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Cloud VR on 5G: A Performance Validation in Industrial Scenarios

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ABSTRACT The emergence of the novel approach of Industry 5.0 entails the utilization of immersive technologies such as XR (Extended Reality), which promise to transform the conceptualization of industry. The advent of new technology enablers, such as next-generation mobile networks, including 5G and B5G (Beyond 5G), plays a pivotal role in enhancing productivity, optimizing operators' training programs, and minimizing unnecessary risks. This study presents a performance assessment of Cloud VR services over 5G and WiFi in industrial scenarios. This scenario involves several factors that can degrade radio links, including fading and interference. To assess the suitability of 5G for the Industry 5.0 hot topic of XR, a 5G SA/WiFi-6 Edge Cloud VR setup was developed in the Smart Production Lab at Aalborg University. The results demonstrate that 5G outperforms WiFi in terms of latency and throughput consistency during the experiments in DL (Downlink), which belongs to the streaming channel with UDP (User Datagram Protocol). In the uplink (UL), WiFi generally exhibits lower latency than 5G when employing Transmission Control Protocol (TCP) for the control channel. To provide a comprehensive End-to-End (E2E) analysis, an objective Quality of experience (QoE) metric has been estimated. The outcomes demonstrate that 5G achieves higher QoE values for mobility than WiFi, which shows a decline in performance. The results indicate that 5G performance is within theoretical limits for XR experiences and suggest that it is a promising candidate for enabling Industry 5.0 and its use cases.

INDEX TERMS Cloud VR, virtual reality, extended reality, multimedia, E2E latency, latency, mobile networks, wireless networks, 5G, B5G, WiFi.

I. INTRODUCTION

THE advent of 5G technology and the recent advancements in standardization for Beyond 5G (B5G) have opened the door to a plethora of new services and applications that were previously unfeasible due to the lack of developed technology enablers. Among the most promising services that are garnering significant attention is Cloud Virtual Reality (VR), which allows users to enjoy VR experiences without the necessity of possessing a highly sophisticated device. This is made possible by the execution of the VR application in the cloud, with the user only requiring a lightweight device for the display of images and the transmission of sensing information back to the cloud.

VR is a subset of a broader category of technologies collectively known as extended reality (XR). This umbrella term encompasses augmented reality (AR) and mixed reality (MR). The defining feature of VR is the level of user immersion it offers. In VR, the user is completely immersed in a virtual world. In AR, the user is in the real world with some virtual objects overlapping or anchored in it.

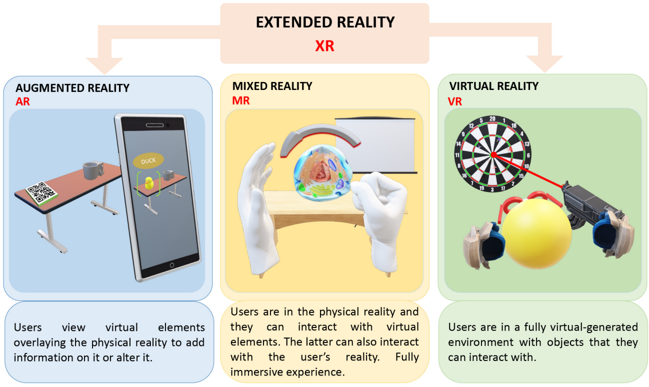


FIGURE 1. Extended Reality as an umbrella term.

These objects can enrich the context with information or alter the physical reality with a virtual overlay. For example, in Pokemon Go, the user is in the real world merged with virtual objects that can be a target of interaction. In MR, the user is in the real world merged with virtual objects that can be interacted with [1], [2]. Figure 1 depicts a graphical summary of the scope of XR.

One of the hot topics of XR is the application of immersive technologies to the industry. This is known as Industry 5.0 and is based on the use of immersive technologies to improve the industry's productivity from a human-centric perspective. This is considered a complementary approach for Industry 4.0 intended to extend and exploit new features such as cognitive systems, immersive technologies, and data-based service customization [3]. In this context, VR can be used to train the workers in a safe environment, design new products, simulate the production line, etc. [4]. However, the use of VR in the industry is limited by the cost of the devices and the need to have powerful computational resources to run the VR application. This is where Cloud VR comes into play. Cloud VR allows the user to enjoy VR experiences without the need to have a powerful device [5].

However, meeting the requirements of Cloud VR is not an easy task. The main challenge is the latency, which is the time the user has to wait to see the changes in the virtual world after moving the head. Latency plays a vital role in XR. For instance, an increase in the delivery time of certain frames can produce a mismatch between the user's actions and the visual feedback, degrading the immersive experience [6]. In this context, the overall latency can be defined as the combination of several components, such as the rendering time, the encoding time, the transmission time, the decoding time, and the display time, among others in the literature.

Likewise, throughput is also an important factor to consider, since the images of the virtual world have to be sent from the cloud to the user. Reaching adequate levels of throughput through a Wireless network is also a challenge due to the limited resources. Bounded data rates can lead to the reduction of the video resolution displayed on the screen. Some research has proven that low resolution produces a loss of immersion and visual comfort.

In addition, ensuring data reliability is important to avoid the loss of information that may affect the interaction and the sense of presence of the user.

The factors mentioned above can highly affect the user's Quality of Experience (QoE). The compromise of any of them can severely degrade the experience of the user causing loss of immersion or even health-related issues such as nausea, dizziness, or even physical damage [7], [8], [9].

To overcome these challenges, the use of 5G networks is a promising solution. This technology promises to enable different use cases, such as enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC). Along these lines, 5G-advanced networks are expected to provide high throughput, low latency, and high reliability according to forecasts made by telco equipment vendors (e.g., Nokia [10], Ericsson [11]). The low latency and data reliability will allow the user to interact with the virtual world in real time, while the high throughput will let the user enjoy high-quality images. However, the performance of Cloud VR depends on the network conditions.

The objective of this study is to assess the performance of an Edge Cloud VR service in various network environments in order to ascertain the influence of mobile networks on the user experience. In this context, a static and a mobility scenario are evaluated using a real Edge Cloud VR implementation based on the 5G SA/WiFi-6 network deployment of the Aalborg University (AAU) within the SmartProduction Lab premises. This kind of scenario provides a realistic assessment of the impact of external factors (e.g., machinery and/or human presence and even communications technologies coexisting in the same environment) on the QoE using objective metrics such as the throughput and latency measured by the VR service.

Currently, there are no commercially available devices that support 5G connectivity. Consequently, this work has also implemented a 5G-to-WiFi gateway that allows a Meta Quest Pro device to connect to the mobile network. The collected results seek to establish whether current 5G deployments can facilitate the deployment of this service, and to compare its performance to that of WiFi. This is achieved through the assessment of the network latency, End-to-End (E2E) latency, and throughput. Moreover, to provide a comprehensive analysis that considers both the network's perspective and that of the objective user, a QoE metric has been calculated to establish the degree of impact of the network on the perceived QoE.

The results indicate that 5G has the potential to support Cloud VR services. The performance in terms of latency and throughput is comparable to that achieved with WiFi. Nevertheless, the most significant finding is that 5G offers a more stable latency and QoE in mobility scenarios than WiFi. This is a crucial factor for Cloud VR, as latency is one of the primary determinants of the user-perceived QoE.

To reference the paper's structure, this is organized as follows. Section II presents the State-of-the-Art (SoTA) requirements for VR and the related work associated with XR's previous research. Section III describes the setup used to evaluate the performance of Cloud VR. Section IV presents the evaluation results. Finally, Section V concludes the paper with the insights gathered through the experimentation and also points out future work lines.

II. VR IN THE LITERATURE

XR is a wide umbrella term used to involve several immersive or interactive technologies (i.e., AR, VR, and MR) that look for revolving the way to consume content or to evolve day-to-day human activities to a new interactive approach.

In light of this, the requirements for XR are diverse concerning the type of service to be used (i.e., AR or VR-based), the kind of communication that interconnects the user with the application servers (fixed or mobile), and thus, the scheme to be deployed (level of disaggregation of functions). In this work, we will focus on VR, its challenges, and its feasibility for deployment using mobile networks.

A. VR BASICS AND REQUIREMENTS

VR is an emerging technology that promises to be one of the key enablers for the communications of the future. In the context of XR technologies, VR aims to create immersive virtual experiences for users, where every object is generated virtually. Contrarily to AR, VR aims to embed the user in a virtual world, thus, the user can interact with these elements using specific gestures through VR controllers or hand-tracking technologies.

To reach this immersive experience, the VR content must be displayed in an omnidirectional manner using a combination of image projection methods (e.g., equirectangular) and/or dedicated screens for each eye, normally embedded in a piece of equipment called a Head-mounted device (HMD).

The key challenge in this latter device is the computing/graphics processing, generally hardware resources that it should integrate to provide a formidable immersive experience to the user. In this context, in the market, there is a plethora of brands and models of HMDs offering different functionalities in terms of visual quality (i.e., pixel density and resolution), refresh rate (i.e., the number of times per second the screen updates) and the capabilities to perform VR applications with or without the need of an additional piece of equipment (e.g., a computer, game console, etc.).

When it comes to the literature, three different architectures can be deployed to provide VR services and applications as depicted in Figure 2. Historically, only the standalone and tethered versions of HMD have been considered as state-of-the-art architectures [12], nonetheless, due to the rise of the "cloudification" of things, the appearance of technology enablers (i.e., mobile networks, cloud computing) the cloud version of the HMD is currently being in consideration of the academia and the industry.

First, the standalone (also known as autonomous) scheme integrates computing and graphics-dedicated hardware to endow the HMD with all the capabilities to process the game logic, rendering, encoding/decoding, and displaying tasks in one single entity. However, loading all these software/hardware features in a single device incurs two different scenarios: high-on-market cost devices for professional/development usage, and devices with bounded functionalities to provide a trade-off between performance and cost in the market for entertainment-content users and VR enthusiasts.

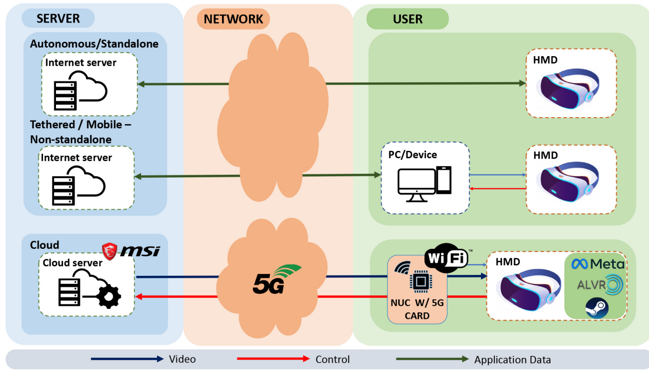


FIGURE 2. VR architectures.

Second, the tethered/mobile or non-standalone equipment can provide high-quality VR experiences, similar to or even better than the standalone architecture in terms of visual quality. Nonetheless, the key disadvantage is these HMDs are required to be linked to a VR-ready device (graphics cards for 3D rendering), which is in charge of all the game logic, rendering, and time and computing-intensive tasks, meanwhile, the HMD is only responsible for displaying the content to the user on the screen. Most devices in this category are designed for professional usage, which means high-cost equipment involving HMD and VR-ready hardware (e.g., a gaming computer or a graphics-enabled server). An alternative to the dedicated VR HMDs, Google developed a project named Cardboard that is intended to provide an open platform for VR-like rendering in mobile Android devices. The content is visualized on the device screen using a cardboard-made HMD [13].

When it comes to the cloud approach, the main goal is to split some of the functionalities of the VR technology between the user device and hardware located in the cloud domain. The architecture of this scheme is similar to the tethered one, where hardware equipment is needed to perform computing-intensive tasks, however, this is not mandatory to be owned by the user. This latter fact opens new opportunities for content delivery and service provider verticals that can lease VR-optimized premises in the manner of Platform as a Service (PaaS), thus, service providers can build applications and services over on-network premises that are reachable by users using hardware-light equipment (e.g., Nvidia's Project Aurora [14]). In addition, these platforms will implement compatibility with Artificial Intelligence (AI) tools which aims to integrate these immersive experiences to comply with the Metaverse concept.

When considering the particular demands of VR, round-trip-time (RTT) latencies of around 20 ms are expected (i.e., Radio Access Network - RAN latency without decoding, encoding latencies) for optimal experiences and 60 ms for regular ones [15], [16]. Nevertheless, latencies up to 100 ms are supported for low-interactivity services (e.g., sports broadcast on 360 degrees) [5].

In addition to low and bounded latencies, VR requires suitable visual quality to create adequate immersion levels. According to Elbamby et al. in [17], a resolution of 60 pixels per degree using a frame rate of 120 Hz within a Field of View (FOV) of 120 degrees is recommended. Although currently streaming of panoramic video at 60 Hz in 4K reaches up to 50 Mbps [5], 5G technology is expected to increase these rates (i.e., higher than 100 Mbps) to support up to 8K video with low latency.

Comparably to XR, other distributed services such as Cloud Gaming (CG), 360-Video, and other multimedia applications, necessitate stringent requirements not to lose the sense of “flow” and “immersion”. For instance, Abdallah et al. in their survey [18] concord that three factors influence the QoE for multimedia applications: visual quality, latency, and packet loss.

In this scope, the degree of disturbance of the user perception depends on the degree of interactivity. For example, weak-interaction services, such as office applications, present degradation at about 120 ms, whilst multimedia services threshold drops at 100 ms. Concerning 360-video, Liu et al. [19] point out that a limit of 10 ms for rendering is needed, however, this time does not consider the network latency. To fill this gap, Choy et al. [20] established that the average latency for an excellent QoE in distributed gaming applications is about 40 ms and 80 ms for a tolerable QoE.

Likewise, the research in [18] indicates that the QoE is relative to the user’s subjective assessment. For visual quality, the frame rate affects the player’s performance depending on the type of content. Moreover, packet loss can affect the perception of smoothness. Clincy and Wilgor [21] reported that when there is 0% of loss, players tend to notice more issues with high latency. However, when packet loss increases, subjects pay more attention to the loss of responsiveness rather than the latency.

B. RELATED WORK

One of the hottest applications of XR is in the industry. XR is an umbrella term involving different technologies enablers that can be applied for quality assessment, training, and design processes in Industry 5.0 [22]. In this context, VR can be directly used to abstract some tasks that used to be done physically, or to provide extra levels of safety in industrial processes that can lead to unnecessary danger to operators.

When it comes to the application fields of VR, there are a plethora of usages for maintenance and operation in the industry. In [23], [24] VR is used for early design, assembly compatibility, and maintenance operation simulations for the nuclear industry. In the scenario of Industrial Maintenance and Assembly (IMA), [25] presents an immersive interface using VR to control robots intuitively in outdoor and indoor scenarios. A similar approach is utilized by Randeniya et al. in [26] to demonstrate the advantages and improvements in the performance of technical task resolution and learning for the rail industry. Another instance of VR for learning is used in [27] to develop a virtual lab for automotive engineering where students can interact with a four-stroke combustion engine virtual model.

Furthermore, VR is analyzed and summarized as a support technology for electrical and electronics engineering in [28]. This review paper lists 82 previous works where VR is utilized to improve learning skills on electricity basics, laboratory equipment, and electrical engineering training over digital twins (DT). In the same line with DT, the study in [29] shows VR’s validity in the aeronautical industry field. The study conducted two experiments: one in real conditions and the other in a virtual environment to develop visibility checks for aircraft interior redesign and cable routing tasks. The results show that learning and training with VR present better performance than conventional procedures and also can help to reduce costs by improving designs.

In the same context of applications, VR is considered a valuable tool for Operator Training Simulators (OTS) in the oil industry. The applicability of Immersive Virtual Environment (IVE) with VR-OTS has allowed companies to endow operators with additional skills that reduce the chances of oil accidents. This kind of solution provides better opportunities for environmental care as well as a decrease in training costs [30]. All these mentioned applications belong to a wide variety of fields where VR is pertinent.

Concerning the scope of the communications, the literature displays a plethora of works pointing out the theoretical requirements for XR applications and services, networks, and equipment. In these lines, Hazarika and Rahmati in [31] describe some B5G technology enablers such as Multi-access Edge Computing (MEC), mmWave, beamforming among others to power URLLC and eMBB XR cases meeting latency and throughput requirements. Moreover, Zhang et al. [32] highlight the big portfolio of Artificial Intelligence of Things (AIoT) applications (e.g., Digital Twins) that can be supported by the use of big data and AI. Taking into account that massive data transfer is needed in IoT networks for industrial, healthcare, and educative scenarios, 5G is the key enabler to leveraging this approach due to its possibility to handle adequate data rates in dense networks.

Furthermore, in [33] is presented a summary of different caching and processing techniques in the cloud/edge to improve the performance of AR/VR applications for 5G. The authors describe different approaches such as caching at the edge or computing at the cloud/edge, network core, or RAN. These proposals are effective in reducing latency for time-intensive services, energy consumption, and alleviating unnecessary traffic in backbone networks.

In addition to the Edge's theoretical applications, George et al. presented OpenRTiST, a benchmarking tool for edge computing, in their article [34]. This tool captures video frames from the user equipment, transmits them to a server, and returns a transformed version that integrates the style from a different source. The results indicated that cloudlet-based deployments are a viable approach for reducing motion-to-photon (MTP) latency compared to cloud-based solutions. The networks utilized were WiFi and an experimental LTE deployment. Although the improvement in processing times is evident, the latency introduced by mobile equipment constrains the provision of the service. The minimum latency observed in this study was 156 ms using WiFi for 720p content processed at the Edge.

Lai et al. in [35] conducted an analysis of the feasibility of using high-end VR devices for high-quality applications. The results demonstrated that the simultaneous processing of foreground interactions in the client and background data does not comply with the minimum values of MTP latency for 60 FPS. To overcome this issue, the authors presented Furion, a framework that divides the processing tasks into a collaborative rendering architecture. The results reported that the latency was reduced up to 14 ms using an IEEE 802.11ac WLAN (Wireless Local Area Network).

Similarly, Liu et al. [36] presented a 4-way rendering and streaming approach to simultaneously manage hardware rendering and encoding processes at the remote server, and decode them on the client side. This solution's reported average E2E latency was 20 ms using 4K content. The evaluation was performed using a VR-ready server, a laptop as the decoder client that feeds the HMD using an High-Definition-Multimedia-Interface (HDMI) cable. The connection between the client and the server was featured by a 60-GHz WiGig link.

Concerning other bandwidth-hungry XR applications, Zhang et al. [37] analyzed the use of WiGig technology to provide Volumetric video service to multiple users. The authors of the study reported that current WLANs are inadequate to ensure sufficient throughput to transport the considerable data generated by high-quality volumetric video, which requires approximately 300 Mbps per user at 30 FPS. To address this limitation, it was necessary to implement mmWave WLAN (e.g., IEEE 802.11ad) in conjunction with multicast beam design and video adaptation. The objective of this strategy was to minimize the impact of constrained throughput on the quality of service (QoS).

Relatedly, Taleb et al. in [38] emphasize the significance of utilizing edge/cloud-based infrastructure to reduce the burden on user-end equipment, enhance energy efficiency, facilitate service scaling for multiple users, and so forth. To achieve this objective, next-generation networks, such as 5G and B5G, are designed to meet the rigorous requirements through the introduction of new 5QI (5G Quality Indicators) classes. This strategy will merge the 5G pillars of URLLC and eMBB to leverage the immersive services use cases.

Given the prominence of XR as a research topic in academia and technology companies globally, there is a substantial presence of research work on the basis of XR. Notwithstanding, the aforementioned efforts primarily concentrate on enhancing the distribution of content between the end-user equipment and remote servers (i.e., improving rendering and encoding schemes). The abovementioned related work aims to provide users with the optimal QoE while minimizing the transferred data and reducing latencies on both ends.

Moreover, the latency introduced by cutting the cable is of paramount importance, as it can significantly impair the user experience. At the moment, the developed SoTA research considers IEEE 802.11 standards (e.g., WiGig) as a technology enabler to fill this gap. However, these standards lack certain advantages that are inherent to mobile networks, such as wide-area coverage, mobility management, robustness against non-line-of-sight (NLOS) conditions, and the integration of services through native quality of service (QoS) classes, among other features.

The absence of research that assesses the relative merits and drawbacks of utilizing mobile networks (e.g., 5G) for XR serves as a catalyst for our investigation. To that end, we have deployed an experimental Cloud VR setup over a real 5G-and-WiFi-enabled industrial scenario with the objective of analyzing and establishing the current state of these technologies for providing this kind of service. The objective of this study is to ascertain whether the current network deployments are sufficiently developed to meet the theoretical requirements for Cloud VR as outlined in Section II-A.

III. SETUP

This section outlines the setup used to evaluate the performance of an experimental implementation of an Edge Cloud VR service over wireless networks. The term "Edge Cloud" refers to the location of the server on-premises, while a pure implementation of Cloud VR corresponds to a server placed on the Internet.

The configuration comprises a VR server, a VR client, and a transport network. The VR server is responsible for managing the game logic, rendering the frames based on the user's feedback (i.e., sensing and tracking), and streaming the images to the VR client. Conversely, the VR client is responsible for decoding and displaying the images to the user and for sensing information that is feedback to the server.

The transport network is responsible for delivering the data in its various formats between the server and the client. In order to facilitate the comparison of the two networks, the latest commercial mobile network, 5G SA, is utilized in this work. This is contrasted with the most mature IEEE 802.11 standard, which is compatible with the current commercial HMDs (i.e., WiFi6 - IEEE 802.11ax).

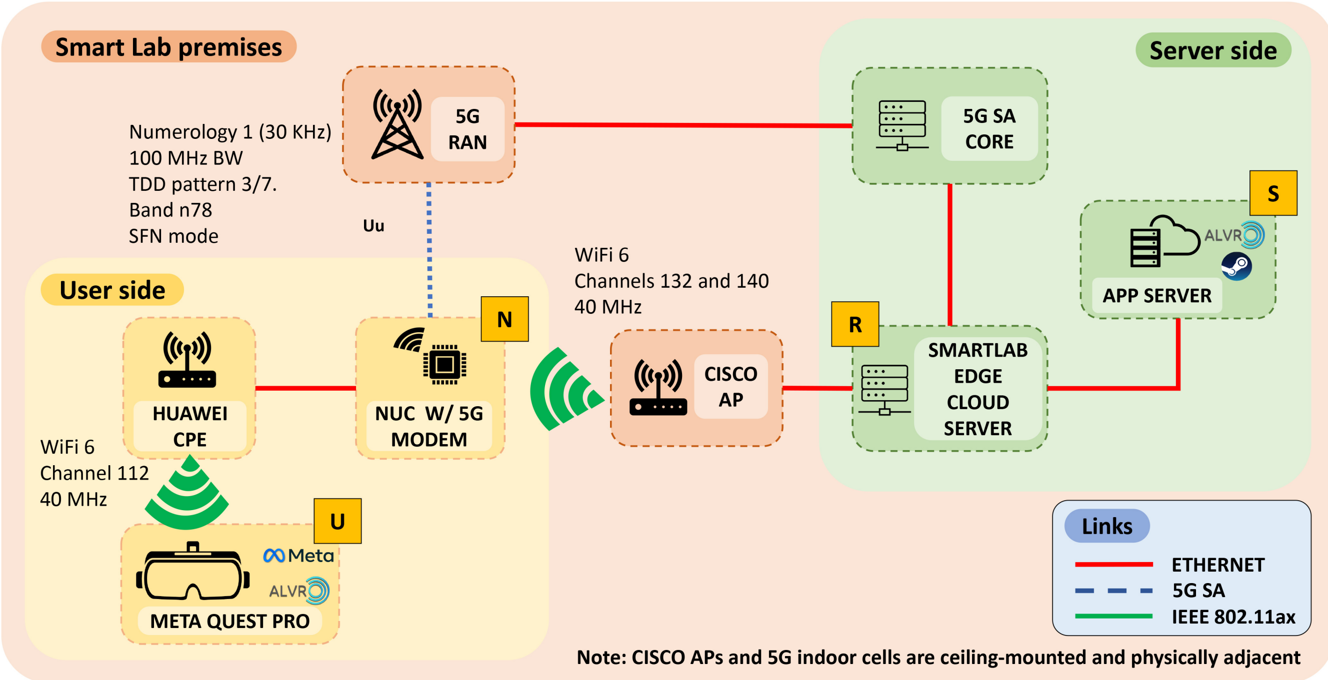


FIGURE 3. Setup's architecture.

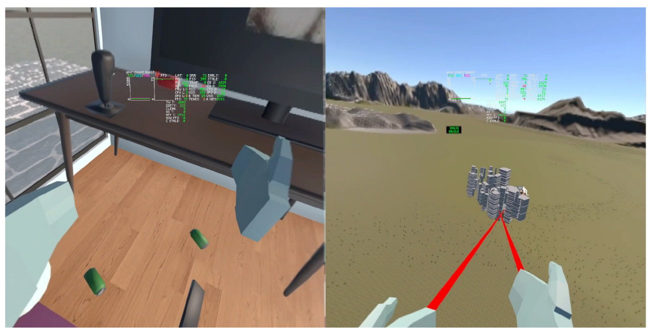
It is remarkable to mention that the server, client (i.e., Meta Quest Pro HMD), and transport network utilize real equipment compatible with the latest commercial standards in the market. Figure 3 shows the setup used to evaluate the performance of Cloud VR.

A. VR SERVER

generating new frames that respond to the user interaction data (i.e., sensor information, tracking, actions, etc.) sent from the client. The VR application is developed in Unity 3D, which serves as the graphics engine, and configured to work with the SteamVR runtime (i.e., OpenVR-compatible). In order to comply with the aforementioned specifications, the application was developed using the Meta XR plugin by default and subsequently added to Steam's library.

Regarding the hardware, the server is implemented on an MSI GP66 Gaming PC, which is equipped with an Intel Core i7 12700H (45W), 16 GB of RAM, and an Nvidia RTX 3070 Ti graphics card. The server is connected to the SmartLab Edge Cloud Server through a Gigabit Ethernet interface, as illustrated in Figure 3. Both servers are situated on the premises of the Smart-Production Lab at the AAU.

The delivery of VR content is accomplished through the ALVR desktop application for Windows [39]. ALVR is a solution that enables the streaming of VR games from a VR-ready PC to a compatible commercial HMD (e.g., Meta Quest 2/3/Pro, Pico 4). This software enables the configuration of certain parameters associated with the service, including transport ports, IP addresses of the client, transport protocol, encoding and decoding formats, and so forth.



(a) Inside. (b) Outside.

FIGURE 4. VR application running in the Edge Cloud server.

As this work is focused on the effects of the network over the service, the default values, which are optimized for the Meta Quest HMD, are selected according to the values displayed in Table 1. Furthermore, Figure 4 depicts a screenshot of the VR application executed by the server.

Besides the service itself, the server runs in the background a metrics extraction tool coded in Python that fetches some metrics from the service and network. The indicators that reflect the performance of the service, from the user's perspective, are named Key Quality Indicators (KQIs). The KQIs collected throughout the experiments are the E2E latency, network latency, content resolution, frame rate, and packet loss. The rest of the metrics are network-related and provide additional insights into the performance (e.g., network throughput).

TABLE 1. Setup configuration.

	Parameter	Description
WiFi CPE	Router model	Huawei 5G CPE Pro 2
	WiFi standard	IEEE 802.11ax (WiFi6)
	WiFi band	5 GHz
	WiFi channel	112 (5560 MHz)
	Channel bandwidth	40 MHz
WiFi CISCO	AP model	CISCO MR36 AP
	WiFi standard	IEEE 802.11ax (WiFi6)
	WiFi Band	5 GHz
	WiFi channel	132 (5660 MHz) 140 (5700 MHz)
	Channel bandwidth	40 MHz
5G	Modem model	SIMCom 8202G M.2 5G
	Chipset	Qualcomm
	MIMO Configuration	2x2
	5G mode	5G SA - Standalone
	5G band	n78
	Network Bandwidth	100 MHz
	5G numerology	1 (30 KHz)
	TDD Pattern	3/7
NUC	Device model	Intel NUC NUC5i3MYHE
	Processor	i3-5010U CPU @ 2.10GHz
	RAM	8 GB DDR3
	Operating system	Ubuntu 20.04.3 LTS
Server	Device model	MSI Vector GP66 12UGS
	Processor	Intel® Core™ i7-12700H
	RAM	16 GB DDR4
	Graphics card	Nvidia RTX 3070Ti 8GB
	Network card	10/100/1000 Ethernet

B. VR CLIENT

The VR client is implemented through the ALVR client for Android installed on a Meta Quest Pro HMD. To install this application, it is necessary to use SideQuest software [40] to *sideload* (i.e., Android-like installation of an application in a Meta Quest device) the APK file. Both server and client applications can be found in the official GitHub repository [39].

The reason that justifies the use of ALVR instead of the default AirLink solution from Meta lies in the flexibility the first offers to this setup. AirLink lets VR users *cut the wire* between the VR-ready computer and the HMD. Nonetheless, this feature is limited within the WLAN of the device. To overcome this barrier, ALVR allows the client to be in a different network while its IP (Internet Protocol) address is reachable by the server. In addition, to ensure network connectivity between ends, a Wireguard [41] Virtual Private Network (VPN) tunnel was created, thus, the server and client are virtually connected in the same network.

Wireguard is a solution that transparently establishes a VPN between endpoints. This software is considered faster, stronger, and easier to configure rather than other VPN protocols like IPSec or OpenVPN [42]. The key feature that enables a better performance is that Wireguard acts as a silent VPN that reduces overhead and message exchange only when necessary, handles IP roaming, and works at kernel level, thus, maximizing throughput and reducing overall latency. In this setting, using Wireguard ensures that the HMD is visible by the server in a network-agnostic manner, even using some router jumps in the transport network. This refers to the case depicted in Figure 3, where the Application Server (AS) is located behind the SmartLab Edge server. Moreover, this feature ensures that the network in between the endpoints is affected negligibly by the VPN, adding no additional latency that would affect the service experience, like a transparent WLAN configuration.

With regard to the client's hardware, it should be noted that the majority of current commercial HMD models are WiFi-enabled, while others are tethered by HDMI or USB. This represents a significant obstacle to the deployment of standalone VR-ready devices, given that there are currently no available models with a mobile connection (i.e., LTE or 5G). To address this limitation, a 5G-enabled configuration has been developed in addition to the default WiFi option to provide wireless connectivity to the HMD using a 5G SA private network (also known as a Non-Public Network, or NPN) deployed within the Smart Production Lab of Aalborg University. The 5G network is configured as a single frequency network (SFN), which enables the deployment of multiple indoor cells that share the same frequency and extend coverage. Further details regarding the AAU's Smart-Production Lab network deployment can be found in [43] and [44].

In order to adapt the new network interface to the HMD, a NUC (Next Unit of Computing) device has been employed as a gateway, connected to the 5G network. The NUC is connected to the network via an 8202G M.2 5G SIMCom modem (Qualcomm version) with MIMO 2x2. The NUC incorporates an Intel Core i3-5010U central processing unit (CPU) operating at 2.10 gigahertz (GHz) with two cores and 8 gigabytes (GB) of random-access memory (RAM). The device, which is running Ubuntu 20.04.3 LTS, establishes the connection with the modem via the ModemManager service. With regard to the IP connection, a Wireguard client has been installed and configured within a virtual private network (VPN) with the SmartLab Edge Cloud Server. The NUC Ethernet interface was bridged and linked to the WiFi 6 router (i.e., a Huawei CPE - Customer Premises Equipment - in Figure 3) in order to provide wireless connectivity to the HMD.

It is noteworthy that the 5G CPE functionality was not utilized in this study due to its inability to connect to the SmartLab 5G network. The issue was attributed to an incompatibility between the network's authentication method and the CPE's firmware, which was in use at the time of the experiment.

With regard to the WiFi configuration, the NUC is linked to the SmartLab Edge Cloud Server via a CISCO WiFi6 network. The WiFi experimental deployment considers two access points (APs) utilizing 40 MHz channels. Moreover,

FIGURE 5. AAU Smart-Production Lab.

both the access points and the remote radio heads (RRHs) are mounted on the ceiling in the laboratory and are in close proximity to one another. The common element between the two technology setups is the NUC. This configuration is expected to maintain the objectivity of the experiments because both 5G and WiFi setups have the same number of wireless jumps before reaching the HMD. In this configuration, the CPE's WiFi interface provides Internet access, maintaining a similar setup to the one described in the 5G setup. Table 1 provides a summary of the configuration.

To conclude this section, it is essential to note that both WiFi and 5G radio heads are situated in the same location within the SmartLab. This physical configuration ensures that the propagation distance is, in practical terms, identical. Moreover, the NUC serves as the gateway for communication with the HMD for WiFi and 5G. These considerations were taken into account in detail in order to ensure consistency in the subsequent analysis of the results.

Figure 5 illustrates the AAU premises where the experiments were performed.

IV. RESULTS

This section presents the experimental results obtained using the WiFi/5G setup described in Section III. The results provide a performance comparison in terms of latency and throughput. Moreover, in order to ascertain the impact of these metrics on the user experience, an objective QoE metric will be estimated using a mathematical model that accounts for the requirements established in Section II-A.

With regard to the measurement of the metrics, it should be noted that some reference points have been highlighted in Figure 3 using yellow squares with a letter. This figure displays four reference points, namely U (User - HMD), N (NUC), R (Edge Cloud Server), and S (Application Server), where the measurements were performed.

A. FIGURES OF MERIT

The Figures of Merit (FoM) to be discussed in this work results are latency and throughput. The metrics have been selected following the requirements outlined in Section II-A. Conversely, the content resolution is disregarded since its value is considered to be constant throughout the experiments. This is due to the configuration of the ALVR server, which is designed for optimal streaming to Meta Quest Pro HMD. The ALVR default resolution is 2592x1072 pixels at a frame rate of 72 Hz. However, the number of displayed frames may vary due to the loss of packets caused by the transport network.

With regard to latency, this metric is analyzed in two distinct ways. Firstly, the latency introduced by the transport network is solely contingent upon the technology employed to interconnect the client and the server. Secondly, the overall latency is comprised of two distinct components: the network delay and the processing delay. The network delay is the time required for data to traverse the network, while the processing delay is the time required for the server to render and encode the content and for the client to decode and present it.

Given that it is not possible to guarantee that latency and throughput measured values belong to normal probability distributions, the arithmetic mean of the samples does not provide reliable information because it can average regular values with statistical outliers. To address this issue, this analysis will rely on the median. Similarly, the standard deviation is not an appropriate metric for measuring dispersion. To quantify the degree of variation with respect to the median, the median absolute deviation (MAD) is estimated. The MAD is a robust measure of data dispersion, as it is not affected by outliers in comparison with the standard deviation.

The MAD is defined as follows:

$$MAD = median(|X_i - median(X_i)|) \tag{1}$$

where X_i is an observation.

Furthermore, to provide a comprehensive analysis of the results beyond the network perspective, it is necessary to understand the results from the service perspective. This means estimating the degree of affection caused by the network effects over the QoE. Consequently, to disregard bias introduced by the user's subjective perspective, an objective quality metric is utilized. This metric is estimated based on the models established by Krogfoss et al. in [45].

The model establishes that the QoE value is a function of the product of the impairments created by coding, latency, and packet loss factors.

$$Q_{vr} = \alpha \cdot \left(I_{cod} \cdot I_{lat} \cdot I_{plr}\right) + \beta \tag{2}$$

where I_{cod} is the coding impairment, I_{lat} is the latency impairment, and I_{plr} is the one generated by the packet loss, α is the scaling factor and β is the offset applied.

In this sense, higher bitrates are expected to produce less negative impact on the visual quality. Likewise, higher latencies cause higher impairment concerning the immersion degree. The increase in packet loss is reflected in the degradation of service smoothness by the loss of user's actions or media coming from the server.

TABLE 2. Model coefficients for Q_{vr} estimation.

Model	Coefficient	Value	Description
I_{cod}	a_0	35	Mobility coeff. (94 for static content)
I_{lat}	a	100	X-axis offset, where Y value is 0.5
	b	5	Slope (penalization)
I_{plr}	a_1	16	Packet loss weight (penalization)
Q_{vr}	α	4	Scaling factor
	β	1	Y-axis offset

The coding impairment is defined as below:

$$I_{cod} = e^{\left(-a_0 \cdot \frac{BR}{PPS}\right)} \quad (3)$$

where a_0 is a coefficient based on the mobility inside the content, BR is the bitrate and PPS is the number of pixels per second.

Correspondingly, the latency impairment is estimated as follows:

$$I_{lat} = 1 - \frac{1 + e^{-b}}{1 + e^{b \cdot \frac{t-a}{a}}} \quad (4)$$

where t is the application latency, while a and b are coefficients that define the degree of penalization applied for higher latency.

The packet loss impairment is calculated in function of the packet loss ratio as a linear function.

$$I_{plr} = a_1 * PLR \quad (5)$$

where a_1 weights the influence of the packet loss in the model and PLR is the packet loss ratio.

The final model coefficients were selected on the basis of both the requirements defined in Section II-A and the previously defined values in [45]. The results of the QoE estimation discussed in the following sections are based on the values presented in Table 2. Moreover, the values of α and β are chosen in order to scale this metric in a manner analogous to that of a Mean Opinion Score (MOS).

B. REFERENCE ALVR RESULTS

This subsection shows the reference results of the ALVR application performance using different transport networks. The USB configuration can be considered as a baseline since the server and the client are connected through a USB 3.1 cable. This configuration ensures that the added transport latency is close to zero milliseconds. However, the network latency values are not zero due to the use of the IP stack between ends through ALVR.

Likewise, sensoring information needs to be sent to the server, this processes the game logic and answers with a video frame that is sent back to the HMD. This generates additional delays that are not accounted for by the network latency but by the E2E latency.

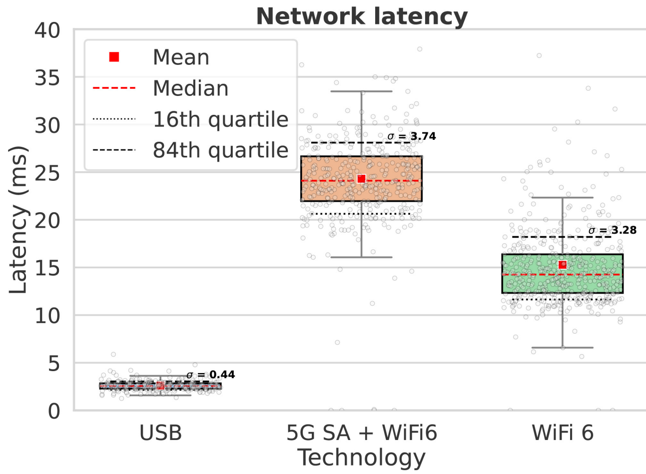


FIGURE 6. Network latency for Cloud VR using ALVR.

To deploy the baseline USB case, the VR client needed to be configured in the server's loopback network since ALVR requires streaming transparently (i.e., like a normal USB-based connection). In addition, TCP (Transmission Control Protocol) is mandatory as the transport protocol.

When it comes to the wireless configurations, Cloud VR through WiFi and 5G networks are being considered. The 5G SA configuration is deployed according to the setup shown in Figure 3. This configuration considers two wireless jumps, one for 5G and the other for WiFi (HMD-native). For WiFi, connectivity is provided by a hotspot configured by the application server (i.e., MSI gaming PC) to determine the degree of influence of the edge router (i.e., SmartLab Edge Cloud Server). The results summarize 10 sessions of Cloud VR, each lasting 60 seconds in static conditions. Note that both wireless evaluations are performed statically with LOS conditions.

Figure 6 shows a statistical analysis of the results through a boxplot per transport network. In a red solid line, it is possible to observe the median value, while the average is drawn as a red square marker. Since it is not possible to guarantee that the samples are normally distributed, the median is considered the key value in this analysis rather than the median. Furthermore, to identify the degree of spread in the data, the 16th and 84th percentiles are drawn. These percentiles are selected because they approximately capture the samples at 1σ (standard deviation). Note that the value above the 84th percentile represents the MAD value in milliseconds.

Furthermore, for the sake of clarity, it should be noted that the width of the boxes does not represent any kind of measurement or unit. The width is solely intended for the purpose of visualization.

Starting with the USB configuration, the network latency shows a median of approximately 2.5 ms with a consistent level of variability of 0.44 ms defined by the MAD. This is expected since wired connections typically provide a low jitter of less than or equal to 1 ms.

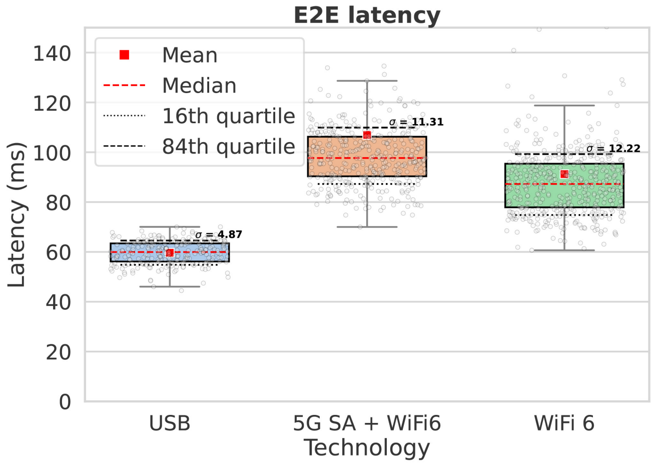


FIGURE 7. E2E latency for Cloud VR using ALVR.

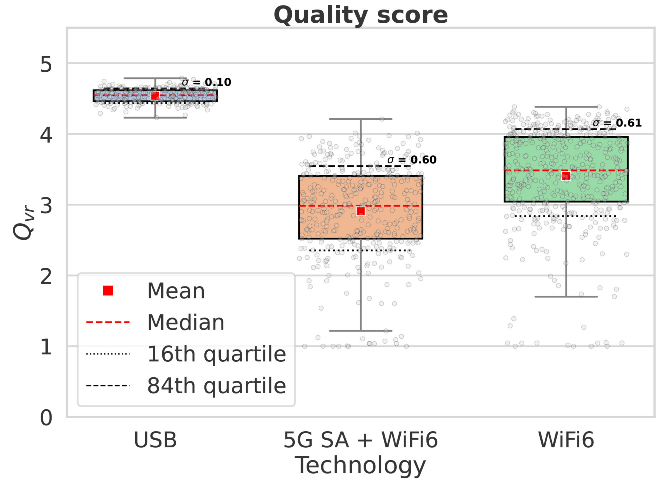


FIGURE 8. Q_{vr} metric for Edge Cloud VR.

Regarding the 5G evaluation, the median value for the network latency is approximately 24 ms with a variation up to 3.74 ms according to the MAD. Likewise, it is possible to observe that WiFi's median value is 14 ms, while its MAD is 3.28 ms. In a nutshell, it is possible to note that 5G performs close to the upper limit for an optimal VR experience (20 ms of radio latency) as suggested in the literature from Section II-A. Nonetheless, WiFi demonstrates to perform better than 5G in normal conditions, with no additional effects such as mobility or NLOS conditions.

Beyond the network delay, the actual latency the user experiences in this kind of service is the E2E one. This interval involves the time the server takes to process the game logic (i.e., the application itself interacting with user actions), rendering, encoding frames to be sent to the client, and the time the client needs to decode the frames to later display them on the HDD screen. These tasks are usually considered time and computing-intensive, however, in most cases, the transport network does not influence them, except when the server waits for a mandatory user action to be delivered, or the client expects a frame.

To complement the information presented in Figure 6, we have collected E2E latency data from the same experiments. This is shown in Figure 7. The results indicate that E2E latency follows a similar trend across different configurations. USB latency displays a median of approximately 60 ms with a variation of 4.87 ms according to its MAD. The difference between the E2E and the network latency is approximately of 57.5 ms.

Concerning 5G, this configuration shows a median value of roughly 100 ms with a dispersion of 11.31 ms. Likewise, the WiFi configuration presents a median value of 87.27 ms while its median variation is 12.22 ms. However, considering the VR requirements mentioned in Section II-A, neither case exceeds the limit of 100 ms for low-interactivity applications.

Since evaluating the performance only from the network's perspective does not provide a holistic view, it is necessary to obtain an estimation of the QoE the user can perceive.

TABLE 3. Median and MAD results for cloud VR.

Parameter	Metric	Technology		
		USB	*5G + WiFi6*	*WiFi6*
Network latency	*Median*	2.55	24.10	14.25
	MAD	0.44	3.74	3.28
E2E latency	*Median*	59.94	97.67	87.27
	MAD	4.87	11.31	12.22
Q_{vr}	*Median*	4.54	2.90	3.40
	MAD	0.10	0.60	0.61

Although, the MOS has been widely used to assess the QoE, the implication of human subjects can introduce unnecessary bias that can mislead to wrong interpretations. Hence, a QoE metric, named Q_{VR} has been estimated following the models defined in Section IV-A.

As shown in Figure 8, the USB configuration displays the best QoE performance with a median of 4.54 points out of 5 and its variation is 0.10 points. Along the same lines, 5G + WiFi6 presents a Q_{vr} median of 2.90 points with a MAD of 0.60. Similarly, WiFi6's median is 3.40 points with a dispersion of 0.61 points.

Comparing the above-mentioned results to the qualitative scale of a MOS, both WiFi and 5G configurations provide a "fair" experience meanwhile USB is defined as "good" with some perception of impairment, as expected for a wired connection.

Following the results, it is evident that the impact of latency on QoE is of paramount importance. This is because the visual quality is expected to be identical, given that the resolution is fixed in all three cases. Similarly, the impact of packet losses on Q_{vr} is minimal in a static LOS scenario.

The analysis of the results indicates that optimizing the server and the media may significantly assist in achieving the theoretical boundaries for optimal VR experiences. Although this issue has been addressed in the related works presented in Section II-B, there is still a research gap concerning the transport network. This highlights the potential of 5G, where the use of technology enablers such as network slicing (NS), MEC, and prioritized traffic strategies (e.g., 5QI), among other features, can leverage the advancements to meet the requirements.

C. REFERENCE POINT ANALYSIS

This subsection describes the results achieved for the latency and throughput in the different reference points signaled in Figure 3. To collect the results, new experiments were performed using static and mobility conditions. The number of sessions in the experiment is 20 with a duration of 120 seconds. The nomenclature adopted in this section corresponds to the ends where the measurements are performed (e.g., R-N means that the metrics belong to the Edge Cloud Server to NUC link). Then, the technology following the link indicates in which setup the information has been gathered. For instance, R-N_5G depicts the value of latency/throughput measured between the Smart Lab Edge Cloud Server and NUC while the VR session was carried under the 5G network.

The only exception in this context is the S-R link, which does not present any technology label. This is because both ends are connected through Ethernet and remain fixed throughout the various experiments. This link latency is shown to confirm that the impact of this segment is negligible, conversely to the effects introduced by the wireless links. It is important to consider that the N-U WiFi segment is common for all the experiments.

1) STATIC MEASUREMENTS

The results displayed in this subsection belong to the experiments performed under static conditions. This means the user and its equipment were placed and remained fixed in the same geographical point throughout the evaluation. In this context, the NUC was positioned in a place with direct LOS to the 5G SA gNB (gNodeB). Concerning the WiFi router, it is connected through Ethernet to the NUC, and this latter to the Edge Cloud Server using a WiFi6 link using the Lab's Cisco network. Furthermore, the user with the HMD is positioned close to the WiFi router with LOS.

This subsection aims to establish a baseline on how the two-wireless link (i.e., 5G + WiFi6) performs in real conditions for an industrial scenario. Consequently, the results will show the degree of affection for VR service deployment generated by the interference of human presence, and machinery, among various factors.

In terms of throughput, the traffic of a VR session was measured using Tshark [46] in each link. The throughput was measured in both directions, that is, in UL (Uplink) the traffic corresponds mainly to the sensing and tracking data collected by the HMD and sent to the server to be processed by the game logic, and in a small part to the stream control data such as statistics needed to handle the connection between server and client. In DL (downlink), the traffic represents the streaming channel, i.e., the video frames rendered and encoded by the server and sent to the client to be decoded and displayed.

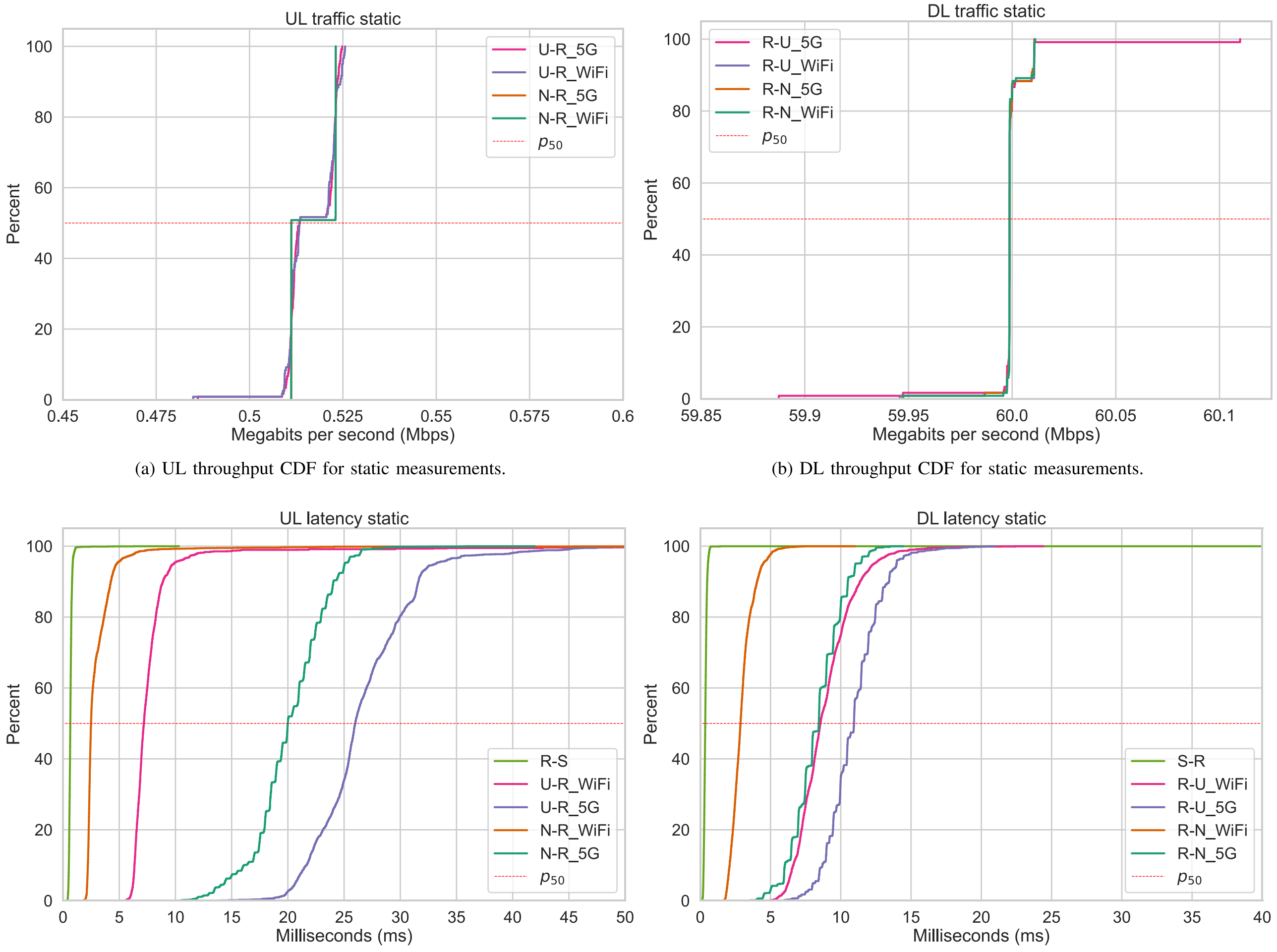
To show that, Figure 9 depicts the Empirical Cumulative Distribution Function (ECDF) of the throughput and the latency measured in different points of the scheme. Concerning the throughput, it is expected to denote a similar bitrate between the NUC and the server, as well as between the HMD and the server. Variations in the resulting values can be translated to congestion or packet-dropping network issues.

In the matter of the UL throughput, the experiments were performed using Cloud VR sessions over the WiFi and 5G setups. As it is possible to observe in Figure 9(a), both technologies can handle the control traffic without any type of problem that stands out. The median can be deduced by finding the point that intersects the 50th percentile (p_{50}) for each line. Then, the median value of bitrate in this direction ranges between 0.5 and 0.525 Mbps, which is a typical amount of traffic that can be served by any wireless network even in radio-constrained conditions (e.g., industrial scenarios with high interference, fading, LOS blockage, etc.).

Similarly, Figure 9(b) shows the ECDF of the DL traffic for the same group of sessions. As it is shown, most of the links are able to manage the throughput adequately. The median value of bitrate in DL is about 60 Mbps for streaming of video encoded at 4K and 60 Frames per second (FPS) for both WiFi and 5G. This is a point that stands out since the DL bitrate represents one of the most important challenges for wireless networks. With this in mind, keeping a stable bitrate throughout the VR sessions means maintaining a stable streaming resolution. In this context, an abrupt reduction of throughput can severely affect the QoE by image-quality degradation but also produce physical discomfort to the HMD operator according to the literature of Section II-A.

When it comes to network latency, this metric has been measured using Wireshark RTT analysis for TCP streams and OWD (One-Way-Delay) for UDP using timestamp difference for the traffic captured at both ends of the communication. In this setting, the analysis has been split again into two parts. The first one describes the latency found in the UL direction. Figure 9(c) shows RTT for the control message, which is sent using TCP protocol. This data is of the utmost importance, as it reflects the user behavior that should be taken into account when generating visual feedback on the HMD glasses. In this context, it can be observed that the setup latencies of WiFi are less than those of 5G. The WiFi R-N link (orange) represents the delay resulting from the initial radio link between the Edge Cloud Server and the NUC. The R-U link (pink) describes the latency introduced by the radio link that communicates the HMD with the server. Furthermore, it can be observed that there is a median latency gap of approximately 17 ms between these technologies.

The second part of the analysis concerns the latency in the DL direction. This case differs from the previous one because



(a) UL throughput CDF for static measurements.

(b) DL throughput CDF for static measurements.

(c) UL latency CDF for static measurements.

(d) DL latency CDF for static measurements.

FIGURE 9. Measurements for industrial static scenario.

the traffic is transported using UDP, which is the preferred protocol for real-time applications. Using this interpretation, the green line corresponds to the latency introduced by the 5G RAN, while the violet line shows an offset that is the sum of the last WiFi-jump latency plus the 5G RAN latency. In general, WiFi latency is approximately 8 ms for OWD, while 5G latency is around 11 ms.

The first conclusion that can be drawn from this analysis is that 5G performs better with UDP rather than with TCP. As illustrated in the UL latency graph, the discrepancy between WiFi's RTT and 5G's is approximately 19 ms. Conversely, when UDP is employed, the gap narrows to 3 ms. This observation underscores the necessity for a revision of traditional transport protocols to accommodate new-generation mobile network approaches or a migration to new protocols for streaming, such as QUIC (Quick UDP Internet Connections).

2) MOBILITY MEASUREMENTS

This section presents a comparative analysis of the performance of 5G and WiFi when the client device is given mobility within the SmartLab environment. In this context, the HMD, the Huawei WiFi router, and the NUC are all in motion simultaneously. This consideration ensures that the final WiFi hop remains constant (i.e., persistent line-of-sight conditions) throughout the sessions. Consequently, the latency and throughput variations are solely attributable to the technology that provides connectivity to the NUC.

The mobility is conducted by a robot that follows a recurring pattern until the end of the experiment (see Figure 10), ensuring consistency in the measurement of figures of merit. The illustrated map was drawn by the robot using its vision and sensoring system [47]. As the robot samples the environment, including walls, equipment, and machines, the definition of the floor plan may appear diffuse.

The evaluation of this section is divided into two parts, one for throughout and the remaining for latency. Moreover, the results of mobility are contrasted with the ones obtained in static conditions. In this context, the segment included between the SmartLab Cloud Edge server and the HMD is studied with no specific focus on any wireless link but as a whole, so it is possible to establish the key characteristics of service performance over WiFi and 5G.

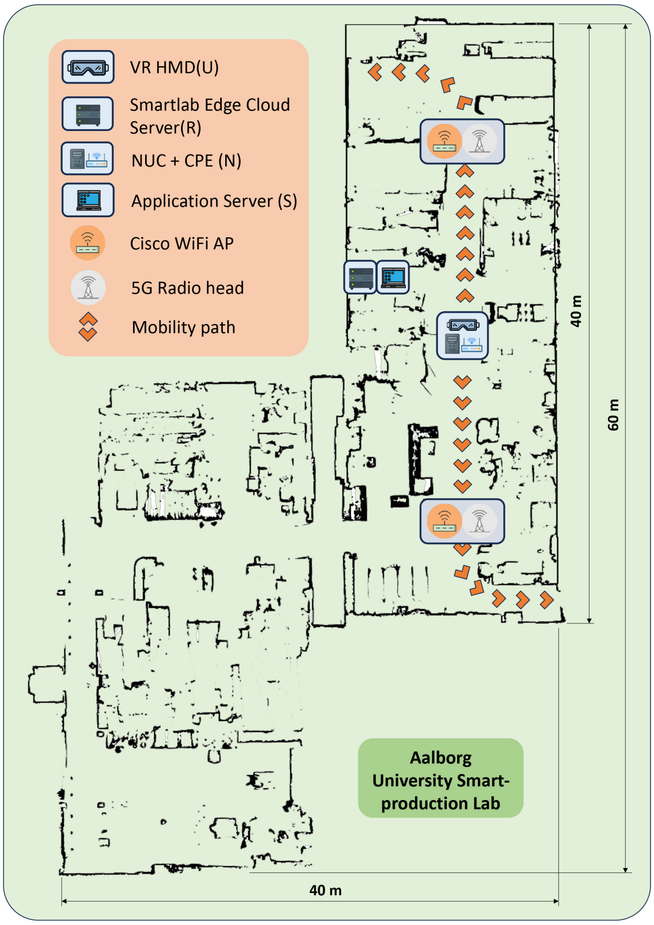


FIGURE 10. Mobility setup.

On the one hand, the UL throughput comparison depicted in Figure 11(a) indicates that in mobility scenarios, both network setups are capable of handling control channel data. The observed variability in the mobility results can be attributed to the fluctuations in the received signal power and its quality. Consequently, the network is capable of adapting to provide the same service conditions. It is also important to note that TCP is used in this communication. The protocol in question adapts its windows in accordance with the quality of the link, yet it fails to account for the fluctuations of the radio channel. From a numerical standpoint, the median throughput value is comparable to that of the static throughput value.

On the other hand, the DL CDFs highlight a key difference in comparison with the static case. As it can be seen in Figure 11(b), the throughput for mobility with WiFi displays a large variability around the median. The high dispersion on the values is caused by the loss of packets in the communication and by the Wireless Access Points adaption to counteract the changes in the radio channel generated by the mobility. This is not the case for 5G, where the bitrate displays a consistent performance similar to that observed in the static case (median 60 Mbps with minimal variability).

Regarding the latency, Figure 11(c) shows the CDF for UL measured as RTT due to the use of TCP in the control channel. Additionally, Figure 11(d) displays the CDF for the DL latency corresponding to the UDP OWD.

In the first case, it can be observed that both the static and mobility measurements present a similar behavior for WiFi and 5G setups. The unique difference between them is the latency offset that WiFi with mobility shows in comparison with the static results. Along the same lines, 5G depicts a similar performance, with an equal median, for both scenarios. Again, the gap between WiFi and 5G in UL is visible with an offset of 18 ms.

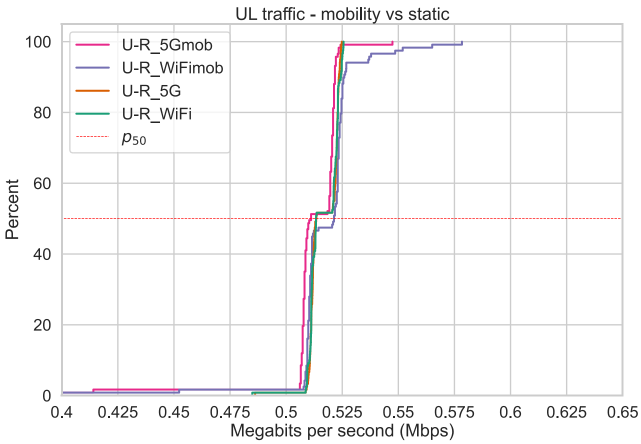
In contrast to the first scenario, it is evident that the introduction of mobility had a more pronounced impact on the quality of service with WiFi than with 5G in the DL direction. Although WiFi still has lower latency than 5G on median (approximately 2 ms of median difference) when using UDP, the performance is significantly impacted in 40% of the sessions, as evidenced by the data above the 60th percentile, with latencies reaching up to 80 ms. The inferior link adaptation mechanism of WiFi compared to 5G is the reason for this. On the other hand, 5G is designed to handle mobility and manage handovers seamlessly. Therefore, it is clear that 5G is a more suitable technology in this regard. While WiFi employs the IEEE 802.11r standard for roaming, this merely enhances the authentication process; the AP is still unable to transmit data until the AP switch is complete.

After observing the latency results, the values are still numerically far from the theoretical bounds established in SoTA for optimum experiences. However, this constraint does not prevent the deployment of high-quality Cloud VR services in industry scenarios that rely on WiFi, where reliability is a must-have feature. It is important to note that 5G is a suitable technology that can adequately respond in scenarios with normal-to-high throughput and varying channel conditions, which is a key finding.

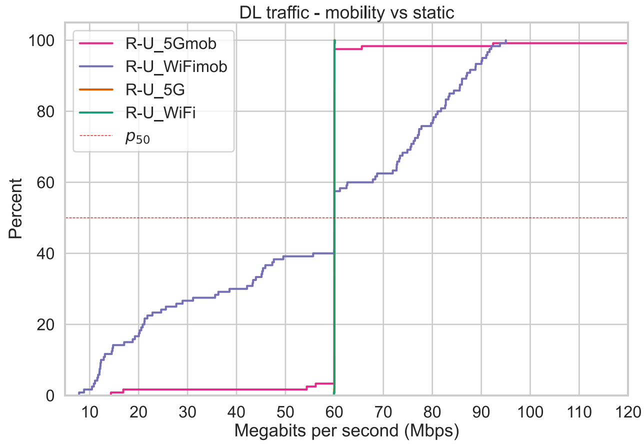
Similarly to the results in Section IV-B, Figure 12 depicts the Q_{vr} metric calculated according to the models of Section IV-A. The results demonstrate a comparable pattern, with WiFi exhibiting a higher score than 5G on median values. Notwithstanding, it is notable that the 5G technology is able to maintain comparable results in both static and mobility scenarios. This is not the case for WiFi, where it can be observed that in mobility scenarios, the dispersion of the values is considerable. It is noteworthy that a number of samples attain a Q_{vr} score of 1, a phenomenon not observed with 5G. Such circumstances can significantly impair the user experience.

V. CONCLUSION

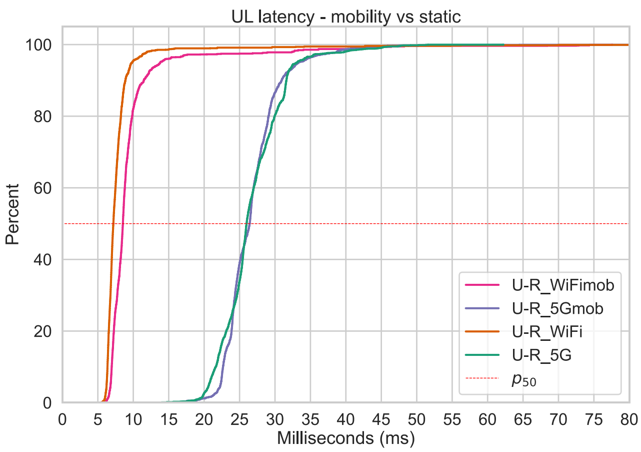
This work presents a performance assessment of an Edge Cloud VR service using wireless networks, specifically 5G and WiFi, in the context of industrial scenarios. The service is intended to provide an immersive experience to users by delegating most of the computing-intensive tasks to a cloud server. In this sense, this work aimed to demonstrate the feasibility of using 5G networks to "cut the cable" between the HMD and the server. This topic has typically



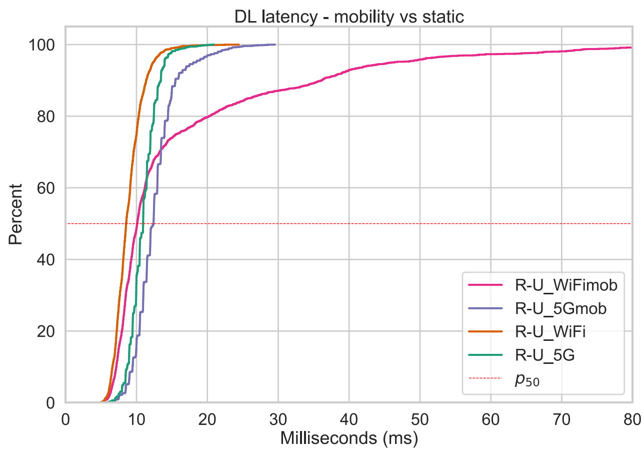
(a) UL throughput CDF.



(b) DL throughput CDF.



(c) UL latency CDF.



(d) DL latency CDF.

FIGURE 11. Measurements for industrial mobility scenario.

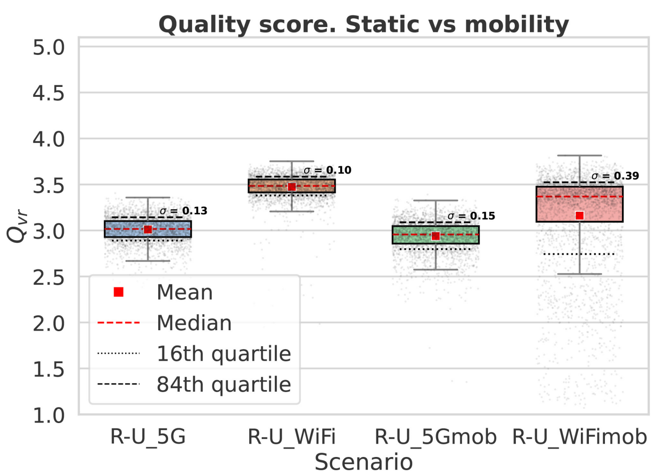


FIGURE 12. Q_{vr} score for static and mobility scenarios.

been discussed and performed in accordance with IEEE 802.11 standards. However, this approach is not viable in scenarios involving mobility, clutter, and non-direct LOS, which impose constraints on the provision of high-quality and ultra-reliable services. These constraints include high interference, multipath, and fading.

To this end, an industrial edge cloud VR setup was developed using the 5GSA/WiFi network deployment at the SmartProduction Lab at AAU. This setup was designed to collect service-level and network-level metrics with the objective of evaluating the performance of the service. Given that current HMDs are only equipped with WiFi or wired interfaces, we implemented a 5G-to-WiFi gateway in an Intel NUC device, along with a SIMCom 5G modem and a CPE, to provide connectivity to a commercial HMD with a WiFi 6 network card. Consequently, the NUC acts as a transparent bridge between the server and the user-end equipment.

This study evaluated the performance of technologies for near-future 5G-enabled cloud VR in two scenarios: static and mobility cases. The results indicated that WiFi exhibited advantages in terms of reduced median latency, particularly in UL, and in the static scenarios. However, in mobility scenarios, 5G demonstrated superior performance in terms of throughput and latency consistency in DL.

In order to provide a comprehensive analysis of the results from a network perspective, an objective quality of experience (QoE) metric was estimated using models that account for E2E latency, visual quality, and packet losses. This metric offers a discussion from the user's perspective, thereby avoiding the potential bias of a subjective methodology. The results demonstrated that, on average, WiFi provides a superior QoE compared to 5G. Notwithstanding, it is noteworthy that 5G consistently performs well in both static and mobility scenarios. This is not the case with WiFi, where a notable decline in QoE can be observed.

In this sense, this work emphasizes the key characteristics of the new generation of mobile networks, where mobility is a killer feature that can be exploited for future XR applications and services for Industry 5.0. In the UL context, comparable performance was demonstrated for both technologies, although 5G exhibited increased latencies. This indicates that TCP may not be the optimal transport protocol for 5G. It is possible that alternative 5G-compatible protocols could be employed in order to minimize latency and thus improve overall cloud VR performance.

As future research lines, it is planned to conduct a multi-user evaluation of this service to assess its performance under different levels of load. Consequently, it is possible to identify appropriate methodologies for optimizing resource management in this type of service utilizing mobile networks.

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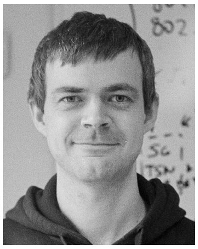

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