2 radio. We first note that the considered XR use cases are DL-limited, not UL-limited, as our study shows that more XR devices per cell can be supported in UL than in DL in every modeled configuration. Hence, DL video is a major factor limiting XR network capacity in Fig. 2. Particularly, only six XR devices are supported per cell for “AR/VR 30 Mbit/s” in DU FR1. The core limitation here is the stringent PDB requirement of only 10 ms imposed for AR/VR services (see Table I). Meanwhile, CG with 15 ms PDB features up to 1.3 times higher XR capacity for the same 30 Mbit/s per UE. The XR capacity for CG ultimately reaches 11 satisfied UEs per FR2 cell in InH. We finally observe that the change of 30 Mbit/s with 45 Mbit/s decreases the XR capacity by up to 2 times, so XR capacity scales non-linearly with the data rate, as latency plays a role.

C. Power consumption evaluation

Fig. 3 shows the DL capacity and XR UE power consumption in FR1 DU with different power saving techniques. We model four connected mode discontinuous reception (CDRX) configurations, where the values in brackets stand for: “DRX long cycle”, “On duration timer value”, and “Inactivity timer value”. The gains are calculated versus “UE Always ON” scheme, where UE is always available for scheduling. From Fig. 3 we first observe that the increase of the “On duration” decreases the power saving gain. After a short “On duration”, there is a high probability of going to sleep, as the chances to immediately receive the next video frame are low.

On the other side, comparing CDRX3 with CDRX4, we note that the capacity loss decreases for the same cycle duration and increases “On duration”. The latter is caused by the fact that higher “On duration” increases the probability of receiving the video frame before its PDB expires. We finally notice that “AR/VR 45 Mbit/s” is the most challenging setup for power saving, featured by lowest power saving gain and highest capacity loss. Here, reception of larger video frames takes a longer time, which both compromises strict PDB of 10 ms and demands the XR UE to stay awake longer.
VI. OUTLOOK ON 5G-ADVANCED INNOVATIONS FOR XR

Although legacy 5G is proven capable of providing basic XR support, massive adoption of XR devices and services in cellular networks imposes new research and engineering challenges. To further boost the XR performance, 5G-Advanced will introduce a multitude of heterogeneous enhancements, including both XR-specific enablers and service-agnostic enhancements that will also help improving the XR performance. 5G-Advanced standardization is currently in the early stage, with Release 18 work starting in RAN in Spring 2022 [12] and further evolving in 3GPP Release 19 and 20. A brief overview of these innovations is given in the following and illustrated in Fig. 3. We particularly focus on Release 18 enhancements, as per December-2021 3GPP RAN and SA plenaries:

1) XR application awareness and scheduling: Among the main XR-specific enhancements, a higher degree of application awareness is to be introduced, thus enabling more efficient Radio Resource Management (RRM) and scheduling. This involves new innovations for both RAN and SA toward an end-to-end optimized XR solutions for advanced multi-modality services supporting efficient interaction between 5G system and application. For example, application layer identifiers (i.e., flow and viewport information) can be shared through the extension of the 5G QoS Flow Identifiers (QFI) to differentiate packets within the same packet data unit (PDU) session. In addition, 6DoF information and Application Data Unit (ADU) metrics may be included in the 5QI as new QoS characteristics signaled by the core network (CN) to the RAN for interactive XR and gaming services. Furthermore, scheduling schemes such as semi-persistent scheduling (SPS) for DL and configure grant for UL are expected to be modernized to better fit the time-variant XR traffic. This includes the adoption of more dynamic radio resource allocations in line with, i.e., video codec adaptation algorithms that change frame size and rate according to network status and user behavior.

2) XR device power saving: Dedicated power saving optimizations for XR devices are also envisioned. These are needed to efficiently minimize battery draining and dissipated heat, which is a major concern for user’s comfort if using XR glasses. To address these challenges, adaptive solutions are to be further developed that autonomously learn the best configuration for existing power saving techniques, including DRX, sparse PDCCH monitoring, and Wake Up Signal (WUS). For example, parameters of the DRX duty cycle and the frequency for monitoring the PDCCH may be dynamically adjusted according to the XR traffic characteristics, XR requirements, network load, and radio channel status.

3) MIMO and beamforming: While 5G already supports advanced multiple-input multiple-output (MIMO) and beamforming, 5G-Advanced is particularly focused on UL enhancements, such as higher ranks and more transmission chains that could bring an estimated additional 20% gain in UL throughput gain. This will offer benefits, especially for UL-heavy AR applications. In addition, optimizations for dynamic beam management will also be considered.

4) Mobility and cell management: Mobility-centric innovations are also on the 5G-Advanced agenda. From an XR perspective, the desire to further lower service interruption time during handover is particularly important. Today, the handover interruption time is around 20-50 ms for basic and conditional handovers and down to 2-10 ms for dual active protocol stack (DAPS) handovers. Such interruption times can be harmful to the user experience if the XR UE is subject to frequent handovers. The intention is, therefore, to lower these values for 5G-Advanced, aiming at truly seamless handovers for the UEs, including devices with only one transmitter/receiver chain and protocol stack (without DAPS support). Further gains can be obtained from advanced carrier aggregation and dual connectivity (CA/DC) mechanisms.

5) Edge computing and slicing: The 5G trend to introduce edge computing enhancements will continue in the 5G-Advanced era, particularly toward bringing the Application Server (AS) on the network side closer to the application client on the UE side. While legacy 5G already includes several edge computing features, it is foreseen that 5G-Advanced may also incorporate, among others, different policies for different categories of UEs, as well as the ability to relocate a given edge application server for a collection of UEs. Here, XR is one of the major use cases for edge computing due to its stringent latency requirements [14]. Network slicing is another useful mechanism to manage highly diverse XR services (as well as other services) over a single 5G network. In this context, network slicing enhancements are envisioned in 5G-Advanced to minimize the service interruption when a slice service area border is crossed.

6) Sidelink enhancements: A plethora of sidelink enhancements are also considered for 5G-Advanced. Among others, those include sidelink carrier aggregation enhancements to support higher data rates and improved reliability, as well as sidelink operation for unlicensed bands. Such sidelink enhancements could pave the way for new XR applications, i.e., between smartphones or smart glasses.
7) **Flexible duplexing:** Finally, 5G-Advanced will also study flexible duplexing (FDU) evolution, including enabling simultaneous UL and DL transmission on an unpaired carrier. FDU is envisioned to offer additional flexibility for latency-throughput demanding XR applications, as compared to the current TDD solution with either exclusive DL or exclusive UL transmission at any given time for each unpaired carrier per cell [15]. However, FDU imposes additional complexity on BSs and UEs. Here, the feasibility and cost of self-interference schemes to enable simultaneous DL and UL transmission on an unpaired carrier is of primary importance.

**VII. CONCLUSIONS AND THE ROAD AHEAD**

Reflecting major 3GPP activities on XR, this article provides an executive summary on the XR via NR in 5G and 5G-Advanced. A case study is also presented confirming that 5G NR can already support XR services, albeit with a limited number of XR devices per cell for the highest data rates.

Massive adoption of XR devices and services is one of the drivers for the development of future cellular systems. Besides discussed Release 18 items, further XR-related innovations are likely to appear in later NR releases. Among many others, this may include enhanced UE positioning and orientation via network localization and sensing techniques as well as adoption of artificial intelligence and machine learning (AI/ML) to better adapt to time-variant XR traffic. Hence, while state-of-the-art 5G networks can already run some XR services, the standardization work on better XR support is still in its early stage, with many open research problems to be tackled for 5G-Advanced and 6G systems.

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