A Survey on Virtual Reality over Wireless Networks: Fundamentals, QoE, Enabling Technologies, Research Trends and Open Issues

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***Abstract*—Virtual reality (VR) technology is rapidly evolving and is poised to revolutionize our modes of communication, service delivery, engineering processes, task execution, and overall lifestyle. Presently, VR services are primarily confined to offline streaming, limiting their exploration across various fields. With wireless networks widely accessible anytime and anywhere, offering unmatched mobility, and continually advancing toward ultra-reliable, high-speed, and low-latency services, wireless communication stands as the obvious choice for future VR applications. However, current wireless technologies fall short in supporting high-quality wireless VR applications with satisfactory quality of experience (QoE). This deficiency arises from the necessity to deliver extensive omnidirectional visual content at exceptionally low latencies, often in the scale of milliseconds. The evolution from fifth generation (5G) cellular network to the subsequent emergence of 6G is expected to establish a foundation for a diverse ecosystem of VR applications. This evolution will integrate cutting-edge technologies such as artificial intelligence (AI) and big data-driven network operations, ultra-massive MIMO (UM-MIMO) systems, millimeter-wave and terahertz (THz) communications, cloud/fog/edge computing, terrestrial and non-terrestrial (UAV and satellite) hybrid network architectures, quantum communications, Internet of Things (IoT), and orbital angular momentum (OAM) multiplexing. These advancements will shape the future of wireless networks, enabling them for supporting real-time truly immersive wireless VR applications. The purpose of this paper is to offer a comprehensive survey on the major technical issues and current research trends in supporting VR services over wireless networks. Additionally, the paper explores the fundamentals of VR technologies, applications, QoE requirements, spectrum requirements and key enabling technologies. Finally, a comprehensive discussion regarding potential research directions aimed at enhancing wireless VR experiences is also presented. Thus, this survey paper is structured to provide a strong baseline for the researchers working in wireless VR systems.**

***Index Terms*—Virtual reality (VR) Fundamentals; Wireless VR; Architectures; Quality of Experience (QoE); Machine Learning (ML);**

I. Introduction

A. Prelude

The concept of metaverse, a truly immersive virtual world that can be moulded by virtualizing and digitizing the real world, has gained tremendous attentions of the telecommunication industries ([1]–[3]), general public, service providers and the standardization bodies (e.g., institute of electrical and electronics engineers (IEEE), 3rd generation partnership project (3GPP), and European telecommunications standards institute (ETSI)) [4]–[7]. The current information and communication technology (ICT) system, built upon the notion of digitization of services empowered with the storage/processing facilities at remote data centres and cloud platforms, has arguably reached its highest potential in terms of service types, capability, performance efficiency and quality of services. Naturally, the demand for improved service experiences with more haptic and immersive capabilities are high among the consumers, while the service providers are particularly keen on advancing their existing standards to the next level. This next phase of digital evolution will revolutionize the digital adoption to a staggering level and extend the service landscape into uncharted territory. The emerging extended reality (XR) technologies encompassing virtual reality (VR), augmented reality (AR) and mixed reality (MR) are touted as the central technologies for the realization of the simulated digitized environment of metaverse [8]. For instance, according to the *International Data Corporation (IDC)*, global shipments of VR headsets will grow from about 10.1 million units in 2023 to nearly 25 million units in 2026 and forecasted a five-year compound annual growth rate (CAGR) of 32.6% during 2023-2027 [9]. The *Counterpoint's Global XR (VR/AR) Forecast* published in December 2021 forecasted that the global XR (AR/VR) headsets (including tethered and standalone) shipment would grow 10 times from 11 million in 2021 to 105 million in 2025 [10].

VR technology creates a three-dimensional (3D) fully virtual environment with total absence of the physical or real-world environment. On the other hand, AR technology creates a composite view of the physical or real-world elements and digital elements by superimposing the elements of the two worlds together. However, there is no interaction between the digital elements and the physical world elements. Finally, MR technology allows not only the superposition of digital elements into the real-world environment, but also their interaction, and thus the users can see and interact with both the digital elements and the physical ones. These emerging XR technologies have a broad spectrum of applications including in industrial, commercial, societal, personal, educational, medical, military, recreational, cultural, social media, tourism and governmental sectors [8], [12]–[15]. The potential of these XR technologies is immense, which can revolutionize our known digital eco-system to a whole new level and open the scope of possibilities beyond imaginations. Moreover, XR can facilitate the achievement of the revolutionary concept of

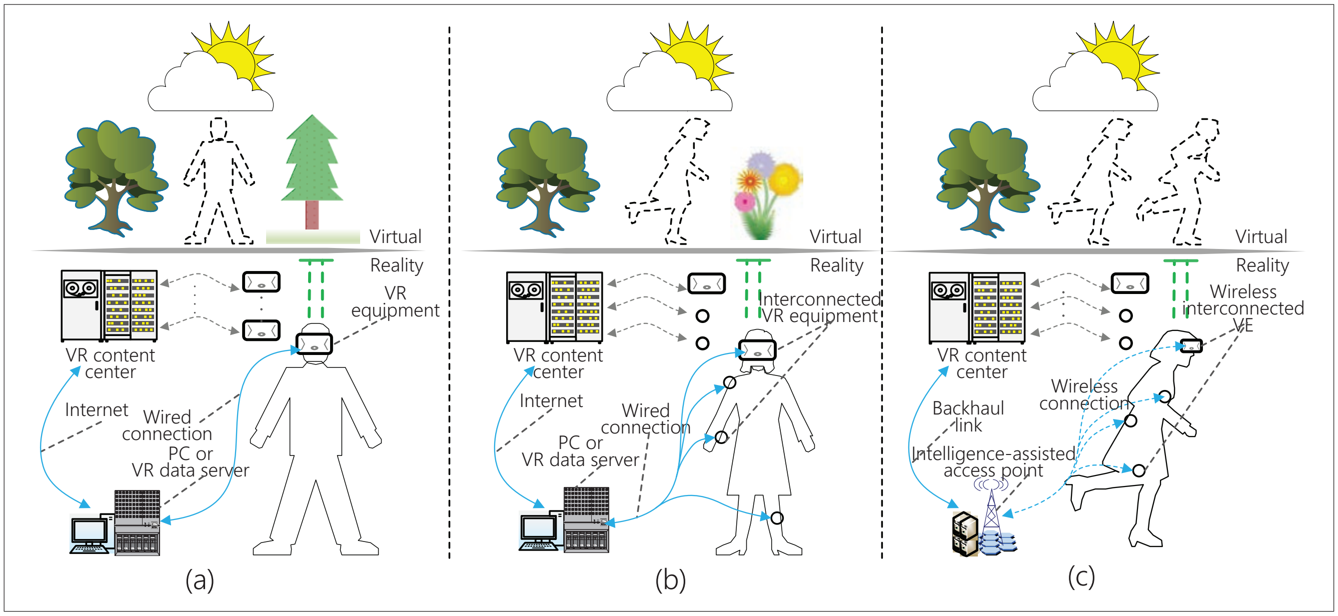

Fig. 1: Evolution towards wireless VR [11]: a) traditional wired VR, b) interconnected VR, and c) wireless fully connected VR.

digital twins (DTs), which can massively empower the remote operation, controlling and precise troubleshooting of all sorts of machines and systems with an amazingly useful three-dimensional visualization and flexible coordination [16]–[18]. This paper, in particular, limits investigation on the issues of VR technologies.

Current VR systems are widely limited to offline streaming, where 360 degree navigable scenes are rendered using a powerful external computer to which the VR device is attached to a cable. Due to the widespread availability of wireless networks at any time and anywhere with sheer mobility flexibility, and its relentless evolution towards ultra reliable, ultra high speed and ultra low latency services, wireless communication is obviously the preferred technology for future VR applications. However, the current wireless technologies are not competent enough for supporting high-quality wireless VR applications with satisfactory quality of experience (QoE) as it requires the delivery of a massive amount of omnidirectional visual contents at extremely low-latency in the scale of few milliseconds. The advancement of 5G and the subsequent emergence of 6G will establish a platform for creating a perfect ecosystem of diverse VR applications. A range of new generation networking technologies are going to shape the future wireless networks for supporting real-time VR applications.

B. Scope of this Survey

Figure 1 illustrates the evolution of VR technologies through three stages: starting with the basic wired VR video streaming system, progressing to interconnected VR, and advancing toward an ideal fully connected VR system that operates wirelessly [11], [19]. The primary objective of VR is to create a digitally immersive experience that replicates human perception, including visual cues, auditory sensations, and other sensory inputs like touch and smell. In current VR setups as depicted in Figs. 1(a) and 1(b), virtual environments (VEs) must be linked to a dedicated personal computer (PC). In this wired setup, users engaged in VR activities are limited by the physical connections, constraining their movements and the range of VR applications they can explore. To unlock the full potential of VR and broaden its applications, there is a push toward fully connected wireless VR scenarios. In wireless VR setups, users are free from external wired devices, enjoying a completely wireless experience. Wireless VR aligns better with the evolving trajectory of VR applications. However, implementing such a wireless VR system presents challenges related to computation, storage, and communication. A groundbreaking framework that can manage these multidimensional resources is essential. This survey paper provides a comprehensive overview on all the major technical issues of VR over wireless networks including the fundamentals of VR video creation, processing and transmission. We summarize and analyse all the recent research works on wireless VR as well as present an in-depth discussion on the future research directions, providing valuable insights for potential researchers.

C. Existing Surveys

The origins of VR can be traced back to 1929, when Edwin A. Link created a flight simulator to give passengers a realistic flying experience [20]. This marked the initial attempt by humans to simulate physical reality. In 1989, Jaron Lanier, the founder of VPL Co., introduced the term ”Virtual Reality,” which gained widespread acceptance among researchers and became the official term for this scientific field. The concept of the metaverse, an advanced form of VR, was first introduced

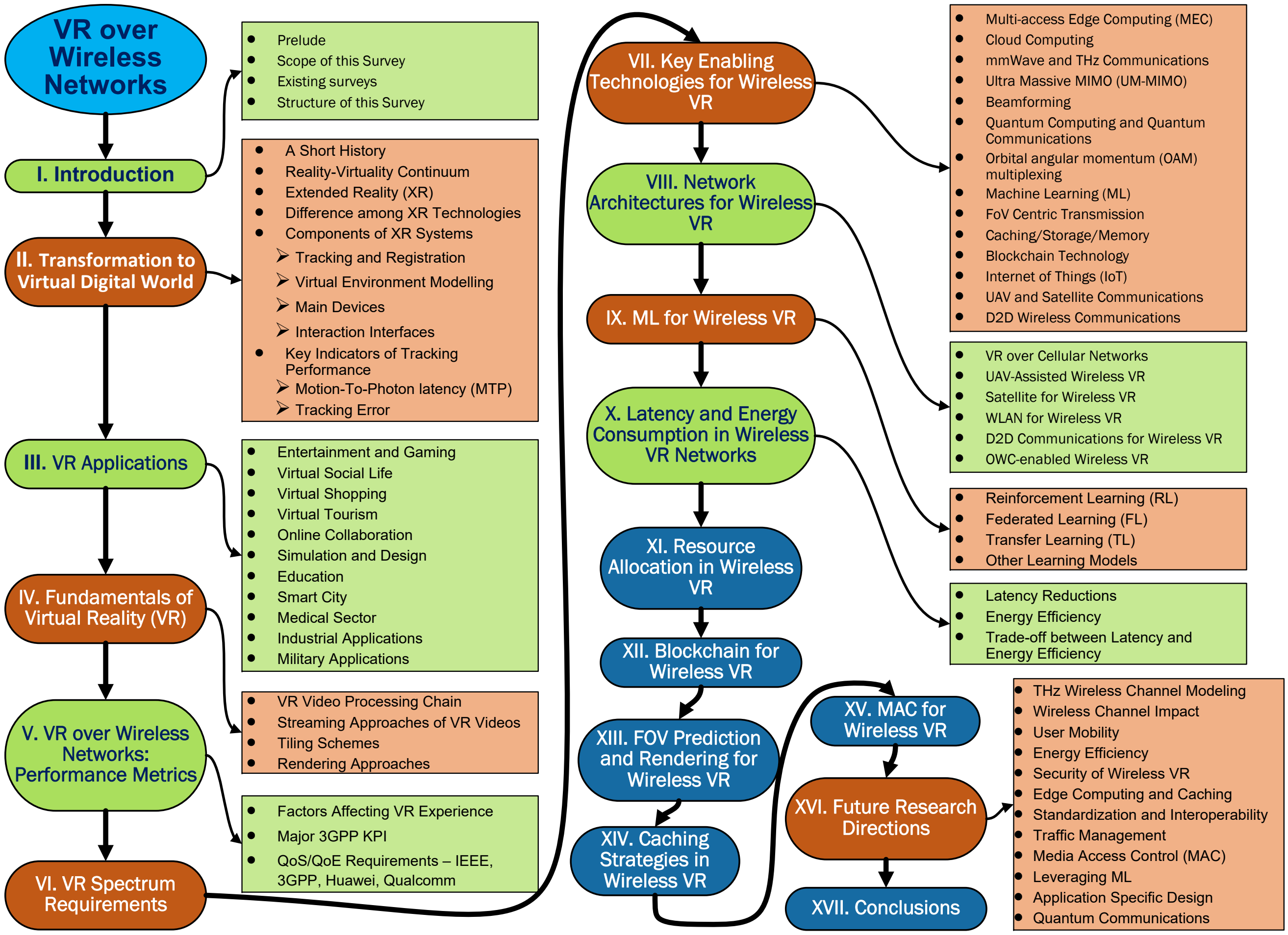

Fig. 2: Structure of this survey paper.

by Neal Stephenson more than 30 years ago in his science fiction novel *Snow Crash* [21], [22]. The global deployment of 5G since 2019 has significantly boosted the development of wireless VR systems, offering enhanced mobility. Recent advancements in supercomputing, powerful AI techniques, big data analytics, massive IoT (mIoT), secure blockchain technology, high-speed optical fiber backhaul, and beyond 5G wireless networking are driving the realization of a secure and fully immersive VR system, which can be accessed from anywhere at any time. Consequently, a growing number of research works on VR over wireless networks are emerging from both academics and industries.

Based on our extensive literature survey, we have identified few review papers on VR as discussed below. The oldest survey that we have found is on AR [26] from 1997, which mainly discussed the characteristics of AR and tradeoff among various AR production technologies. Authors in [20] presented a survey on VR with special focus on the VR types and corresponding issues, and then discussed the latest research and development trends. Few surveys were published on various issues of metaverse including technologies, applications, security and privacy in [27]–[29]. However, none of these papers discussed the networking issues for VR transmission. A closely related paper [15] surveyed only 23 articles on the edge caching and computing technologies in 5G for mobile AR/VR and tactile internet. Thus the scope of the paper is limited to only one of the wireless networking technologies and one enabling technology as well. Two other surveys on the state-of-the-art research and developments on VR privacy and security including the potential threats and their causes and effects was presented in [30], [31] with no focus on the networking aspects.

Thus, we can safely conclude that there exists no comprehensive survey paper on the wireless VR issues and research trends, which motivates us to prepare this article. This survey paper presents the details of the fundamentals of wireless VR systems, pinpoints the requirements for truly immersive VR, identifies the major enabling technologies, explores various wireless networking technologies for VR, summarizes the state-of-the-art research outcomes and provides deep insights on the future research directions, which will give the researchers a strong baseline for a kick-start in this research domain.

D. *Structure of this Survey*

This paper presents a comprehensive survey on all the major technical issues and research works regarding VR over wireless networks. For the convenience of the readers, we organize

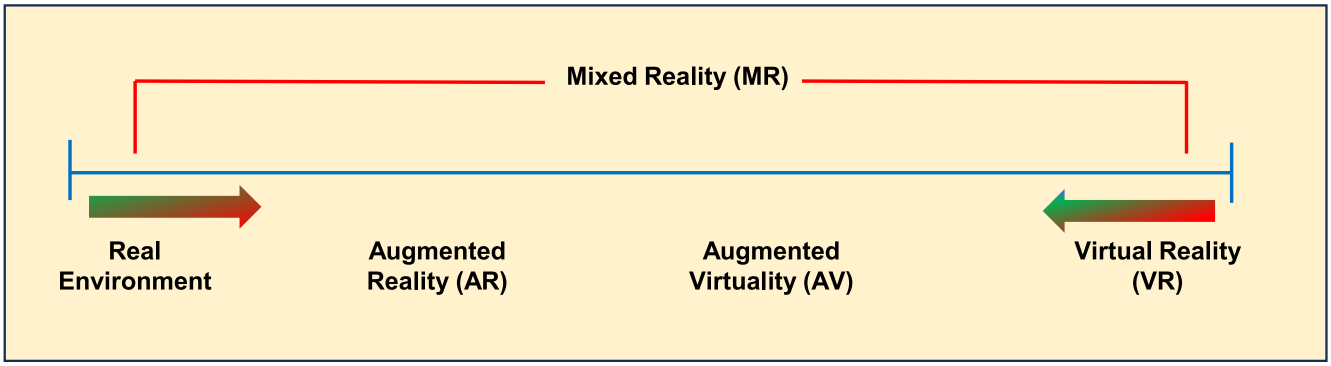

Fig. 3: The reality-virtuality (RV) continuum [23]–[25].

the entire content into several sections and subsections as illustrated in Fig. 2. We start from the history of alternative reality of digital world and slowly dive into the technical fundamentals of reality-virtuality continuum, VR applications, technical details of VR, key performance metrics, spectrum requirements, key enabling technologies, recent research in different areas and end with an insightful discussion on the open issues for research as presented in various sections below.

II. Transformation to Virtual Digital World

A. A Short History

The term XR technologies (i.e., VR, AR and MR) as well as Metaverse have recently become some of the hottest buzzwords. However, the concept of such realities is not new at all. The concept can be dated back to as early as 1929, when Edwin A. Link invented a type of flight simulator for making the passengers experience the feeling of flight [20]. It was the first try that human beings simulated or emulated physical reality. In 1956, Morton Heilig invented the *Sensorama* - a motorcycle emulator that showed 3D display and stereophonic effects and produced vibration feeling. He advanced some basic thought of VR technology [32] in the Sensorama Simulator patent in 1962. The development of electronic technology and the miniaturization of computers facilitated the development of simulation technology. In 1965, the significant founder of computer graphics, Dr. Sutherland [33] published a piece of essay *The Ultimate Display*, portraying a type of new display technology through his sharp insight and abundant imaginations. He assumed that, supported by this display technology, observers may be surrounded by a virtual environment controlled by a computer, just like daily life in the real world. Meanwhile, observers may also interact with the objects in virtual environment by natural means, like touch perception, control of virtual objects, etc. During the 1980s, with the development of computer technologies, especially the update of PC and computer network, VR technology made much headway. Historically, computer generated AR/VR applications started as early as flight simulator engines, telesphere masks, and head-mounted displays. In 1977, Sayre Glove was designed by the University of Illinois; in 1982, the technology advanced to form the power and the data gloves. Subsequently, in 1989, Jaron Lanier, the founder of VPL Co., put forward the phrase of "Virtual Reality", which was generally accepted by researchers and became the specific title of this scientific technology field. During the 1990s, with the breakthrough and rapid development of computer technology and high performance computation, human-machine interaction technology and equipment, computer network and communication, as well as huge demands in the significant application fields such as military drill, aeronautics and astronautics, and complicated equipment research, VR technology came into a rapid development stage.

The concept of metaverse, a form of ultimate VR, was first coined by Neal Stephenson more than 30 years ago in 1992 in his science fiction novel named *Snow Crash* [21], [22]. In 1993, Heim [34] portrayed seven characteristics of VR in Metaphysics of Virtual Reality: simulation, interaction effect, artificial reality, immersion, telepresence, general immersion and network communication. In 1994, Burdea and Coiffet [35] published their book, *Virtual Reality Technology*, in which they used 3I (Immersion, Interaction, Imagination) to generalize the basic characteristics of VR. Since 2019, the deployment of 5G across the globe has accelerated the momentum of wireless VR system with the flexibility of mobility. The current advances in super computing, powerful AI techniques, big data analytics, massive IoT (mIoT), secured blockchain, high-speed optical fiber backhaul and beyond 5G wireless networking technologies are pushing forward the vision of a secured and truly immersive VR system into a reality, which can be accessed from anywhere at any time.

B. Reality-Virtuality Continuum

The reality-virtuality continuum consists of environments ranging from real to virtual and all possible variations and compositions of real and virtual objects in these environments. It spans between real and virtual environments, with AR and augmented virtuality (AV) in between as shown in Fig. 3 [23]–[25]. AR is close to the real world, while AV is close to the fully virtual environment.

C. Extended Reality (XR)

Extended reality (XR) is an umbrella term that encompasses any sort of technology that alters reality by adding digital elements to the physical or real-world environment by any

Fig. 4: Difference between AR, VR and MR technologies [36].

extent, blurring the line between the physical and the digital world. These technologies are going to change the way we live, view the world and work. XR technologies, namely AR, VR and MR, are the enabling game changers for the Industry 4.0 paradigm [37], [38]. Popularity of such applications are also growing in many other domains including healthcare, cultural heritage, architectural designs and natural disaster management [25], [36], [39]–[41].

D. Difference among XR Technologies

The main objective of all the AR, VR and MR technologies is to connect the virtual digital world and the real world. However, there are some fundamental differences among these three technologies with distinguishing characteristics as discussed below. A figure illustrating the key differences is also shown in Fig. 4. We also have to understand that XR technologies are continuously evolving, and thus their full potential yet to be realized.

1) Augmented Reality (AR): AR is a computer-based technology that superimposes the digital world on the real world. It works on the computer vision of real-world surfaces and objects detected by systems like object recognition, plane detection, facial recognition, movement tracking, and more. Then, it overlaps computer-generated data, such as graphics, sounds, images, and texts accordingly on these planes detected before and thus creates a composite view. By doing so, AR allows real-time interactions between digital items and users, while letting the users to remain within the real-world surroundings. However, no interaction between the digital world and the real world elements is allowed in AR.

AR experiences are close to the physical world end of the reality-virtuality continuum. The ability to overlay digital objects onto the physical world is revolutionizing many industries such as gaming, aviation, education, healthcare, automotive and manufacturing. Besides, thanks to mobile devices' developments, it is not only used by corporations but now also in our daily life, everybody can use AR easily through their smartphone screens and cameras.

2) Virtual Reality (VR): VR creates a computer generated synthetic fully-immersive, but interactive digital environment. It uses software and headset devices to replace one's view from the real-world to a digitally created scene. Using full-coverage, headsets completely blocks out our surroundings and shuts out the physical world while using. With the liquid crystal display (LCD) or organic light-emitting diode (OLED) panels inside the lenses of these headset devices, a computer-generated virtual environment is reflected, and our worldview is replaced. Usually, the devices are connected to a PC, console, or a smartphone that provides virtual visions. These visions can be replicas of a real-world place or a place from an entirely imaginary world.

VR enables people to have a fully immersive experience in these virtual places. It tricks your senses by allowing you only to see what the lenses are reflecting your eyes. We can experience artificial sounds, sights and all the feels (e.g., touch) as if we are in a digital world. Also, with realistic sounds, 360-degree visuals, and motion capture gears, it can simulate our actions, allow interactive encounters with the virtual items and make us feel like we are actually in that simulated place.

3) Mixed Reality (MR): As the name suggests, MR is a combination of AR and VR. It covers the continuum from AR to AV. It is also specified as merged reality as it blends real-world and digital elements. While it is mainly a technology used for mixing the physical and virtual world, the best side of MR is the realistic interaction among the users, physical elements and the digital objects. Therefore, MR experiences get input from the environment and will change according to it. Flexibility, immersion, interaction, coexistence, and enhancement are the essential aspects of a mixed reality experience [39].

Digital devices should be used while handling MR to have a fully immersive experience. Microsoft's HoloLens is a trendy example of these devices. Through these translucent MR devices and gestures, gaze, or voice recognition technologies, users can react from digital objects to their actions. They can interact with both the physical and virtual environment at the same time. Instead of relying only on remote control devices, smart glasses, or smartphones, users can also use their gestures, glancing or blinking, and much more. These interactions and the realistic renderings make the experience of MR more convincing as if it is in real life. It is the newest immersive technology from these three reality types, and maybe the least used one; however, it has a huge potential of being integrated into our daily life as an essential tool.

4) Augmented Virtuality (AV): : The term AV is easily confused with AR. Both AR and AV have the common goal of enhancing the actual world with virtual information. However, the AV technology aims at augmenting the virtual world with scenes, objects and people from the real world. Whereas, in AR, objects and scenes in the real world are augmented with computer-generated virtual information.

E. Components of XR Systems

Regardless of the domain, the essential aspects of AR, VR, and MR applications are as follows [20], [39]: (i) Tracking and registration, (ii) Virtual environment modelling, (iii) Computers, display, and devices for input and tracking, and (iv) Interaction interfaces.

1) Tracking and Registration: Tracking technology involves monitoring the position of a user or object concerning the surrounding environment [42]. In VR applications, the focus is on tracking the user's viewpoint, although it's not always necessary unless a fully immersive experience is desired. For example, non-immersive VR systems on desktop or mobile devices can display virtual content without tracking the user's movements. Tracking is typically used alongside mapping techniques to identify the environment and is essential for real-time recognition of the user's surroundings and current location, a process known as simultaneous localization and mapping (SLAM).

The effectiveness of registration largely depends on the speed and accuracy of the tracking method. Tracking methods can be broadly categorized into those using cameras and those relying on physical sensors. Positional tracking in VR often involves sensor-based technologies like electromagnetic, acoustic, inertial, and hybrid tracking. Alternatively, optical infrared (IR) tracking estimates the pose of a target in real time by tracking the position and orientation of active or passive IR markers. This type of tracking consistently employs IR markers and is not affected by lighting conditions, distinguishing it from other methods.

2) Virtual Environment Modelling: In a broader context, modeling virtual environments involves simulating real objects and their conditions within a digital space, including the behavioral rules governing these objects and their relationships and interactions. To achieve this, various types of model data and modeling methods are employed. From a data acquisition perspective, model data can be categorized into three types: actual measurement, mathematical measurement, and artificial construction. Actual measurement refers to model data obtained through processes like 2D and 3D scanning and other methods involving data capture equipment. Mathematical measurement involves using mathematical models, abstractions, and experimental analyses to generate model data based on the real environment. Artificial construction, on the other hand, involves creating model data through human imagination, representing a completely fictional world.

Modeling methods can be classified based on the sensory perceptions of the intended user and the aspects of the simulated objects in the VR environment. From a sensory perspective, modeling methods are categorized as visual, auditory, and haptic. Considering the simulated objects, modeling methods fall into scene appearance, physics-based behavior, and real-virtual combined modeling.

When it comes to actual modeling, the choice of model data type and modeling method depends on three guiding factors: the complexity of real-world objects, the intended sensory modality of the users, and the desired level of model accuracy. Often, multiple modeling methods and data acquisition techniques are combined to generate model data that meets the required level of fidelity.

3) Main Devices: In general, the fundamental devices necessary for AR, VR, and MR systems include displays, computers, tracking cameras, and input devices. Display devices are categorized based on the type of virtual content they are designed to showcase. In terms of computing devices, a high-performance system is typically required to generate and render lifelike virtual scenes in real time. Cameras are utilized in AR and MR applications that rely on marker-based or markerless tracking methods. If a hybrid tracking approach is needed, cameras and tracking devices are used in combination. Additionally, various input devices such as speech, gaze, and gesture sensors, including wearable devices, are available. However, the choice of input device should be determined by both the application's domain and the specific system requirements. Common input devices for interaction in VR applications include data gloves, gesture sensors, joysticks, mice, wands, gamepads, and certain wearable haptic sensors.

4) Interaction Interfaces: The interaction between users and virtual information stands as a fundamental aspect of immersive reality across various fields. Research in areas such as tangible user interfaces (TUI) and human-computer interaction (HCI) aims to provide intuitive and natural interaction interfaces. Interaction also significantly influences the sense of presence. From a VR perspective, presence refers to the feeling of being physically present in a non-physical world. Improving a user's presence in a virtual environment, a crucial experiential aspect of VR, results from a combination of immersion and interaction. Immersion relates to feeling surrounded by a virtual environment, while interaction represents the range of users' engagement with the virtual environment. Thus, when VR applications achieve high levels of immersion and natural interaction interfaces seamlessly integrate users into virtual surroundings, individuals can be tricked into believing they are in a separate but realistic world. While immersion has dominated VR development, it's essential to recognize the significant role that interaction plays in shaping the VR experience.

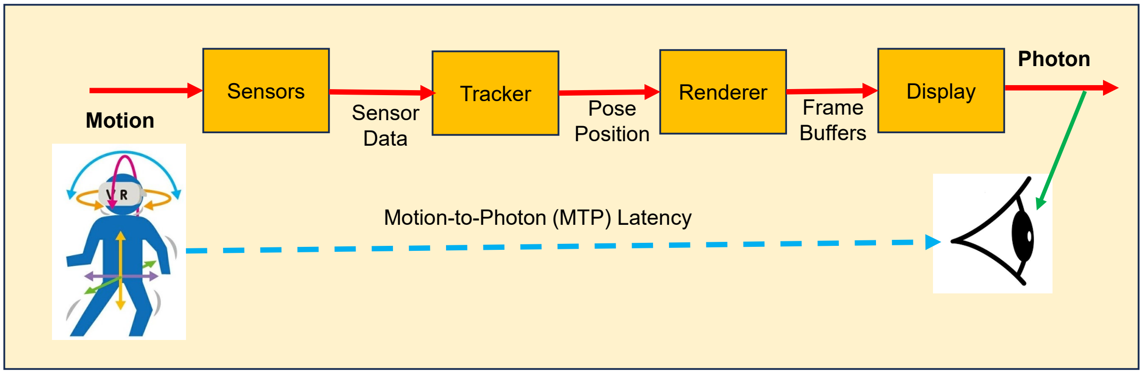

Fig. 5: MTP latency in VR systems [42].

F. Key Indicators of Tracking Performance

1) Motion-To-Photon latency (MTP): MTP latency is the amount of time from the moment the wearer of the device moves until the corresponding content is displayed on the screen. MTP latency consists of sensor latency, tracking latency, rendering latency, and display latency as shown in Fig. 5. Sensor latency is the time it takes for the sensor to detect motion, convert it into an electrical signal and output it. The tracking latency is the time it takes for the position and posture to be calculated using the signals output from the sensor, and the rendering latency is the time it takes to synthesize the image of the virtual/augmented contents seen from the calculated position and posture. Display latency is the time it takes for the rendered image to be output to the screen through the runtime platform of the virtual augmentation device. As the MTP latency is shorter, the user can view the matched contents naturally without feeling uncomfortable.

Typically, the recommended MTP delay time is 20ms or less in VR that displays a virtual environment [7], [43], [44], and 5ms or less in AR that displays virtual content on a real background [45]. The MTP latency of the VR/AR device can be calculated as the difference between the two time points by measuring the time point at which motion occurs and the time point at which content is output to the display.

2) Tracking Error: SLAM is used in VR/AR/MR devices to display virtual/augmented content corresponding to the user's position and posture. It uses sensors such as camera, depth sensor, and IMU to identify the surrounding environment and estimate the position of an object in the environment. Tracking errors occur due to errors caused by the characteristics of each sensor such as drift error caused by accumulated measurement errors, recognition error due to illuminance change or moving object, and measurement error of reflected light due to the reflectance problem of the object.

III. VR Applications

The application horizon of VR services is truly unlimited as new amazing applications are emerging everyday and existing applications are evolving very fast. Various industries and business organizations have already developed and launched different VR applications, whereas countries across the worlds are racing to develop standards, policies and regulations for adapting the VR technologies and services. In the VR world, people can live as digital neighbours and perform various activities creating a parallel alternate virtual world. Thus, a true immersive VR paradigm will revolutionize nearly every aspects of our life in a very different way that humans have ever imagined. Here below, we discuss some of the potential applications of VR services [27]–[29].

A. Entertainment and Gaming

Entertainment and gaming are the most popular applications of VR videos [46]. The entertainment industry including movie theatres and televisions is going to change forever from the traditional nature of 2D videos. Programs will be increasingly more and more VR video based, where the viewers will feel immersed in a 3D digital world and enjoy the videos in more details as in real-life. On the other hand, VR games are already extremely popular among the people. These games can be both single player or multi-players. In a multi-player scenario, players can interact among themselves as if in real-life and play collaborative games. On the other hand, such games can be both offline and online types. Offline games can be played in standalone devices using tethered or wireless HMDs. Network support is not required in such case. In relatime online games, players from different part of the world can play together in the virtual world, which requires network support with high data rates and low latency.

B. Virtual Social Life

VR services will revolutionize our daily life within the next decade by enabling diverse kinds of social applications including virtual festivals (e.g., concerts, graduation ceremonies, cultural programs and exhibitions), virtual conferences, virtual chatting and virtual dating [29], [47], [48]. People will be able to make virtual gathering and find friends. Such VR services will obviously remove the boundary of time and space among the people giving them an outstanding opportunity to socialize from anywhere at anytime. Thus, VR is going to create a new social culture and socials norms.

C. Virtual Shopping

With the introduction of VR technology, online shopping is going to change forever. Avatars of shoppers will be able to walk through the 3D space of stores and can choose their products through more detailed 3D inspections, which can significantly influence the shopping behaviour of customers [49]–[51]. Fashion conscious consumers will be able to wear any dress in VR environment for better understanding of appearance after the dress putting on and thus the the experience of online shopping will be more realistic and satisfying. Online shopping giants, such as Amazon and Alibaba have been working for the last few years on developing virtual shopping applications [27], [28].

D. Virtual Tourism

Virtual tourism to different natural spots, museum and archaeological sites, even to the most difficult places such as caves, deep forest, underwater world, mountain tops and waterfalls, can be realized by using VR technologies [47], [52]–[54]. VR videos of difficult to access places can be created by employing various technologies such as drones, satellite communications, IoT sensors and high resolution cameras. VR technology can also be used even for space tourism. The development of such VR videos will allow the users to overcome the obstacle of time, space and financial limitations with the opportunity to freely visit scenic spots around the world and get an immersive experience.

E. Online Collaboration

VR services is going to open numerous possibilities for immersive virtual collaboration in terms of telecommuting in virtual workplaces, and panel discussion and meeting in virtual conference rooms [29]. Several initiatives are already there for developing such technologies. For instance, Meta has released an office collaboration software named *Horizon Workroom* that enables participants located at any physical location to work and meet together in the same virtual room [27]. Another initiative is the *Microsoft Mesh* platform supported by Azure, which allows users working from different sites to cooperate virtually via holographic presence [27].

F. Simulation and Design

VR can be an amazing technology for 3D simulation, modeling and architectural design [55]–[57]. For instance, an architect can move across his/her design in the virtual domain and modify the design to meet the design requirements. The process of architectural design will be much simpler, ease to access different parts of the design, flexible to modify the design, and convenient for better visualization. Similarly, any 3D modeling and simulations in VR space will be extremely convenient for modification of the designs, construction inspection and construction analysis. Additionally, multiple designers located at different places will be able to work collaboratively and interacts in VR space for more efficient modelling and designs. In fact, VR can be used virtually for every kind of design process including apparels, pottery, packaging, aerospace engineering, automobile industries and wireless communication networks [58]–[60].

G. Education

With the application of VR services, the culture of teaching-learning practice and experiences will be changed. Studying and learning in virtual classrooms will be more common, which will help the students to improve their learning experience substantially, in particular, creative learning can be facilitated [61]–[64]. Teachers will be able to deliver their lecture materials in a more effective way. For instance, when geography or cosmology will be taught, students will be able to enter the virtual worlds of these spaces, explore the features in more details and visualize their constructions and architectures by moving around the objects, zooming in and out, and interacting with the objects. Moreover, students will be able to have virtual orientation of their campus and different facilities including classrooms, laboratories, dormitories and sport utilities.

H. Smart City

Smart cities deploy information and communication technologies for intelligent management of its various systems, such as safety and security systems, transport network, energy supply and management, water supply networks and waste management systems. VR technologies can be efficiently used for planning, building and managing sustainable smart cities for improved quality of life of its citizens by addressing the environmental, social, cultural, and physical needs of a society [65], [66]. It can create digital twin of an existing city by mapping the physical world of a city including its geological features, people, vehicles, objects, and space. This digital twin of a smart city can assist to monitor, secure and manage the city through improved resource utilization and optimized urban management and services [67]. On the other hand, VR can be a powerful tool as it can provide visualization tools for planning, modelling, simulating and evaluating the economical, environmental and social consequences of creating a new city.

I. Medical Sector

VR services can be effectively applied for telemedicine, virtual medical, remote surgery and remote care. Thus, highly mobile, real-time and remote medical services can be provided utilizing limited amount of medical resources. On the other hand, medical students and professionals can also be trained in an immersive way by adapting VR technologies for accessing and exploring each and every organ of human anatomy, which can dramatically improve their competencies for professional practice [62], [68].

J. Industrial Applications

VR technologies will find numerous applications in industrial domains including running manufacturing plants, troubleshooting of technical problems and optimizing the manufacturing process [69], [70]. Furthermore, installation, testing and commissioning of production sites can be performed in virtual domains for finding any potential technical issues, which can be solved before the actual commissioning of

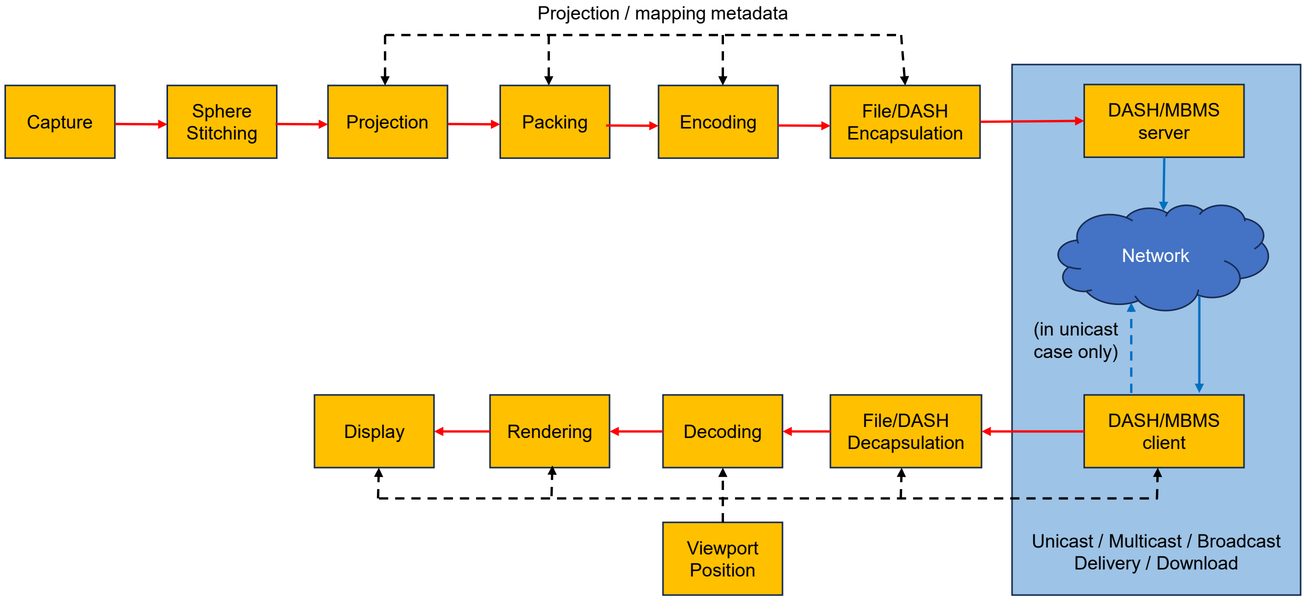

Fig. 6: A VR video processing chain for delivery of DASH over MBMS [5].

a plant leading to reduction of commissioning time and expensive trial time. 3D modeling of new products, virtual prototyping and product evaluation can be effectively and quickly conducted in VR space [71]. Rapidly deployable VR modules can be used for providing job specific training for upskilling and reskilling the employees [72]–[74].

K. Military Applications

VR has massive number of applications in military field [75]–[77]. Virtual training by simulating actual vehicles, real soldiers or actual combat environment can be conducted fostering the combat skills of soldiers. Such trainings can rapidly develop situational awareness and judgemental skills among the defence personnel. VR based flight simulators can be used for training the pilots for manoeuvring fighter jets and conducting warfare in extreme adversarial situations. Such opportunities will prepare the soldiers in advance before they get the actual delivery of the weapons leading to reduced time to be expert in operating the weaponry systems.

IV. Fundamentals of Virtual Reality (VR)

This section presents the fundamental technical details of VR video creation, processing and transmission issues.

A. VR Video Processing Chain

VR video processing varies depending on the type of services and the type of delivery mechanisms. To demonstrate the major functional steps required for VR video over an end-to-end (E2E) delivery chain, the workflow for dynamic adaptive streaming over HTTP (DASH) delivery over multimedia broadcast multicast service (MBMS) is presented in Fig. 6 and discussed below [5].

1) Capture: Virtual reality content can be depicted in various formats, such as panoramas or spheres, depending on the capabilities of the capture systems. Numerous systems record spherical videos that encompass the entire $360° \times 180°$ sphere. Capturing this type of content usually involves the use of multiple cameras. Different camera setups can be employed for capturing both 2D and 3D content.

2) Sphere Stitching: The captured images from each camera are melded together during stitching to merge the individual perspectives from omnidirectional camera systems into a seamless panorama or sphere. This stitching process must be meticulous, preventing parallax errors and noticeable seams between the views. Stitching can occur offline in post-production or in real-time. In live broadcasts, real-time stitching is essential, capable of handling substantial data from multiple cameras to deliver a flawless, high-quality panorama or sphere without errors.

3) Projection: Current video coding standards are not optimized for handling spherical content in VR systems. To address this, a projection technique is employed to convert spherical (or 360°) videos into two-dimensional rectangular videos before encoding. There are various methods to project a sphere onto a plane, but none can completely eliminate distortion. The distortion arising from the conversion process from spherical to planar form is known as ”sampling distortion.” The final quality of a spherical video depends on both sampling and coding distortions. The most widely used projection method is the equirectangular projection (ERP), where the horizontal and vertical coordinates directly correspond to longitude and latitude, respectively, without any transformation or scaling. However, equirectangular projected images exhibit significant redundancy near the poles due to stretching in the latitude direction. This results in an excessive number of bits being allocated to encode the polar regions of the image, relative to the actual informational content. Other typical planar formats for 360 videos include Cubemap (CMP), Adjusted Cubemap (ACP), Equi-Angular Cubemap (EAC), Adjusted Equal-Area (AEP), Octahedron (OHP), Icosahedron (ISP), Segmented Sphere (SSP), Rotated Sphere (RSP), Equatorial Cylindrical (ECP) and Truncated square Pyramid (TSP) projection formats [78]. These formats are different in size and the number/shape of faces.

4) Packing: Following projection, the resulting two-dimensional rectangular image can be divided into sections that can be rearranged to create ”packed” frames. The process of generating packed frames from projected frames, often referred to as ”packing” or ”region-wise mapping,” may involve operations like translation, scaling, rotation, padding, affine transformation, and so on. Region-wise mapping is carried out to enhance coding efficiency or to arrange streams based on the viewport's requirements.

5) Encoding and Decoding: Present 360 video services provide a restricted user experience due to the resolution within the user's viewport, resulting in visual quality that falls short of traditional video services. Achieving a visually satisfactory resolution for the entire 360-degree environment requires resolutions several times higher than ultra high definition (UHD). This presents a significant challenge to both the existing video processing workflow and the available end-user devices. There are mainly three approaches for 360 video delivery, namely single stream approach, multi-stream approach and tiled stream approach, which are discussed later in Section IV-B.

Tiled stream approach is the most popular one. In this scheme, each tile is encoded into multiple versions of different bit rates [79], [80], quantization parameter (QP) values [81], [82], or resolutions [83]. So far, some encoding techniques for 360 video have been proposed such as region adaptive distortion calculation [84], adaptive QP selection [85], weighted-based rate control [86], spherical geometry padding [87], and fast intra estimation [88]. In addition, evaluation frameworks for 360 video coding have been designed in [89].

6) File/DASH Encapsulation/Decapsulation: Following this, the process of encapsulation occurs. If 360 video is delivered using DASH, extra signaling might be essential. For example, projection and mapping formats may need to be indicated in the media presentation description (MPD) so that clients can request suitable representations and/or adaptation sets. The file/DASH encapsulation varies based on the type of solution being used (e.g., single-stream, multi-stream or tiled stream). Depending on the current viewport position and/or device capabilities (such as video decoder capabilities), the receiver can opt to decapsulate only a subset of the received video stream.

7) Delivery: Panoramic or 360-degree videos can be transmitted via unicast, multicast, or broadcast methods. In any of these modes, delivery can occur through downloading or streaming, either in real-time or non-real time. Unicast streaming delivery can be facilitated using DASH, while DASH over MBMS can be utilized for multicast or broadcast delivery. Unicast delivery can employ single-stream, multi-stream, or tiled stream methods. In both unicast and MBMS delivery, the DASH client selects appropriate segments based on factors such as the viewport position, available network bandwidth, device capabilities, and service requirements. For example, in the multi-stream approach, the DASH client requests the stream (representation) that best matches the expected viewport position, considering network latency and user movement.

8) Rendering: Once a series of 2D images has been decoded, several post-processing steps including rendering are carried out, such as sphere mapping, field of view (FoV) generation, region-wise unpacking, creating individual views for each eye in stereoscopic content, rendering limited coverage, smooth transitioning between various FoVs and resolutions in the sequence of 2D images, and other standard 2D operations like removing bar data and tone-mapping. Rendering maps the pixels from a viewing sphere to a 2D plane. More in-depth information about rendering processes is provided later in Section IV-D.

B. Streaming Approaches of VR Videos

VR videos can be created entirely by using software, where the created content will be completely imaginary digital world. On the other hand, VR videos can be created by capturing the real-world and then converting them into VR videos, which will be replicas of the real-world, which is popularly known as 360-degree videos. In this paper, we will refer both the imaginary world and the real-world replica VR videos as the 360-degree VR videos. The methodology, techniques and tools for the creation of VR videos are beyond the scope of this paper. There are mainly three approaches that can be considered for 360 video delivery - single stream approach, multi-stream approach and tiled stream approach, as discussed below [5].

1) Single Stream Approach: Single stream method involves encoding the entire 360-degree video, transmitting it to the receiver, and decoding the complete video while displaying only the viewport. However, approaches within this category have a drawback. They either lack scalability or pose significant challenges in terms of necessary network resources (due to high bitrate or high-resolution video) and the processing power required at the client end (to decode very high-resolution video).

Mobile devices typically come with hardware video decoders optimized for resolutions common in traditional video services, such as HD or UHD. Hence, it's crucial to limit the overall resolution that is transmitted and decoded on mobile devices. With the single stream approach, the receiver decodes the entire video corresponding to either the viewport or the full 360-degree video.

2) Multi-Stream Approach: The multi-stream approach involves encoding multiple streams, each emphasizing a specific viewport and making them accessible to the receiver, allowing the receiver to select the appropriate stream for each moment. The number of available streams can vary and can be optimized; having more streams allows for a better match to users' viewports. However, this necessitates greater storage capacity on the server side. Despite multiple streams being encoded and accessible, only one stream needs to be decoded based on users' viewports.

There are two methods for generating viewport-dependent video bit streams in the multi-stream approach - projection/mapping based and encoding based. The projection/mapping based approach employs a viewport-dependent projection (e.g., truncated pyramid) or a projection (e.g., cubic) combined with a viewport-dependent mapping/packing (such as multi-resolution cubemap). In this method, the number of samples is higher in the viewport area and lower in the surrounding regions. Encoding is performed in the usual manner, without awareness of the viewport. On the other hand, in encoding based approach, the encoder is configured so that samples within the viewport are encoded at higher quality, for example, with a lower QP.

With the multi-stream approach, the receiver decodes the entire video, resulting in areas of different resolutions or qualities. As mobile devices typically feature hardware video decoders optimized for resolutions commonly used in traditional video services, it is crucial to restrict the overall resolution transmitted and decoded on mobile devices.

3) Tiled Stream Approach: In tile-based streaming for VR video, the projected video in each frame is divided into tiles, as illustrated in Fig. 7 [90]. Each tile can be encoded, decoded, and rendered independently as separate video streams. This approach allows emphasizing the current user's viewport by transmitting non-viewport samples at reduced resolution. Specifically, the tiles within the viewport are transmitted at high resolution, while those outside the viewport are transmitted at lower resolution [5]. Consequently, the full 360° surroundings are always available on the end device, but the number of samples outside the users' FoV is minimized. The FoV is defined as the range of angle of a 360-degree video that is in the users' line of sight [91]. These tiles can also be encoded into multiple versions [92].

During playback of these 360-degree videos, the video player renders the portion of the spherical surface in the direction of the user's view, typically covering only a small section of the entire 360-degree surface. When separately encoded video streams are used, several decoders are required at the receiver's end, corresponding to the number of video streams the receiver chooses to decode. The receiver can opt to decode only a subset of the received video stream based on the current viewport position and/or device capabilities, such as video decoder capabilities.

Implementing real-time tile-based FoV streaming to a network of VR users involves several time-consuming steps. Initially, edge controllers/servers need to acquire pose data, process it to determine the tiles within the FoV, and then schedule their transmission. Subsequently, on-HMD processing is performed to compose, stitch, and display the corresponding portion of the video frame. The E2E delay of this process is significant. Consequently, as the number of users in the network increases, managing this cycle within the MTP delay budget for each frame for every user becomes challenging, especially if the server/edge controllers and users are not connected via wired networks.

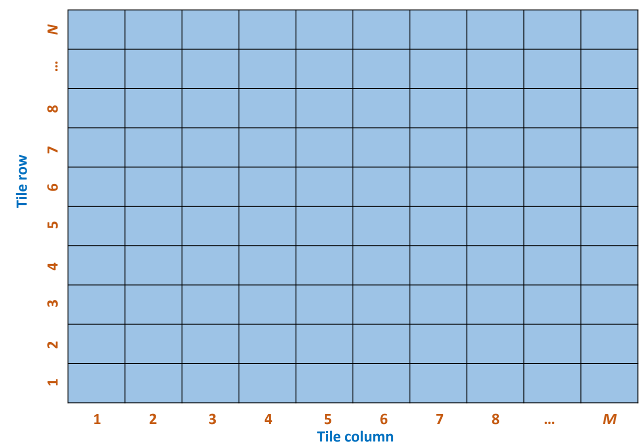

Fig. 7: A frame of VR video showing tiles.

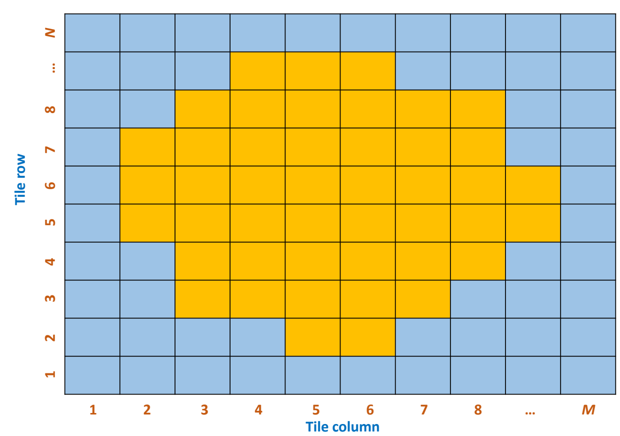

Fig. 8: A FoV (yellow coloured) in a frame of VR video.

C. Tiling Schemes

In tiling-based streaming approaches, a 360 video is spatially divided into tiles. Many works in developing the appropriate and more efficient tiling schemes for the best use of resources are available in literatures. Many works have adopted the uniform tiling method of partitioning every face of the video into tiles of equal size using a $P \times Q$ grid, such as $3 \times 2, 5 \times 3, 6 \times 4$, 8×5 (ERP) [81], 8×8 (ERP) [80], 12×6 (ERP) [93], 2×2 (CMP) [94], [95], and 4×4 (CMP) [95]. Adaptive tiling based on the various requirements has drawn considerable attention from the research community. For instance, a content adaptive non-uniform tiling scheme proposed in [96], a visual attention-driven adaptive tile splitting method presented in [97], and a reinforcement learning (RL)-based rate adaptation with adaptive prediction and tiling investigated in [98] are some of these works. On the other hand, authors in [99] presented a scheme to determine the optimal tile size based on the content-specific characteristics and empirical distributions over user views of the video segments.

D. Rendering Approaches

As stated earlier, due to the limited visual area of human eyes, only a part of the panoramic frame can be seen at a time slot, that is the FoV of the user as shown in Fig. 8. To

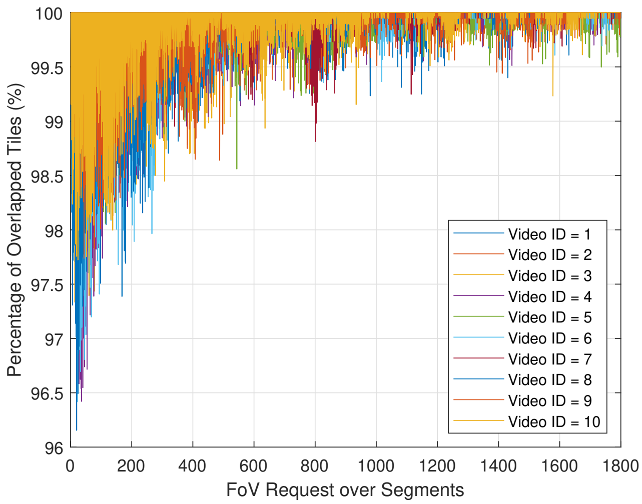

Fig. 9: Average percentage of overlapped tiles in consecutive FoV requests [100].

realize stereoscopic visual experience, a projection that maps the pixels from a viewing sphere to a 2D plane (referred to as viewport) must be employed. This projection is called viewport rendering, which creates the viewport images shown to users and plays an important role on the quality of experience (QoE). Rendering is the process of creating sensory images that depict a virtual world. Viewport rendering is a computation-intensive task, and is generally pre-executed and downloaded at VR equipment (VE) in traditional VR applications. On the other hand, for virtual reality and other interactive computer-generated media, new sensory images need to be produced fast enough to be perceived as a continuous flow rather than discrete instances. The ability to create and display images at a realistic rate is referred to as real-time rendering.

The success of an immersive VR experience relies significantly on the construction of omnidirectional (or 360-degree) visual contents. VR videos are typically characterized by larger file sizes when compared to traditional planar video since they provide UHD 360-degree viewing experience. Though high efficiency video coding (HEVC) can be used to encode VR video, compressed VR video still has 5-10 times the data size of HD video. One of the key differences from the traditional planar video is that VR video is interactively viewed on a users' HMD by freely selecting the FoV, namely the viewport, from a 360-degree space. During VR video viewing, the user moves the HMD to capture the interesting objects in any viewing direction, and thus the frequent viewport requests require more bandwidth to deliver these time-varying viewports. Rendering and transmitting the users' FoV instead of the panoramic frame can effectively reduce the latency of transmission and save computing resources [101]–[103]. Moreover, redering can be done either at the VEs, MEC devices or in the cloud in a flexible way such that the QoE is satisfied [101]–[103]. Bandwidth consumption can also be reduced by sending tiles in user FoV only in high resolution, while other tiles are sent in low resolution or not at all [92].

Furthermore, we can observe that the views of different users are likely to be similar, i.e., the FoVs of different VR users may overlap, meaning that different users may request the same rendered tile at the same time. Exploiting the correlation between different FoVs can further improve computing resource utilization. Specifically, compared to rendering each tile that is included in different users' requested FoVs at the same time, selecting the suitable BSs to render the tiles in the users' overlapping FoVs, and then multicasting the rendered tiles to the corresponding user can reduce the number of repeated rendering of tiles in overlapping FoV and improve the utilization of computing resources on edge nodes. With the same computing resources, reusing the rendered tiles can reduce the total amount of tiles that need to be rendered, and the rendering delay naturally decreases.

On the other hand, it is also worth noting that VR users tend to request overlapping FoV tiles over time as shown in Fig. 9 [100], where a user is repeatedly requesting the same region of FoV tiles over 1800 segments. The figure is plotted for 10 different publicly available VR videos [104]. It is evident that the percentage of overlapped tiles increases over time, indicating that the number of new tiles required for transmission is decreasing over time. Thus, by transmitting only the non-overlapping tiles will further reduce the data transmission requirement significantly. Relevant papers will be discussed in details in the following sections.

V. VR over Wireless Networks: Performance Metrics

A. Factors Affecting VR Experience

The three characteristics, which are also the advantages of VR, are immersion, interaction, and imagination (3I) as discussed below [3].

- *Immersion*: It refers to the feeling of being fully absorbed in the simulated environment of VR. It is the fundamental goal of VR technology and is achieved through a combination of realistic visuals, convincing sounds, and interactive feedback. High-resolution displays and advanced graphics create visually immersive environments, allowing users to perceive depth, scale, and detail.
- *Interaction*: VR technology enables users to interact with the virtual environment in meaningful ways by utilizing various sensors. This interaction can be as simple as using hand controllers to pick up virtual objects or as complex as simulating real-life tasks for training purposes. Hand-tracking technology allows users to use their hands and gestures naturally, making the interaction more intuitive. Additionally, haptic feedback devices provide users with a sense of touch, allowing them to feel textures, vibrations, and even resistance, enhancing the sense of presence and realism. Interactive storytelling in VR also allows users to influence the narrative, making their choices and actions part of the virtual experience.
- *Imagination*: Imagination in VR refers to the creative and limitless possibilities it offers. VR allows us to explore fantastical worlds, historical eras, or fictional universes. It enables artists, designers, and storytellers to push the boundaries of creativity, designing experiences that were

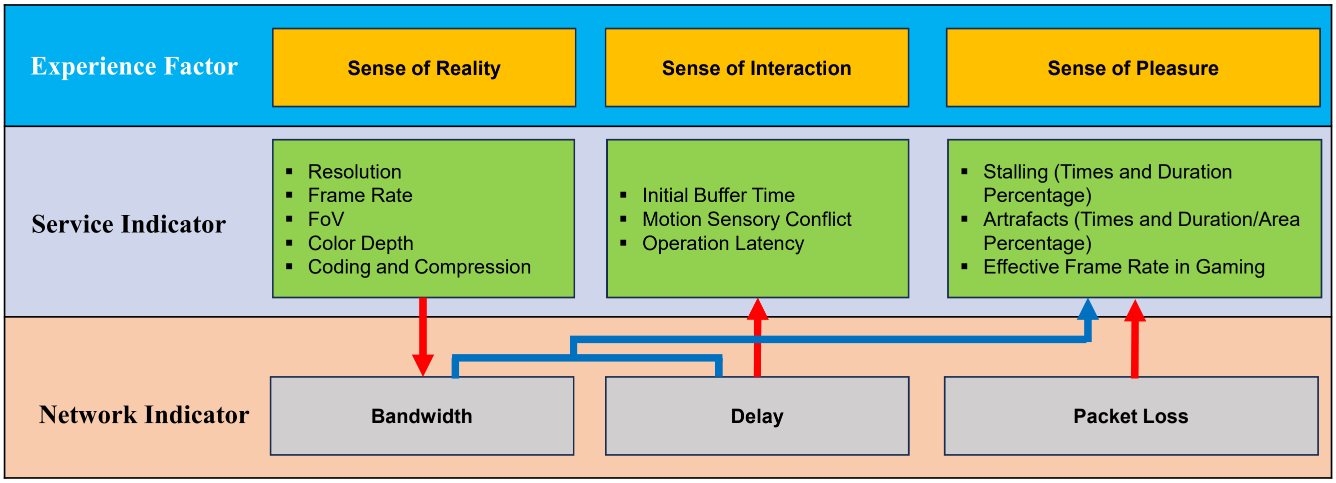

Fig. 10: Relationship between VR experience factors and network parameters [3].

previously impossible in the physical world. VR can be a canvas for imaginative expression, where users can create art, music, or architecture in entirely new ways. It also serves as a powerful educational tool, allowing students to travel back in time, dissect virtual organisms, or explore distant planets, sparking their curiosity and imagination.

Correspondingly, the experience evaluation factors of VR include sense of reality, interaction, and pleasure as discussed below.

- *Sense of Reality*: The perception of reality relies on factors such as resolution, color depth, frame rate, and encoding compression technologies. When audio and video quality are insufficient, the virtual environment lacks realism, preventing users from immersing themselves fully. To guarantee a seamless user experience, the VR transport network must have sufficient bandwidth for high-quality video transmission.
- *Sense of Interaction*: VR utilizes computing and rendering either in the cloud, on edge devices, or directly on the users' device. Latency from remote processing can significantly diminish the feeling of immersion and creativity. The most significant challenge VR faces is the dizziness induced by latency. Moreover, latency during loading, switching, and joystick operations hampers VR interaction.
- *Sense of Pleasure*: The enjoyment of VR experiences relies on the seamless delivery of VR services. Frame freezing and visual artifacts can disrupt this enjoyment. Hence, network performance metrics like bandwidth, latency, and packet loss rate must align with the specifications of VR to ensure a satisfying user experience.

A relationship between the key factors of VR experience and VR network parameters is shown below in Fig. 10 [3].

Therefore, the assessment of human experiences with VR services can be conducted by considering resolution, FoV, refresh rate, and VR interaction latency [105]. These elements affect the quality of service (QoS) criteria necessary for creating an immersive VR experience across different applications and user profiles. It is important to note that human perception can vary due to individual differences, including age, health, occupation, and other factors. These human perception standards can be translated into QoS requirements, specifically focusing on data rate, latency, and error rate or reliability.

B. Major 3GPP Key Performance Indicators (KPIs)

[106], [107] considered two major KPIs for XR including VR: capacity and power consumption. First, a joint user-centric metric is defined (*Metric 1*) for capacity and latency constraints. As VR use cases are delay sensitive, receiving a packet late has almost the same effect as losing the packet completely. So, the metric adds all the late packets to the packet error rate (PER).

1) Metric 1: A Satisfied user equipment (UE): A UE is declared satisfied if more than $X\%$ of application layer packets are successfully transmitted within a given packet delay budget (PDB). Multiple values of X can be considered, while the baseline is 99% [107].

This user-centric satisfaction is further extended to the system level as below:

2) Metric 2: System Capacity: System capacity is defined as the maximum number of UEs per cell with at least $Y\%$ of these UEs being satisfied. As per 3GPP specifications, the baseline Y is 90% [107].

Besides capacity, battery life is another vital criterion which would determine the commercial success of cellular-connected VR devices. However, the absolute UE power consumption can vary significantly among the device vendors. Therefore, only metrics for the relative power consumption are adopted as below:

3) Metric 3: UE Power Saving Gain versus "Always ON": UE power saving gain (PSG) is defined as $(P_2 - P_1)/P_2 \times 100\%$, where P_1 is the average UE power consumption when employing a certain power saving technique and P_2 is the average UE power consumption when the UE continuously monitors control channels and is always available for base station (BS) scheduling.

TABLE I: QoS/QoE parameters set for VR videos by different working groups of IEEE

		VR HMD requirements	**Capabilities**		
			IEEE P802.11ax [119]	**IEEE P802.11ay [120]**	**ITU-R M.2083-0 [121]**
Data transmission rate		~ 20 Gbps (IEEE P802.11 [118])	~10 Gbps (at least 4 times improvement over IEEE 802.11ac)	~100 Gbps	20 Gbps peak, 100 Mbps use-experience data rate
Latency		~ 5 ms (at wireless medium) (IEEE P802.11 [118]) 20 ms (MTP/audio)	"A desirable level to meet QoS requirements in high dense deployment scenario"	10 ms	1 ms
Jitter		< 5 ms (IEEE P802.11 [118])	Not specified	Not specified	Not specified
Transmission range	Indoor	5 m (IEEE P802.11 [118])	Not specified	10 m indoor	Not specified
	Outdoor	Several hundred meters		100 m outdoor	
Mobility	Indoor	Pedestrian speed < 4 km/h (IEEE P802.11 [118])	Not specified	3 km/h	500 km/h
	Outdoor	200 km/h			
PER		10−6 (IEEE P802.11 [118])	Not specified	~10^{-8}	Not specified

However, UE PSG typically comes with the loss in capacity and more precisely, the loss in the satisfied UE ratio. Consequently, it is intuitive to consider all these KPIs jointly.

C. QoS/QoE Requirements

In networks, QoS is defined as network delay, jitter, audio/video drop ratio, and bandwidth. To enhance user experience and interactivity with multi-applications, quality-of-experience (QoE) is defined in terms of the degree to which any application or service provides flexibility, ease of interactivity, and overall annoyance or delight to the user [108]. There are multiple factors that play a role in the VR QoE requirements, such as architectures of the VR devices in which they offload computation partially or completely to another device, how interactive the application (e.g., gaming is highly interactive when compared with virtual meetings) is, display size and resolution, and power consumption [109].

VR services are characterized by the requirement of both low latency and high data rates. In VR use cases, E2E latency is a practical challenge for achieving high-fidelity wireless VR video streaming. High latency can cause a loss of performance in interactive graphics applications and, even worse, can provoke motion sickness in VR applications [110]–[112]. MTP latency as defined earlier is an important metric that is considered in a lot of studies. On the other hand, VR videos are typically of larger file sizes and require 5-10 times the data size of HD video [101]. At the same time, the transmission has to be near loss-less requiring extremely high reliability. To this end, there is no unified standardized QoS/QoE requirements. Different organizations are working independently to finalize the QoS/QoE requirements of VR videos. Therefore, we here discuss the QoS/QoE requirements proposed by different industries and academia.

There are multiple references proposing different latency requirements. For example, [113] states that for a good VR experience, the MTP latency should be below 50ms and latency above 63ms causes significant motion sickness. Another paper reports that high jitter in MTP latency causes motion sickness [114]. This means that the tail of the latency histogram is also critical in the users' experience. Some works suggest that the acceptable MTP latency requirement is 15-20 ms, although it is clear that some acute users will be able to discern much lower interaction latency times [5], [7], [112], [115], [116].

1) IEEE: Latency of the wireless links, such as that of Wi-Fi, is one part of the overall MTP latency. In [4], the QoS requirements in wireless local area network (WLAN) based on the data rate, latency, jitter and reliability requirements for various real-time video applications including VR/AR videos are discussed. The E2E latency considered all the factors that contribute to impact latency, including IEEE 802.11 link transmission delay, non-802.11 link transmission delay, signal processing delay, delay caused by synchronization, etc. The latency and reliability requirements for VR/AR applications are recommended to be less than 3-10 ms and near-lossless respectively. A summary of the the current QoE requirements set by IEEE are presented in Table I [117]–[121].

2) 3GPP: On the other hand, in [122], the QoS requirements in 5G cellular networks for the high data rate and low latency services such as cloud/edge/split rendering, gaming or interactive data exchanging, and consumption of VR content via tethered VR headset are presented. In particular, for the consumption of VR content via tethered VR headset by stationary and pedestrian users, the requirements for the direct wireless link between tethered headset and the connected UE are set to 5-10 ms latency, 99.99% reliability and 0.1-10 Gbps bit rate. To support VR environments with low MTP capabilities, the 5G system shall support - MTP latency in the range of 7 ms to 15ms, while maintaining the required resolution of up to 8K giving user data rate of up to 1Gbps and motion-to-sound (MTS) latency of less than 20 ms. As defined earlier, MTP latency is the latency between the physical

TABLE II: QoS/QoE parameters set for VR videos by Huawei [1]

	Phase 0	Phase 1	Phase 2	Phase 3	Phase 4
Parameter	PC VR	Panoramic Video VR	FoV Video VR	CG Cloud VR	Extreme Experience
Resolution (Single FoV)	1080 x 1200 p	720 p	1080 x 1200 p	1080 x 1200 p	6600 x 6600 p
RTT	---	50 ms	20 ms	5-10 ms	5 ms
DOF	6	3	3	6+	N
Frame Rate	---	30 FPS	30 FPS or 90 FPS	60-90 FPS	90-120 FPS
Bit Rate	5.6 Gbps (24 bits) 2.8 Gbps (12 bits)	20-25 Mbps (12 bits) (for 4K panoramic video streaming, pseudo-3D) 80-100 Mbps (12 bits) (for 8K panoramic video streaming, pseudo-3D, FoV 2K)	12 or 37 Mbps (12 bits) (Single FoV 4K) 80 or 240 Mbps (12 bits) (Single FoV 6600 x 6600 p) 0.4 or 1.2 Gbps (12 bits) (for prestored stereo panoramic video streaming, real 3D)	100-150 Mbps (24 bits) (Compression ratio: 40:1) (for rendered FoV transmission, real 3D)	9.4 Gbps (12 bits) (Compression ratio: 10:1) 4.7 Gbps (24 bits) (Compression ratio: 40:1) (for rendered FoV transmission, real 3D)

TABLE III: QoS/QoE requirements of different versions of cloud VR services by Huawei [3]

Phase		Fair-Experience Phase	Comfortable-Experience Phase	Ideal-Experience Phase
Predicted commercial application time		2018	2019-2020	2023-2025
Video full-view resolution		4K-8K	8K-12K	12K-24K
Strong-interaction content resolution		2K-4K	4K-8K	8K-16K
Terminal resolution		2K-4K	4K-8K	8K-16K
FoV		90º – 110º	120º	120º – 140º
Color depth (bit)		8	8	10~12
Coding standard		H.264/H.265	H.265	H.265/266
Frame rate (FPS)		30 (video services) 50-90 (Strong-interaction services)	30 (video services) 90 (Strong-interaction services)	60-120 (video services) 120-200 (Strong-interaction services)
VR Video service	Bitrate	≥ 40 Mbps (4K)	Full-view: ≥ 90 Mbps FoV: ≥ 50 Mbps	Full-view: ≥ 290 Mbps (12K), ≥ 1090 Mbps (24K) FoV: ≥ 155 Mbps (12K), ≥ 580 Mbps (24K)
	Bandwidth	≥ 60 Mbps (4K)	Full-view: ≥ 140 Mbps FoV: ≥ 75 Mbps	Full-view: ≥ 440 Mbps (12K), ≥ 1.6 Gbps (24K) FoV: ≥ 230 Mbps (12K), ≥ 870 Mbps (24K)
	Network RTT	≤ 20 ms	≤ 20 ms	≤ 20 ms
	Packet loss	≤ 9e-5	≤ 1.7e-5	≤ 1.7e-5
Strong-interaction VR service	Bitrate	≥ 40 Mbps	≥ 90 Mbps	≥ 360 Mbps (8K), ≥ 440 Mbps (16K)
	Bandwidth	≥ 80 Mbps	≥ 260 Mbps	≥ 1 Gbps (8K), ≥ 1.5 Gbps (16K)
	Network RTT	≤ 20 ms	≤ 15 ms	≤ 8 ms
	Packet loss	≤ 1e-5	≤ 1e-5	≤ 1e-6

TABLE IV: QoS/QoE parameters set for various cellular VR services as defined in [105]

Requirement		Pre-VR	Entry-level VR	Advanced VR	Human Perception	Ultimate VR
Experience duration		< 20 min	< 20 min	< 1 hr	---	> 1 hr
Video resolution		3840 × 1920 (full-view 4K video)	7680 × 3840 (full-view 8K video)	11,520 × 5760 (full-view 12K video)	21,600 × 10,800 (full-view video)	23040 × 11520 (full view 24K video)
Single-eye resolution		1080 × 1080	1920 × 1920	3840 × 3840	9000 × 8100	9600 × 9600
FoV (Single-eye)		100 × 100	110 × 110	120 × 120	150 ×135	150 × 150
Bit per color (RGB)		8	8	10	---	12
Refresh rate		60	90	120	120	200
Pixel per degree		10	17	32	60	64
Service requirement	Uncompressed bit rate (progressive 1:1)*	10.62 Gbps	63.70 Gbps	238.89 Gbps	1007.77 Gbps	1911.03 Gbps
	Transmitting bit rate (low-latency compression 20:1)	530 Mbps	3.18 Gbps (Full-view) 796 Mbps (FoV)	11.94 Gbps (Full-view) 5.31 Gbps (FoV)	50.39 Gbps (Full-view) 31.49 Gbps (FoV)	95.55 Gbps (Full-view) 66.36 Gbps (FoV)
	Transmitting bit rate (lossy compression 300:1)	35 Mbps	210 Mbps (Full-view) 53 Mbps (FoV)	796 Mbps (Full-view) 354 Mbps (FoV)	3.36 Gbps (Full-View) 2.10 Gbps (FoV)	6.37 Gbps (Full-view) 4.42 Gbps (FoV)
	RTT	10 ms	10 ms	5 ms	10 ms	5 ms
	Packet loss	10^{-6}	10^{-6}	10^{-6}	10^{-6}	10^{-6}
*Progressive data rate = (3 × Bit per color) × (Pixel per degree × FoV (full-view or single-eye)) × Refresh rate / Compression ratio						

movement of a users' head and the updated picture in the VR headset. The MTS latency is the latency between the physical movement of a user's head and updated sound waves from a head mounted speaker reaching their ears.

3) Huawei: Huawei has multiple works on the QoS/QoE requirements of VR services. In [1], Huawei identified the evolution steps from PC based cloud VR to the extreme experience (EE) cloud VR services and recommended the technical requirements as presented in Table II.

Another report published by Huawei in 2018 reported different QoE requirements of cloud VR videos determined based on the actual tests and theoretical analysis as presented below in Table III. It is to be noted that Huawei has divided the VR services into two categories - weak-interaction VR service (i.e., VR video services including IMAX theatre, 360-degree panoramic video and video broadcast) and strong-interaction VR services (e.g., VR games, VR home fitness and VR social networking). Both of them are then considered to be evolved into three phases having different QoE requirements - fair-experience phase, comfortable experience phase and ideal-experience phase. The detail requirements and technical specifications of these three phases can be found in the report.

Huawei also categorized the evolution of VR services into four phases: pre-VR, early-level VR, advanced VR and ultimate VR in [105], [123]. Major QoE requirements and other technical specifications for these classes were also presented as summarized in Table IV. The authors also claimed that the current 5G cellular networks can at best support advanced VR services.

4) Qualcomm: Qualcomm has also classified cellular-connected VR applications into four main use cases, which are automotive video streaming (VR-AVS), social sharing at crowded venues (VR-SS), six degree-of-freedom content streaming (VR-DoF), and remote control/tactile Internet (VR-RC) [124]. Some QoE requirements are specified in the same document.

VI. VR/AR Spectrum Requirements

Due to the high bit rate and strict latency requirement of VR services, the spectrum requirement will be obviously large. Thus, wireless VR services can be provided either through 5G/6G cellular networks or by Wi-Fi networks. However, the spectrum requirement for VR services is not well established yet. Various industries and standardization bodies are working independently for understanding the spectrum requirements for VR services.

Huawei in [3] reported that 2.4GHz Wi-Fi is not suitable for VR services as it does not have sufficient channel bandwidth left. On the other hand, spectrum bandwidth of 5GHz Wi-Fi can be 20 MHz, 40 MHz, 80 MHz, or 160 MHz, which can support different bit rates. The theoretical maximum bit rate of 5GHz Wi-Fi is 3466 Mbps, which is suitable for VR services. However, most of the 5GHz Wi-Fi channels are dynamic frequency selection (DFS) type and only one non-DFS channel of 80MHz is available. To reduce complexity, most of the existing consumer-level APs in the market do not support DFS channels. As a result, the 5G Wi-Fi in the home network is congested in non-DFS channels, causing serious interference, which will cause increased packet-loss and latency [3], [109], [125]. Thus, 5G Wi-Fi is not much appropriate for VR services though it can be used for the time being through careful planning and optimization. The recommendation of Huawei for current cloud VR services is to use 80MHz spectrum bandwidth and HMD with 2×2 multiple-input multiple-output (MIMO) support.

Moreover, by realizing the insufficiency of 2.4GHz and 5GHz Wi-Fi networks for VR services, authors in [109] conducted studies on the 6GHz carrier based IEEE 802.11ax 6E Wi-Fi network performance for AR/VR applications. In this paper, the authors investigated the impact of the amount of 6 GHz spectrum on the performance of the AR/VR headsets which are used by the students for e-education in a school scenario. More specifically, this paper determined the maximum number of AR/VR headsets that can be supported when 1200 MHz or 500 MHz of spectrum with channels of 160MHz bandwidth are available. The investigation was conducted for a school scenario of three-story building having 14 classrooms in each floor and 20-30 students per class and each student has a wireless VR headset. The authors concluded that 500 MHz was not enough to support the VR/AR e-learning of the school, while 1200 MHz provided enough capacity for the use case.

On the other hand, 3GPP is working on the standardization of VR services into the core of 5G and beyond 5G cellular networks [5]–[7], [107]. The report [107] has provided two different evaluation frameworks of XR videos considering sub-6GHz and millimetre-wave (mmWave) spectrum respectively as follows. *Framework 1 (sub-6GHz)*: Carrier frequency 4GHz, sub-carrier spacing 30 kHz, single carrier (SC) evaluation bandwidth: baseline 100 MHz and optional 20/40 MHz, and carrier aggregation (CA) evaluation bandwidth: Optional 2×100 MHz [107]. *Framework 2 (mmWave)*: Carrier frequency 30GHz, sub-carrier spacing 120 kHz, SC evaluation bandwidth: Option 1: 100 MHz and Option 2: 400 MHz. Academias are also following these 3GPP frameworks for evaluating performance of their proposed wireless VR network architectures and algorithms [106].

However, there is a growing concern that the 5G spectrum, corresponding bandwidth and other physical layer specifications might not be appropriate for many current as well as future VR services, especially for the future immersive communications [105], [126]. Therefore, industries and academia have started to work on finding new spectrum for VR services. For instance, Ericsson in their white paper [126] on 6G cellular networks has concluded that for supporting emerging sensory experience use cases, new spectrum in the centimetric (7-20 GHz) and the complementary sub-THz (92-300 GHz) ranges is essential. On the other hand, high-frequency transmission like mmWave (30-300 GHz) and THz (100 GHz–10THz) communication are being considered promising technologies to deliver VR-DoF content for wearable VR devices due to their high bandwidth availability and small form factor [105], [127], [128].

VII. Key Enabling Technologies for Wireless VR

VR services has some stringent requirements for satisfying the users. Wireless communications technologies are evolving to meet the VR service QoS requirements. This section discusses the major enabling technologies for immersive wireless VR experiences.

A. Multi-Access Edge Computing (MEC)

The implementation of interactive real-time wireless VR applications with the low MTP delay and high QoE relies on fast rendering and transmission of mass data, which poses a huge challenge both to the computing power and transmission rate of existing mobile networks system [90], [129]–[132]. MEC brings the cloud computing facilities to the edge of networks through terminal, edge and fog computing infrastructure. Thus, MEC is as a promising computing paradigm offering an opportunity to address the above challenges by offloading the high-computation rendering tasks from the VR devices to the network edge node with computation and communication resources [133]–[138]. For this purpose, MEC will enable VR devices to access edge resources in an on-demand fashion. While the cloud computing solutions allocate radio and computing resources (infrastructures, platforms, and software) in a centralized manner at the cloud, MEC construct the networks by allowing to have computing resources distributed across various levels of networks. VR users can enjoy the facility of distributed computing/storage/memory resources at close proximity by leveraging the availability of Wi-Fi networks and dense small cell base stations. In the most extreme cases, one can consider the computation at a very local level, say with fully/partially embedded devices in the human body, having computing capabilities. This phenomenon is commonly referred to as "*skin computing*" [19]. MEC architectures can also be categorized in two classes - vertical collaboration (VC)-based MEC and horizontal collaboration (HC)-based MEC, which can either independently or jointly be deployed for the performance optimization of VR services [139]. VC-based VR networks generally use a three-tier hierarchical architecture having terminal tier, edge tier and the cloud tier for conducting collaborative caching and computation offloading [139], [140]. On the other hand, HC-based wireless VR architecture deploys cooperation among MEC servers [139], [141]. MEC can reduce the energy consumption of VR devices, which is a crucial issue for battery powered VR wireless devices.

B. Cloud Computing

Cloud computing is a model for enabling on-demand access to a centralized shared pool of configurable resources (e.g., servers, storage, applications, services, and so on) [142], which is the enabling technology for cloud VR services [1], [3], [123], [143], [144]. While MEC devices can perform the less intensive computations as various edges, cloud computing provides the access of powerful centralized computing servers in the cloud for intensive computation purposes [145]. In VR applications, cloud servers will be used to store the VR videos or applications so that they can be accessed from anywhere at any time with sheer flexibility, perform computation intensive rendering process, and encoded, compress, and transmit VR contents to user terminals. Local rendering requires expensive high-performance devices to provide acceptable user experience. With Cloud VR, users enjoy VR services without purchasing expensive hosts or high-end PCs, promoting VR service popularity. On the other hand, the integration of cloud computing into the mobile environment enables mobile cloud computing (MCC), which enables offloading the computing power and data storage requirements from mobile devices into the powerful computing platforms in the cloud, bridging the gap between the increasing computing demands and the traditional mobile computing technologies with limited computing, storage, and energy resources in mobile devices [142].

C. mmWave and THz Communications

Immersive VR applications require ultra-reliable communication link, ultra-high data rate and ultra-low latency communications for smooth operation, which requires to explore new spectrum with high bandwidth [112]. Exploiting the unused mmWave [106], [107], [146], [147] and THz communications [148]–[150] is essential for supporting VR services [127], [151]. High-frequency transmissions, such as those in the mmWave range (30-300 GHz) and THz spectrum (100 GHz–10 THz), are currently regarded as promising technologies for delivering VR-DoF content to wearable VR devices. The appeal lies in their abundant bandwidth and compact form factor, as highlighted in references [105], [127], [128]. Industries are also supporting this initiative. For instance, in a report, Ericsson has recommended the use of new spectrum in the centimetric (7-20 GHz) and the complementary sub-THz (92-300 GHz) ranges for sensory applications [126].

D. Ultra Massive MIMO (UM-MIMO)

Massive/ultra massive MIMO (m/UM-MIMO) enables ultra-high throughput and low latency, which is vital for attaining QoE of VR video transmission over wireless network [152]–[155]. In tile-based VR transmission, multiple tiles, treated as multiple streams, can be easily transmitted to users simultaneously by taking advantage of the m/UM-MIMO systems. Moreover, existence of large number of antennas in m/UM-MIMO systems can easily be exploited for beamforming for supporting VR services, which is discussed in the next section.

E. Beamforming

As VR requires a high data rate for user satisfaction, beamforming can be a powerful enabling technology since it can significantly enhance the spectral and energy efficiency, and improve coverage [147], [156]. For example, beamforming can efficiently be used to achieve sufficiently high signal strength at the HMD by focusing the energy of the transmitter to the HMD [147]. Beamforming is achieved by using 2D phased antenna arrays, consisting of many separate, individually phase controllable antenna elements [157]. By carefully tuning each element's phase shift, all elements' signals become phase aligned, and interfere constructively, in some intended direction. Potential usage of high frequency signals in mmWave and THz communications in VR services will make it even easier for compacting many antennas in a small space. However, estimating the relative positions of communicating devices (e.g., access point and HMD) can assist largely in creating precise beamforming directing to each other [158], [159]. However, beamforming is always a sophisticated task, while the HMD-side beamforming is the most challenging one. Analog, digital and hybrid beamforming are the three possible options, where the first two are jointly applied to achieve hybrid beamforming. Among these three options, hybrid beamforming is the most promising due to its relative advantages [160]. On the other hand, both 2D and 3D beamforming are possible [161]–[166], while the 3D beamforming is considered promising for VR services as (m-MIMO) systems in 5G and UM-MIMO in 6G cellular networks would facilitate 3D beamforming and it has advantages over 2D beamforming as well [159], [161].

F. Quantum Computing and Quantum Communications

A large amount of data handling and computations is required for VR services [167], which is a bigger issue in real-time VR services compared to the off-line counterpart. The computation can be done in the cloud or at the edge, which is quite challenging, especially for the current edge computing devices. On the other hand, quantum computing with its super computing capability is overturning the contemporary notions of computational methods and devices, which will totally change the economic, industrial, academic, and societal landscape [168], [169]. Thus, quantum computation can be a great rescuer in such VR services as it can calculate much faster than any classical computer could ever hope to do. Instead of serial or even parallel computation/ processing, quantum computation allows to calculate/compute high-dimensional objects in lower dimensions, exploiting entanglement and superposition [19], [170]. On the other hand, quantum communications take the quantum state as the information carrier and realize quantum information or classical information transmission technology through the transmission of the quantum state [170], [171]. Quantum communications is non-reproducible and absolutely secure, efficient in in transmitting and processing information due to the superposition and entanglement properties of quantum states, and stronger anti-interference capable [170]–[172]. Thus, it is undoubtedly a game changer for highly resource demanding services such as VR. Therefore, quantum communications, in recent years, have drawn tremendous attention of research communities [170]. Research on quantum network architectures, quantum repeaters (e.g., drone/satellite), short-/medium-/long-range quantum communication protocols, quantum full duplex communication protocols, quantum memories and quantum computers are some of the burning research issues at the moment [169], [170], [173], [174].

G. Orbital Angular Momentum (OAM) Multiplexing

OAM is a general property of many different electromagnetic (EM) and mechanical waves. Independent data-carrying beams with different OAM values are orthogonal to each other. This orthogonality enables beams of different OAM values to be multiplexed at a transmitter, spatially co-propagate in the same medium, and demultiplexed at a receiver - all with little inherent crosstalk [175]. OAM can unleash its potential in achieving high spectrum efficiency [176], [177]. Consequently, OAM multiplexing has recently been proposed as a solution to the ultimate goal of increasing the channel capacity of wireless communication links because of the existence of infinite orthogonal modes [175], [178]–[181]. It can also be combined with the existing conventional multiplexing techniques to boost up the data rate multiple times for future wireless communication systems [176], [181]. Thus, OAM is an extremely potent candidate for enabling the emerging truly immersive VR services including future holographic communications.

H. Machine Learning (ML)

Machine learning (ML)-based design has evolved as one of the most promising enablers for wireless communications [90], [160], [182]. Learning-based sub-systems of VR service can efficiently exploit the various patterns of VR videos as well as the different features of VR systems for improving user satisfaction [151], [182]. For instance, ML-based prediction of FoV, rendering, multi-quality encoding of tiles, multi-cast transmission, computation offloading, caching, user association, transmit power allocation and so on. can drastically reduce the computation burden, data rate requirements, latency and energy consumption [151], while improve the communication reliability and efficient utilization of resources of VR systems. Extensive research is being conducted in this regard, which is evident through a large number of emerging publications of using ML in VR systems. Deep RL (DRL)-based ML techniques for FoV prediction in [182] and for QoE maximization in [183], recurrent neural network (RNN) based on long short-term memory (LSTM) architecture in [184] and gated recurrent unit (GRU) architecture for FoV predictionu in [90], [183], collective reinforcement learning (CRL) algorithm for allocate resources adaptively in [185], and meta-reinforcement learning (MRL) algorithm for access point (AP) selection and user association in [148], [186] are some of the recent works on the application of ML in VR networks.

I. FoV Centric Transmission

Rendering the full 360 degree video in real-time can be costly both for downlink transmission and computation as it involves complex matrix computation [151]. One potential solution is to only render the requested FoV each time based on the uplink tracking information of VR users' motion, including head and eye movements. According to a study, the data size of the rendered FoV is 75% of that of the stitched 2D image, which means that the size of data to be delivered via downlink transmission can be reduced by 25% compared to delivering the stitched 2D images [182]. Reduction of downlink transmission will lower pressure on bandwidth requirement, reduce computation burden and saves battery energy. Thus, FoV centric video transmission where only the requested FoV is rendered is dubbed as the most feasible one for wireless VR [151], [182], [187]. The transmitted FoV can be the one predicted proactively in advance based on the previous head-motion behaviour of the user [182], [187]–[189] or the one detected reactively based on the real-time eye and head movements of the user [151], [188]. Nevertheless, FoV prediction is not error-free. The limitation of the proactive FoV streaming is that in case if the predicted FoV is not same as the actual FoV, black holes or video quality deterioration will be there in the missing tiles during the playback of video segments [187], [188].

J. Caching/Storage/Memory

The concept of content caching has recently been investigated in great details [190], [191], where the idea is to cache strategic contents at the network edge (e.g., at a base station, devices, or other intermediate locations). There can be reactive and proactive caching. While the former serves end users when they request contents, the latter is proactive and anticipates users' requests. Proactive caching depends on the availability of fine-grained spatio-temporal traffic predictions. Other side information, such as the users' location, mobility patterns, and social ties can be further exploited especially when context information is sparse [19]. Storage will play a crucial role in VR where, for instance, upon the arrival of a task query, the network/server needs to swiftly decide whether to store the object if the same request will come in the near future or instead recompute the query from scratch if the arrival rate of the queries will be sparse in the future. Content/media placement and delivery will also be important in terms of storing different qualities of the same content at various network locations [192]–[194].

K. Blockchain Technology

Although VR is an exciting technology going to create a parallel world, it raises a number of concerns about the privacy of its users. Securing the digital content in possession of all the users of the VR ecosystem is of prime importance. Not only data, the inevitable economic ecology of VR world will be vast and highly complex in terms of diverse and large number of participating terminals and users. This ecosystem needs to have an efficient technology for accounting their content and transactions to ensure user integrity, privacy, and reputation. In this regard, blockchain as a decentralized ledger without a centralized authority is a promising security and privacy preservation solution. Blockchain owns consecutive blocks, which are linked with each other through the hash value of previous block header. Other than the inevitable cryptographic hash, timestamp, nonce and transaction data are also included in a block [195]. Owing to its distinct features of decentralization, immutability, and transparency [196]–[199], blockchain is the pertinent enabler intended to enforce accountability into the digital ecosystem.

L. Internet of Things (IoT)

The most important task for real world truly immersive VR services is to reconstruct a VR space that can provide

3-DOF (3-DOF (roll, pitch and yaw) or 6-DOF (yaw, pitch, roll, surge, sway, and heave) [200]. In particular, VR services require an interactive haptic system with seamless immersion and sense of reality through feedback that can satisfy the five senses, including visual, auditory, and tactile, to enhance the user's sense of being present in a VR environment [201]. Large scale wearable sensor network with accurate sensing and measurement capabilities, negligible communication latency and ultra reliable links is the key to enable such VR videos [13], [201]. However, due to the difficulty of achieving 6-DOF for real world VR services, most of the recent real world VR videos are 3-DOF type. Current 6-DOF VR videos are predominantly of computer generated virtual world. Massive IoT (mIoT) infrastructure is the most important tool for collecting important data for VR space reconstruction enabling 6-DOF videos of real world [200], [202]. Remote IoT devices will also enable long distance VR services (e.g., VR tourism) and remove the distance between the VR user and the originating location of the VR videos [203]. Not only that, IoT is enabling the long-distance haptic communication creating sense of physical presence, touch, motion and control in VR space in real-time. Emergence of mIoT as VR service enabler largely depends on 5G/B5G cellular networks and Wi-Fi networks [167]. However, mIoT will also bring a huge challenge in managing large scale IoT devices and the massive volume of data generated by them [167], [204]. VR services enabled by mIOT will have to handle and overcome these challenges. Integration of data from large number of IoT devices in real-time for real-time VR services will be even more challenging.

M. Unmanned aerial vehicle (UAV) and Satellite Communications

UAV and satellite assisted hybrid terrestrial and non-terrestrial wireless network is going to be an indispensable part of future mobile communication systems [205]–[207]. This integration will drive for achieving true global connectivity, bridging the coverage gaps and enhances the overall user satisfaction. Moreover, on board mobile sensors including cameras and light detection and ranging (LIDAR) radars have gained UAV and satellites much popularity for remote monitoring of objects, infrastructures and events [208], [209]. Thus, they are powerful technologies for acquiring the images, videos and context information of various objects and places, especially difficult to access as well as remote sites including space objects, structures, archaeological sites, mountains, forests, waterfalls, volcanoes and caves, which can be integrated to create both off-line and real-time VR contents [14], [203], [210]–[212]. Integration of IoT with UAV further enhances the potential for using in VR video creations [203].

N. Device-to-device (D2D) Wireless Communications

D2D wireless communications allow mobile devices in close proximity to communicate directly without the help of a cellular BS [213], [214]. This results in high throughput, low latency, energy efficient and high bandwidth efficient communications leading to reduced workload of BS and the core network [215]. For exploiting the potential of D2D communications, extensive research has been carried out in the filed [213], [216]. Thus, it is clear that by leveraging the short-range communications among the collocated VR users, D2D communications can also be able to support the VR users for satisfying QoE requirements [19]. For instance, if a user device has VR videos in its cache memory, that can be shared with the neighboring VR users, which will reduce the load on the network [217]. Also, a device can perform the VR video rendering for another device in case the second device does not have much computation capacity. D2D communication devices can also extend the coverage of VR distribution networks by working as a relay for the nearby VR users [218]. Such cooperative communications can make it much easier for users to enjoy true VR experiences.

VIII. Network Architectures for Wireless VR

Most of the works in literature have formulated problems and proposed solutions considering VR services over cellular mobile networks, more specifically, 5G and beyond 5G cellular networks [15], [46], [102], [139], [141], [143], [151], [182], [219]–[224]. Some of the proposals have also considered WLAN, satellite communications, UAV networks and D2D communications solely or in combination of cellular networks for providing wireless VR services. On the other hand, our extensive survey has identified that MEC is considered almost universally for enabling wireless VR as this technology brings VR content and essential computing resources near the users, leading to improved latency performance and reduced burden on the backhaul. A VR ecosystem which exploits various modes of wireless networking is shown in Fig. 11. A brief discussion on these various architectural options is presented below.

A. VR over Cellular Networks

5G and beyond 5G cellular networks with MEC and/or cloud computing are considered as the most viable architectures for wireless VR [15], [46], [102], [139], [141], [143], [151], [182], [219]–[222], [224]–[228]. A short survey on mobile VR over cellular networks with edge computing and cloud computing was presented in [15]. On the other hand, a framework with edge/cloud computing with rendering at cloud/edge/local server was proposed and investigated in [143].

Authors in [46] proposed a wireless multi-player interactive VR game framework over cellular network with MEC for avoiding VR vertigo and minimizing inter-player delay. To achieve this, an iterative algorithm is proposed for optimizing the MEC computing resource allocation, wireless bandwidth allocation and the post-processing decision policy with the constraints of the absolute delay requirements, the local energy limits of players, the total bandwidth limit and the computing resources limit. FoV rendering is computed at the MEC server, while the post-processing of the rendered content is computed at the MEC server or the VR device.

A VR streaming system by jointly utilizing the mmWave and sub-6 GHz spectrum over cellular networks with MEC was presented in [220]. In this system, mmWave is the primary

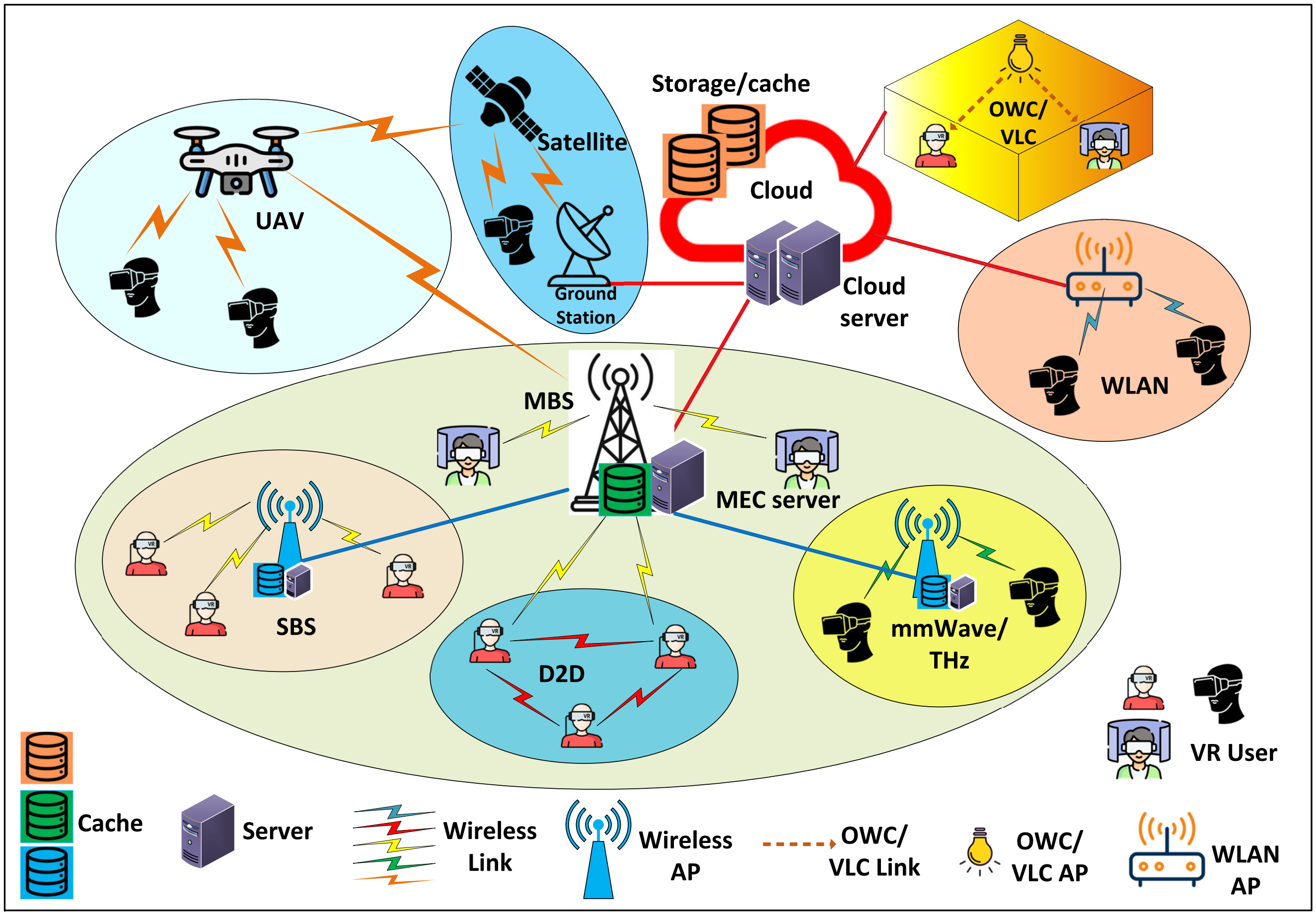

Fig. 11: A network architecture for wireless VR with heterogeneous modes of operations.

spectrum for supporting high bandwidth requirements of VR streaming, while sub-6 GHz link is used as the secondary link for replacing the mmWave links in outages, and thus, ensures disruption-free wireless communications. A multi-objective joint optimization of video chunk quality, link adaptation, and adaptive viewport rendering offloading is solved using genetic algorithm (GA) for enhancing performance in terms of latency, energy requirements and the received viewport quality. On the other hand, a heterogeneous cellular network framework with MEC for supporting high performance VR services over 5G-and-beyond networks was proposed in [225].

Another MEC-enabled wireless VR network with RNN-based FoV prediction and rendering at MEC server was investigated in [182]. Centralized and distributed decoupled DRL strategies are proposed and analyzed for maximizing the long-term QoE of VR users. Furthermore, impact of high user mobility on the QoE performance for interactive VR applications in MEC-enabled cellular network was thoroughly evaluated in [222]. In addition, a VR framework with mmWave and MEC for wireless VR applications was proposed in [226] for maximizing QoE by jointly optimizing UE association, caching policy and offloading mode selection.

A MEC-enabled small-cell cellular network architecture implementing joint HC and VC was proposed in [139]. Under HC scheme, multiple MEC servers are provisioned to jointly provide edge caching and viewpoint computation services to the HMDs, while the caching and computation strategies can collaborate among vertical layers under VC scheme. A joint caching, BS power allocation and task offloading problem is then formulated and solved for improving the quality of VR service delivery.

Architectures of wireless VR networks using cloud radio access networks (C-RAN) are also proposed in several works [102], [219]. For instance, authors in [219] proposed C-RAN based VR system, where a MEC-cache server for VR video synthesizing is placed in the centralized base band unit (BBU) pool. A hierarchical and collaborative caching scheme, keeping the option of caching at both the BBU pool and the radio remote heads (RRHs), is proposed and optimized to minimize transmission latency. The same authors then extended their C-RAN based wireless VR system in [102] for further improving caching performance, backhaul traffic balancing, latency and QoE.

On the other hand, fog radio access network (F-RAN) deploying computing facilities at the fog layer is being considered promising for wireless VR delivery [19], [228]. The fundamental idea of caching contents in fog-layer in advance and computing post-processing procedures on demand at the edge can reduce fronthaul load and improve response time. An F-RAN-based wireless VR delivery framework by taking the advantages of both edge computing and caching scheme was proposed in [229]. A joint radio communication, caching and computing decision problem with resource allocations at both the VR devices and the fog APs is solved for optimizing the average tolerant delay under a given constraint of transmission rate. The optimization problem is formulated as a multiple choice multiple dimensional knapsack problem and solved using Lagrangian dual decomposition approach.

B. UAV-Assisted Wireless VR

A number of proposals were published on providing wireless VR services by using UAV mounted BS and computing facilities [203], [230]–[234]. Some works proposed UAVs as an extension of the terrestrial cellular networks to non-terrestrial domain for facilitating the wireless VR services [230], [232], [233], [235]. Besides, there are few works, where only UAV network was proposed for wireless VR [203], [231], [234]. In general, UAVs adds an extra layer of flexibility by exploiting the opportunity to implement air-borne MEC. UAV also improves the reliability of the wireless links between mobile devices and the terrestrial BSs.

Authors in [232] considered an architecture where both cellular small BSs (SBSs) and cellular connected static UAVs are jointly deployed for wireless VR. The UAVs are equipped with cameras for collecting real-time VR contents, which are then transmitted to the SBSs via wireless backhaul links for finally delivering to the VR users. For meeting the delay requirement, UAVs are enabled to extract specific visible contents, while the SBSs are enabled to cache popular contents for reducing traffic load on backhaul. Finally, a joint content caching and transmission problem is formulated for satisfying instantaneous VR delay target, which is solved using a distributed deep learning approach. On the other hand, considering the fact that cellular MEC resources could be insufficient for providing VR services during peak times or in dense environments, authors in [230] proposed a network architecture where VR service provider would be able to deploy UAVs to serve as micro BSs for expanding service coverage and improving spectrum efficiency. In this work, UAVs are enabled to pre-cache VR contents and serve UEs directly via air-to-ground (A2G) communications. This paper also proposed and investigated a contract theory-based incentive mechanism for providing incentives to the UAVs by the MECs for serving as micro BS. Another work by jointly deploying cellular networks and UAVs for wireless VR was proposed in [233]. In this architecture, both the cellular network and the UAVs are powered by MEC facility. UAVs can work as aerial BSs or as full-duplex relays for forwarding VR contents from cellular BSs to the VR users. Then, a joint problem is formulated and analyzed that allocates computing and communications resources, and selects the appropriate locations of the UAVs for maximizing delivered QoE.

Fully UAV-enabled wireless network architectures for providing low-latency VR services are proposed in [203], [231]. In the work [231], rotary-wing UAVs act as aerial BSs for VR content delivery to the terrestrial mobile VR users. The UAVs are connected to a terrestrial control center through wireless backhauls. Each UAV is assumed to have a panoramic camera and a rendering module for processing panoramic videos to VR videos. The proposed architecture focused on the latency minimization under the constraints on the UAVs' energy consumption, kinematic, and computation and transmission capabilities. On the other hand, an architecture for remote VR immersion by deploying a network of UAVs along with IoT was outlined in [203]. UAVs are spatially distributed over the remote scene of interest for capturing different viewpoints. The UAVs are connected to a ground/air-based station over wireless links, which transmits the captured data towards a ground-based aggregation point for constructing a viewport-driven immersive representation of the remote scene. Another work considering UAV-enabled MEC system, where a wireless network of only UAVs are proposed for caching, processing, and delivering VR contents to the users from a cloud server, is presented in [234]. This work optimized resource allocations considering a Rician fading channel model for minimizing the maximum latency under computing, caching, and power constraints of the UAVs.

C. Satellite for Wireless VR

Similar to UAVs, satellites can also be used for enhanced services to the VR users as satellite network is considered as an integral part of next generation wireless networks [236]. For instance, applications of satellite-borne and international space station (ISS)-borne remote sensing data for education are thoroughly discussed in [64]. Furthermore, a low earth orbit (LEO) satellite-assisted low-latency architecture of wireless VR network was proposed and investigated in [237]. In the proposed system, a LEO satellite connects to a satellite gateway, which is then connected to multiple indoor THz femtocells using optical fiber links. The LEO satellite transmits VR contents to the gateway over Ka-band, then the gateway forwards the received information to the femtocells which then serve the VR users. An algorithm is also proposed for minimizing transmission delay in the proposed architecture.

D. WLAN for Wireless VR

Due to the advantage of high throughput and low-cost easy installation using unlicensed spectrum, IEEE 8022.11 WLAN-based system is also considered promising for delivering wireless VR services [153], [238]–[241]. Feasibility of wireless VR over next generation WLAN by proposing a multi user VR communication scheme for multi-user VR services was conducted in [239]. In this paper, a delay oriented channel access scheme is proposed for demonstrating its superiority over the conventional scheme. On the other hand, a framework for disseminating multi-view VR/AR videos over WLANs was proposed in [240]. This work proposed to utilize WLAN multicast for satisfying VR users. A user satisfaction problem is formulated and a multi-view allocation (MVA) algorithm is proposed for optimum user associations with the WLAN APs to maximize the number of satisfied users. Whereas, a mmWave multi-user MIMO (MU-MIMO) enabled IEEE 802.11ay WLAN based VR system was proposed in [241]. The system designed both analog-digital hybrid precoders and combiners, and leveraged the spatial multiplexing capability of IEEE 802.11ay WLAN at mmWave. Another work proposing MU-MIMO based WLAN for indoor VR services was presented in citeShin2020.

E. D2D Communications for Wireless VR

The short-range D2D communications capability among the collocated VR users can effectively enhance the satisfaction of VR users. An architecture of a D2D-assisted 5G heterogeneous cellular networks was presented in [217]. In this architecture, a VR broadband user can get the delivery of VR content using three different modes, namely, macro cell broadcasting, mmWave small cell unicasting and D2D multicasting. In macro cell broadcasting, all users associated to a macro cell simultaneously receive the same VR content. If a user fails to associate with a macro cell due to poor channel quality, the user can associate with the nearest mmWave small cell and receive VR content using broadband mmWave unicast. On the other hand, a user can be associated a D2D cluster multicast network. The D2D cluster head receives data from a mmWave small cell. The paper also formulated an intelligent mode selection problem and solved it using a RL-based ML model for improving edge user QoE and resource utilization. Another D2D-assisted cellular network architecture for wireless VR video distribution system at public environment was proposed in [218]. In this scheme, D2D gateways stores and distributes VR videos to the users rapidly using high speed D2D links, while the BS manages the overall information coordination and scheduling. The architecture also implements pre-caching strategy, where a user can pre-cache VR videos for minimizing video downloading time.

F. OWC-enabled Wireless VR

Optical wireless communications (OWC) technologies, such as visible light communications (VLC), optical camera communications (OCC), free space optics (FSO) and LiFi, are extremely potent options for supporting the QoE requirements of wireless VR services, especially for indoor users [148], [242], [243]. Research on the OWC-enabled wireless VR was extensively studied under the European Horizon 2020 (H2020) project termed as WORTECS (Wireless Optical and Radio TErabit CommunicationS) [242], [243]. The main focus of the project was to provide ultra-high speed and ultra-low latency (below 3 ms) VR platform with optimal quality of experience. High-speed OWC, 240 GHz RF links, and fiber-wireless-fiber (FWF) with beam steering capabilities were jointly considered for achieving these milestones. Design of a hybrid OWC and RF system, establishment of several proof of concepts and development of several digital boards for VR applications were some of the achievements of the project. On the other hand, a VR network framework deploying both THz communications and VLC for indoor users was presented in [148]. VLC APs (VAPs) are used for accurate localization of VR users in real-time and the THz SBSs are used for VR content transmission. A MRL-based scheme is proposed for maximizing the average number of served VR users with joint consideration of VAP selection, user association with THz SBSs, and time varying user mobility patterns.

IX. ML for Wireless VR

Research on deploying ML for improving various aspects of QoE of wireless VR systems has become a huge research area as evident from the growing number of such publications [90], [103], [112], [130], [148], [151], [182], [185]–[187], [226], [232], [244]–[250]. We discuss some of these papers by categorizing according to the learning mechanisms. A comprehensive summary of the papers deploying ML in designing wireless VR network is also presented in Table V.

A. Reinforcement Learning (RL)

Different variations of RL have drawn much interest for designing wireless VR networks [130], [148], [151], [182], [185]–[187], [226], [245], [246]. Authors in [151] proposed an asynchronous advantage actor-critic (A3C) algorithm, which employs deep RL (DRL) for jointly optimizing the viewport rendering offloading decision and downlink transmit power of the MECs in a THz wireless VR network. In this proposal, multiple DNNs are employed, which are trained asynchronously using gradient descent method. Whereas, a user-centric critic with heterogeneous actors (UCHA) algorithm based on user-centric DRL for jointly optimizing wireless channel access scheme and transmission powers in the downlink from the server to the users was presented in [245].

Both centralized and distributed decoupled DRL (DDRL) strategies were proposed for exploiting the correlation between the geographical location and the predicted FoV request for interactive wireless VR applications [130], [182]. The strategies are based on deep Q-Network (DQN) and actor critic (AC), which are designed to maximize the long-term QoE of VR users by establishing optimal MEC-VR user group association, and selecting optimal rendering MEC for model migration. An adaptive wireless VR framework by integrating distributed DRL for jointly optimizing user association, offloading mode selection and caching policy was investigated in [226]. Proposed VR framework has two phases - offline training phase based on distributed DRL and the running phase based on game theory. The proposed framework demonstrated good adaptability to the network dynamics and improved scalability as well.

Application of meta RL (MRL) for reliable communications of THz/VLC wireless VR networks was explored in [148], [186]. Both the works considered unpredictable mobility of users requiring accurate localization of users in real-time for establishing THz links to transmit VR contents. Traditional RL algorithms are not appropriate for such dynamic scenarios as they can only be trained for a fixed environment having fixed movement pattern of users. Therefore, the authors proposed MRL algorithm for enabling to quickly adapt to the user movement patterns. Authors in [185] formulated a viewport rendering task offloading to the edge access points and resource allocation problem of a blockchain enabled wireless VR network for medical treatment as a Markov decision process. The problem is then solved using a novel collective reinforcement learning (CRL) algorithm. More specifically, a quantum inspired actor-critic (AC) algorithm is deployed for adaptively allocating resources with the consideration of block consensus, content correlation, and fluctuating wireless channel. Convergence of the algorithm and its performance in terms of energy consumption and stalling rate are investigated thoroughly.

A wireless VR network with collaborative MEC among the edge servers with the consideration of channel fading was proposed in [246]. An joint optimization problem is formulated for maintaining effective buffer state in VR devices, which is then solved using a multi-agent RL (MARL) approach, namely, multi-agent deep deterministic policy gradient (MADDPG) scheme. On the other hand, FoV prediction and pre-rendering at the MEC servers is a promising approach for wireless VR. However, this FoV prediction could be erroneous leading to reduced video quality at the VR devices. To address this, authors in [187] formulated a partially observable Markov decision process (POMDP) problem to maximize video quality, which is then solved using a constrained DRL (CDRL) algorithm. In this approach, three DNNs are deployed for approximating the long-term video quality, the latency requirement failure probability, and the policy that determines the redundant range, respectively.

B. Federated Learning (FL)

FL is increasingly being popular for applying in wireless VR network due to its distributed collaborative training facilities [244], [248], [249]. MEC facilities of wireless VR network make FL an attractive choice. A deep FL (DFL) based wireless VR streaming scheme, where single-view images are transmitted to the VR users with the overlaped FoV was proposed in [244]. The corresponding multi-view consistent content is produced by a synthesizing model, which is trained by the proposed DFL scheme. Developed multi-view synthesizing scheme reduces data transmission requirement and dependency on the FoV prediction accuracy. On the other hand, FL based ML framework of deep echo state networks (ESNs) for wireless VR to minimize the occurrence of breaks in presence (BIPs) was utilized in [248], [249]. User mobility and their orientation change are the major reasons of BIPs. The proposed algorithms enable the BSs to train their deep ESNs using locally collected data, which are then cooperatively shared to build a global learning model for predicting user mobility patterns and orientations. Outcome of the prediction system is then used for user association leading to reduced BIPs.

C. Transfer Learning (TL)

TL has the vital advantage over other conventional learning approaches (e.g., Q-learning) as it exploits a function approximation method to record all of the information related to the network and users. It can smartly transfer learned information across time and systems, which is particularly vital for dynamically changing networks. TL thus requires to stores less data about the network and users, which makes TL suitable for dense networks [251]. A liquid state machine based transfer learning (LSM-TL) algorithm for optimizing the performance of VR image transmission in the downlink of a wireless VR network was proposed in [247]. The network can change the format of transmitted image for optimizing downlink load, while the user can rotate VR images for further reducing downlink traffic. This image transmission and rotation is formulated as an optimization problem for maximizing the successful transmission probability of users. This problem is then solved using the proposed LSM-TL algorithm deployed in each BS with faster convergence. TL is also utilized in [251], [252] for resource allocation in wireless VR networks, which are discussed later in Section XI.

D. Other Learning Models

Authors in [232] and [235] proposed echo-liquid state deep learning models for wireless VR networks, where the first paper considered a UAV-enabled cellular network and the second one investigated a combined network of UAVs and Wi-Fi APs (WAPs). In the proposed VR network of [232], UAVs collect the requested contents, which are then transmitted to cache-enabled SBSs for serving the requesting VR users. Proposed deep learning model integrates both the LSM spiking neural networks and the echo state networks (ESNs) for optimizing the transmission and caching strategies by predicting the reliability of VR users. The framework exploits historical relationship between the user reliability, caching, and content transmission format, and has lower training complexity. Such ML framework of ESNs was also investigated in [253], [254] for solving a resource management problem (jointly optimized the uplink and the downlink spectrum) in SBS-based VR network. On the other hand, a LSTM auto-encoder is used [250] for effectively utilizing the caching and computing resources of a wireless VR network. In particular, a LSTM auto-encoder deep deterministic policy gradient (LSTMAE-DDPG) algorithm is developed for solving a multi-objective optimization problem revealing the energy-latency tradeoff.

TABLE V: Use of ML in wireless VR networks

Reference	Focus of the Paper	Network Model	ML Model/Algorithm	Implementation Node
[90]	Maximizing the total users' QoE under MTP latency constraints	Cellular network with MEC at BSs	RNN model with GRU architecture is integrated with proximal policy optimization (PPO)	Each MEC server
[103]	Minimizing the system latency/energy consumption	Single-user system with a MEC-enabled single SBS	DDPG algorithm using a multi-layer LSTM neural network	The MEC server
[112]	Maximizing the quality of the delivered VR videos with low-latency	mmWave SBS network in a theatre, where each SBS with multiple spatially orthogonal beams	Deep RNN (DRNN) with GRU architecture	Network edge
[148], [186]	Maximizing the sum successful transmission probability of all VR users	THz/VLC wireless networks with SBSs and VLC access points (VAPs)	Policy gradient-based RL algorithm using meta-learning framework	A central controller
[130], [182]	Maximizing the long-term QoE of VR users under the VR interaction latency constraint	Cellular network with MECs	RNN model using GRU architecture to predict FoV, and DRL strategies based on DQN and AC algorithms for maximizing QoE	Central coordinator (centralized schemes) and MECs (distributed schemes)
[185]	Allocating resources adaptively based on the requirements of FoV rendering, block consensus, and content transmission	VR-enabled medical system with MEC-assisted APs	CRL-based quantum inspired actor-critic (AC) algorithm	Each AP
[187]	Minimizing the video quality loss ratio subject to the latency constraint	Cellular network with MEC at BSs	Constrained DRL algorithm	MEC server at each BS
[151]	Minimizing the long-term averaged energy consumption of an HMD	THz cellular network with MEC	DRL A3C algorithm	Each MEC server
[218]	Developing transmission mode selection to improve the performance of edge users and resource utilization	D2D assisted 5G networks with macrocell BS and mmWave BS	Online multi-agent RL strategy	Each user device
[226]	Maximizing the QoE of users	mmWave/ sub-6 GHz based cellular network with MEC	DRL and game theory	User devices
[232], [235]	Satisfying the instantaneous transmission delay target of each user	Cellular network with UAVs	Echo-liquid state deep learning	SBSs
[237]	Reducing VR transmission delay	Satellite assisted THz wireless network for indoor	Q-learning RL	Satellite gateway
[244]	Developing a novel VR single-view image transmission scheme	A single BS with multiple VR users with a server	FL-based based generative adversarial network (GAN)	The server

[245]	Jointly optimizing the channel access arrangement and transmission powers for the downlink communications	Indoor network with one AP, multiple users and a server	DRL-based UCHA algorithm	The server
[246]	Optimizing buffer state state in VR devices for enhancing QoE	Cellular network with MEC at each BS	DRL-based MADDPG algorithm	Each MEC server
[247]	Maximizing the users' successful transmission probability	Cellular network	Liquid state machine (LSM) based transfer learning (TL)	Each BS
[248]	Deriving user association policy for minimizing BIPs	Cellular network	FL for deep ESN	BSs
[249]	Minimizing the occurrence of BIP that detach users from VR world	Cellular networks with both sub-GHz and mmWave links	Distributed FL-based deep ESNs	BSs
[250]	Minimizing system energy consumption and the latency as well as to investigating tradeoff between them	SBS-based cellular network with MEC	LSTMAE-DDPG algorithm	Each MEC server
[251], [252]	Optimizing resource (spectrum and computing resources) allocation in both uplink and downlink	SBS-based cellular VR networks	ESN TL-based ML model	Each SBS
[255]	Optimizing energy and latency	Reconfigurable intelligent surface (RIS)-assisted SBS-based indoor wireless network	ML-based multi-objective soft actor-critic (MO-SAC) algorithm	A central controller
[253], [254]	Jointly optimizing the uplink and the downlink spectrum allocation	SBS-based cellular networks	ESN-based ML algorithm	Each SBS
[256]	Predicting viewpoint of the VR user using real VR dataset	An SBS with fiber connection to core network	Linear regression (LR), neural network (NN) and LSTM/GRU algorithms	The SBS
[257]	Designing energy-aware resource management scheme	Wireless VR supported industrial IoT (IIoT) network	Quantum parallelism integrated RL (QRL) online algorithm	Edge-computing assisted APs (EAPs)

X. Latency and Energy Consumption in Wireless VR Networks

Latency and energy consumption is wireless VR systems are two of the most crucial performance indicators which are highly inter-related. recent research on the latency, energy efficiency and their tradeoffs are thoroughly discussed in this section.

A. Latency Reductions

Latency is a vital performance metrics for delivering truly immersive experience for the wireless VR users [111]. However, the requirement of large volume of data as well as the user mobility make it even more challenging to manage VR latency within the acceptable limits. Therefore, a large number of researchers are working on the reduction of latency in VR services [100], [112], [231], [234], [237], [238], [255], [258]. Various directions including architectural enhancements, caching at the edges with adaptive features, flexible rendering location selection, adaptive FoV selection for rendering, task scheduling and ML techniques are investigated to improve the latency performance of wireless VR systems.

A novel transmission scheme, where only the non-overlapped tiles are transmitted in the successive requests of users in a cellular wireless VR system was proposed in [100]. The scheme exploited the fact that successive FoVs have some overlapping tiles, which are not required to be transmitted as those overlapping tiles are already available in the cache of the MECs or user devices. Selection of rendering location and spectrum allocation strategy are also proposed for minimizing the latency. Thus, the system involves substantially reduced downlink data transmission leading to much improved latency performance. Authors in [112] exploited the correlations between the predicted FoV and the locations of users for mitigating the latency and optimizing video quality in a mmWave-based multi-user multicast wireless VR transmission. Users are associated to the mmWave SBSs for unicast or multicast transmission using a matching game theory. A real VR head-tracking dataset and a DRNN based on GRUs architecture are utilized for predicting FoVs and evaluating the system performance.

Latency minimization problem of a VR social network over cellular systems was investigated in [258]. A strategy for allocating uplink spectrum for VR users considering the virtual and physical locations of users and the edge servers is proposed for minimizing latency. A work proposing LEO satellites for outdoor communications and fiber linked THz femtocells connected with the satellite gateway for indoor communications was presented in [237], which proposed a joint user association and serving order strategy for reducing latency. The joint problem is solved by using convex optimization for suboptimal solution and by using Q-learning based RL technique for optimal solution demonstrating a significant reduction in latency. Caching schemes for reducing latency in VR cellular networks with view-port rendering at the MEC servers were also presented and investigated in [101], [259].

Authors in [234] also optimized latency of a UAV-enabled VR network, where the UAVs works as BSs and serve the VR users from a VR cloud. UAVs have the caching and computing facilities. Association of users with UAVs, caching policy and computing-capacity allocation are jointly considered for minimizing the maximum latency. The formulated non-convex problem is solved by using alternating optimization and successive convex approximation techniques demonstrating the effectiveness in reducing latency. A work on the the improvement of motion feedback latency in the uplink of a IEEE 802.11 WLAN based wireless VR network was presented in [238]. Three distinct strategies, namely, prioritizing aged motion data, using reverse direction and limiting the aggregation size of downlink transmission, are proposed and investigated the impacts of each of them separately as well as the joint application of them. The effectiveness of the combined application of all these three strategies in reducing motion feedback latency and its jitter is demonstrated through simulations.

B. Energy Efficiency

High energy consumption in wireless VR networks due to the transmission of large volume of data at extremely high speed is a huge challenge. Improving energy efficiency of network entities including VR user devices (e.g., HMDs) and MEC/fog/cloud servers is thus crucial [151], [156], [231], [257]. Authors in [151] proposed a framework for minimizing the long-term energy consumption of HMDs in a MEC-enabled THz cellular network. Viewport rendering offloading and downlink transmit power control of MECs under time-varying wireless channel are jointly optimized for the objective. The optimization problem is solved using an A3C-based algorithm, which utilizes multi-agent DRL networks for learning the optimal viewport rendering offloading and transmit power control policies for configuring the cellular network leading to minimum energy consumption in HMDs. On the other hand, an optimal wireless multi-quality VR video streaming scheme in a MIMO orthogonal frequency division multiple access (OFDMA) system with the objective to minimize transmission power of BSs was designed in [156]. Optimization problems are formulated and solved for both with and without user transcoding scenarios. The system jointly optimized the VR quality level selection, beamforming and subcarrier allocation, transmission power and rate allocation. A globally optimal solution for small multicast groups, an asymptotically optimal solution for a large antenna array and a low-complexity suboptimal solution for the general case are derived for both the above scenarios demonstrating the effectiveness of the proposed scheme. Authors in [257] also proposed a scheme for minimizing energy consumption in VR equipments in an IIoT system by jointly optimizing the viewport rendering offloading, computing and resource allocation. The optimization problem is first transformed to a Markov decision process and then, an RL-based online algorithm with quantum parallelism is proposed for learning the optimal policy.

C. Trade-off between Latency and Energy Efficiency

As energy consumption in VR networks and latency are highly correlated, there is a growing trend on the research of investigating the trade-off between these two crucial performance metrics [103], [231], [250], [255], [260].

A UAV-enabled wireless VR network for supporting low-latency delivery of on-demand VR contents was investigated in [231]. An average latency minimization problem with a constraint on the energy consumption in UAVs is formulated and solved using an iterative algorithm by transforming the problem into three subproblems - trajectory design subproblem, processing frequency allocation subproblem and transmission power control subproblem of UAVs. Efficient trade-off between the average latency and energy consumption in UAVs is illustrated through simulations. Another investigation on the trade-off of latency and energy usage of VR devices in a RIS-assisted indoor VR network was presented in [255]. A meta-learning-based multi-objective soft actor-critic (MO-SAC) RL algorithm is proposed. The algorithm assigns dynamic weights to the objectives during training for making the trained model fast adaptive to new tasks leading to balance between latency and energy consumption in VR devices.

Furthermore, a hybrid policy learning framework was developed for minimizing system latency and energy consumption as well as investigating the energy-latency trade-off of a MEC-enabled SBS-based wireless VR system as presented in [103]. The energy that is minimized is defined as the sum of the transmission energy from SBSs to VR devices, computation energy of the MEC server and the computation energy of the VR devices. A hybrid policy incorporating the caching and computing capacities of both the MEC server and the VR devices for coordinating the dynamic caching replacement and the deterministic offloading is developed. The optimization problem is solved using an iterative deep deterministic policy gradient algorithm, which utilizes a LSTM neural network to learn the optimal policy. Another work on LSTM-based learning strategy powered energy-latency tradeoff was presented in [250]. A service chaining graph (SCG)-based mechanism for achieving latency-energy trade-off in a MEC-based wireless VR network was proposed in [260]. The proposal splits each VR application into atomic services comprising a chain and then deploys them across HMDs and MEC servers according to an optimization problem for jointly minimizing latency and energy consumption and achieving the trade-off. The developed policy is claimed to achieve a good balance between average latency and energy consumption in HMDs by migrating services between MEC servers and HMDs.

XI. Resource Allocations in Wireless VR

Radio resource allocation in wireless VR network is extremely crucial for optimizing streaming performance under various constraints [132], [235], [251]–[254], [261]–[264]. In addition, given the processing requirements of VR videos and the evolved network architectures with the facilities of cloud/fog/edge computing and virtual machines (VMs), scheduling computing and caching resource have added new dimensions to the resource allocation problem [132], [251], [252], [257], [265]–[269].

All the works in [235], [253], [254] jointly optimized the uplink and the downlink radio resource (i.e., spectrum) allocation in VR wireless networks for improving QoE metrics. In particular, [253], [254] considered SBS-based cellular systems, while [235] deployed a combination of UAVs and Wi-Fi APs (WAPs) as the wireless VR networks. However, all these works formulated the resource allocation as non-cooperative games and solved using ESN-based ML algorithms. Works in [251], [252] exploited the time-varying spatial correlation among the data requested or transmitted by different VR users for proposing resource management schemes for efficient management of both uplink and downlink traffic in SBS-based cellular VR networks. Resource block (i.e., spectrum) is managed in [251] for maximizing the successful transmission probability of user data, while both computation and spectrum resources are jointly optimized in [252] for improving delay performance. Both the schemes utilized ESN TL-based ML models.

A cross-frame based context-aware spectrum allocation technique considering both the QoE contribution of each individual tiles within the predicted viewport and the viewport prediction error in a cellular VR network was presented in [261]. The scheme preferably allocates resources for the tiles with the significant QoE contribution leading to improved QoE and reduced resource wastage. Whereas, an uplink spectrum allocation mechanism by jointly considering the quality of content distribution of each tile and the wireless channel quality was investigated in [262]. The resource allocation problem was formulated as a frequency and time dependent non-deterministic polynomial (NP)-hard problem, which was then solved using three different algorithms. On the other hand, a bandwidth allocation convex problem for the downlink of a cellular VR network with edge computing was developed and solved in [263] using Karush-Kuhn-Tucker (KKT) conditions for minimizing the maximum user transmission and computation delay. Furthermore, [264] utilized a stochastic game approach for developing a downlink spectrum allocation scheme in small cell VR networks. The goal of the scheme was to maximize system-wide mean opinion score (MOS), which was solved by a distributed multi-agent learning algorithm.

On the other hand, a resource allocation scheme in a cellular network based multi-player interactive VR game system for optimizing MEC server computing resource allocation and spectrum allocation to minimize inter-player delay was proposed in [132]. The formulated problem is nonconvex, which was then solved using an iterative algorithm based on the nonconvex primal-dual splitting (NESTT) algorithm. For a similar network architecture with MEC designed for IIoT, another resource management framework for jointly allocating viewport rendering offloading, computing and spectrum resources was proposed in [257]. This work transformed the original resource management problem into a Markov decision process (MDP) by applying dual approximation and then, an RL-based online learning algorithm was developed for finding the optimal policy. Whereas, two other resource allocation works by jointly considering caching, computing and spectrum allocation in a MEC-enabled cellular VR network were presented in [265], [267]. The objective of the work in [265] is to support seamless VR video to the handoff users, while [267] minimized content delivery latency.

XII. Blockchain for Wireless VR

Data security has always been a critical issue for all sorts of networking applications, which has become even more vital in recent days due to the increasing amount of sensitive data and applications. Blockchain, also known as distributed ledger, is a decentralized powerful technology to provide strong data integrity and reliability in untrusted environments like wireless communications. The immutability of each completed transaction in blockchain combined with the availability of the information to every involved party has made it a highly promising solution for facilitating enhanced security, reliability and transparency of information processing in VR applications [29], [197], [270]. Consequently, blockchain technology has drawn tremendous attention of both the research communities and the industries from diverse fields including financial sectors (e.g., digital currency and insurance), supply-chain management, smart cities, healthcare, IoT and cellular networks [29], [197].

However, there is not much research work on the blockchain-enabled wireless VR systems. A work on the integration of blockchain for security in wireless VR network for medical treatment was proposed in [185]. Here, the edge access points (EAPs) works as the blockchain nodes for reaching a consensus of the global information of task offloading to the EAPs and data processing and thus blockchain can resist malicious attacks. The computation offloading and resource allocation problems are modeled as a Markov decision problem. Then, a novel AC-based CRL algorithm is developed for adaptively allocating resources based on the system requirements including viewport rendering, block consensus and content transmission. The investigation identified an increase in energy consumption due to the integration of blockchain in the system, while blockchain ensures security and privacy which is vital for medical data. On the other hand, an architecture using permissioned blockchain-enabled information-centric mIoT (IC-mIoT) for 6G large-scale VR/AR applications was proposed in [167]. A new consensus mechanism named as proof-of-cache-offloading (PoCO) was also developed for the blockchain system. The blockchain was integrated to secure the system by recording the transactions and collaboration contracts in IC-mIoT, including VR/AR content trading and resource transactions (computing, storage, graphics, communication) between network nodes and IoT. Furthermore, the works in [196] has explored the opportunities of integrating blockchain in 6G. This paper also discussed the corresponding challenges and future research directions recommending the requirement of common formats for communication protocols and globally structured standards.

XIII. FoV Prediction and Rendering Schemes for Wireless VR

As the FoV of human eye is limited, users can watch only a small portion of the VR frame at any moment. Thus, it is not essential to transmit the entire VR frame, which can readily exploited for reducing the data rate demand for VR applications. One such approach is where UE tracks the HMD position and posture in real-time for determining the necessary tiles for rendering the viewport. Then the UE sends the FoV request to the VR server. The server can then route the requested FoV to the user device. If the requested FoV moves out the region of current tiles, the UE will then send a new viewport request. One step further, if the FoV can be predicted in advance, that information can be leveraged for improving the QoE performcne, especially the MTP latency can be reduced significantly [90], [182], [271].

Learning-based data-driven FoV prediction for MEC-enabled wireless VR network is a popular research stream [90], [182], [256], [259], [271]. For instance, FoV prediction scheme is employed for proactive caching decision in MEC-enabled cellular VR networks [259]. The FoV prediction is performed in the MEC server using the saliency map generated by the cloud server and the sensory data from the user. The cloud server generates the saliency map by employing a 3D convolutional neural network (CNN) + LSTM + Gaussian mixture model (GMM) multilayer network. A thorough investigation on the impact of FoV prediction accuracy on system parameters including E2E latency was presented. In [182], FoV of each VR user was predicted in real-time by using RNN-based on GRU architecture, while the rendering is moved from VR device to MEC server. Then, both centralized and distributed type DRL algorithms, based on DQN and AC, were proposed by jointly considering the geographical and FoV request correlation for maximizing the long-term QoE of users under the VR interaction latency constraint. Depending on the predicted FoV, rendering is done either at MEC or at VR user devices.

On the other hand, both offline and online learning algorithms were proposed in [256], [271] for FoV prediction, where the prediction is based on the prediction of pitch, yaw and roll. Three offline algorithms are proposed, namely by deploying n-order linear regression (LR), neural network (NN) and RNN based on the LSTM/GRU architecture. The online algorithm is executed at the SBS, which is appropriate for the dynamically changing environment, implements uplink retransmissions to counteract the transmission failure due to the unpredictable wireless channel into account. In both cases, the SBS renders the predicted FoV and send it to the VR user in the downlink in advance.

Authos in [90] utilized FoV prediction for avoiding rendering of overlapped tiles in consecutive FoVs in a MEC-enabled VR network. Thus the system reduced the burden on the computing resources of edge nodes and improves MTP delay performance. A RNN model with GRU architecture located in the cloud server was proposed for FoV prediction from the historical FoV information of users. Rendering was performed either at the VR device or at the MECs located at the BSs with the provision of rendering a single tile at multiple MECs simultaneously.

FoV prediction for optimizing caching and computing decisions at MEC servers located at SBSs were proposed in [250], [272]. For the FoV prediction, an autoregressive moving-average (ARMA) model was utilized in [272], while the work in [250] deployed a LSTM auto-encoder (LSTM-AE) based FoV predictor. Furthermore, based on the head and gaze movement information of a user provided by the HMD, a support vector regression based technique was used for predicting the FoV and the attention of the user in [273]. This prediction was then utilized for scheduling VR content for meeting the bandwidth and QoE constraints, and computing resource requirements.

XIV. Caching Strategies in Wireless VR

Proper caching scheme in wireless VR networks can create great difference in user experience. A Cache management scheme mainly focus on three issues - what to cache (the content), where to cache (specific node or the layer in a hierarchical architecture) and how to cache (the update scheme of content).

View synthesis-based hierarchical collaborative caching schemes for C-RAN based cellular VR networks were proposed in [102], [219]. View synthesis is a feature of multi-view video, which can generate free-viewpoint video from a limited number of views. Proposed caching strategies were designed to cache VR content either in the MEC-cache server deployed in the BBU pool or in the RRHs with the objective to minimize transmission latency. The authors also proposed a a low-complexity MaxMinDistance online algorithm for the caching scheme. Another collaborative caching scheme was proposed in [274], where macrocell BSs (MBSs) and SBSs in a heterogeneous cellular network collaborate to cache VR contents. Considering the limited storage capacity of the MEC server installed at MBSs, popularity of a content is calculated which is then used to make the decision of caching at MBSs. While, an utility based caching scheme was proposed for the SBSs, which is used to decide the portion of the content to be cached at an SBS.

A rendering-aware tile caching scheme for a multi-cell MEC-enabled VR network to minimize E2E latency was presented in [101]. In this system, caches are deployed at the cell sites and multiple cells cooperatively share cache to reduce the redundant data in the network and the rendering is performed at the MEC servers. A tile popularity prediction model by fusing the tile saliency and the VR video popularity was integrated to decide which tiles to be cached. A proactive caching scheme for similar cellular VR networks was investigated in [259]. Caching at MEC servers is decided based on the FoV prediction, while VR data are processed and stored in advance in the cloud server. The FoV prediction is also done by the MEC server using the saliency map from the cloud server and the sensory data from the user. Another proactive caching-enabled mmWave SBS-based VR network for indoor applications was presented in [275], where the SBSs are connected to a cloud server with MEC and caching facility. Most popular viewports are cached, which is determined by the spatial popularity profiles.

On the other hand, a transcoding-enabled edge cooperative caching scheme based on multi-agent RL for two-tier heterogeneous cellular network was introduced in [129] to improve the utilization efficiency of computing and storage resources, and then reduce service delay. Here, edge MBS and SBSs collaboratively decide to make the caching decision, which was formulated as a networked multi-agent MDP, which is then solved using multi-agent AC algorithm. Transcoding was integrated for converting the cached content to a lower bit rate enabling more users to be served.

A pre-caching strategy for D2D-assisted VR video distribution was proposed in [217]. The decision by a user to cache VR videos to a node is determined by observing the user residence time at a given node, which also takes the popularity of a node, available storage space and the energy of the user device into account. Although most papers proposed caching at edge devices, authors in [276] explored the opportunity of caching at the HMD devices. A cache management strategy termed as maximum QoE increase (MQI) for cellular network with coding helper serving VR HTTP adaptive streaming (HAS) was proposed in [277]. The coding helper has storage capacity for caching as well as video coding functionality to encode VR video into different rates. A scheduling algorithm is proposed for the coding helper to decide when to serve users from its own cache and when to download VR video from the server through the BS.

XV. MAC for Wireless VR

Media access control (MAC) protocol plays a vital role for satisfying the QoE requirements of wireless VR services. However, only a handful number of works on wireless VR MAC protocol exists [278]–[280]. For satisfactory QoE of users, VR video streaming must support three ultra-high requirements - ultra-high data rate, ultra-high responsive speed and ultra-high transfer reliability [278]. Thus, the traditional MAC scheduling protocols optimizing sum-capacity of all served users while maintaining their proportional fairness are not appropriate for wireless VR. In light of this, authors in [278] defined delay-capacity utility (DCU) for each user and then proposed a recursive multi-user MAC scheduling mechanism for maximizing the aggregate DCU of VR users in 5G MIMO-OFDM networks. The MAC scheme also incorporated video frame differentiation, delay-based weight calculation of each user and a novel link adaptation with dynamic block-error-rate (BLER) target. Proposed MAC protocol was found to achieve 31.6% increase in the number of simultaneously served VR users.

On the other hand, a multi-beam MAC scheme for uplink VR services with mmWave analog beamforming was investigated in [280]. Proposed scheme composed of two iteratively executed functions - a beamforming function and a frequency-division user scheduling scheme. Thus, it can generate the required number of beams with flexible beam directions, beam widths and beamforming gain ratios leading to increased number of served users. Furthermore, a modified MAC protocol for a scenario of short-range VR services between AR/VR wearable terminal and smart phones was presented in [279]. The MAC protocol is designed to support ultra-high speed, low power and low latency characteristics, which is achieved by designing a new frame structure and frame reading scheme. Performance of the proposed protocol is evaluated using simulations as well as by implementing through an FPGA platform.

XVI. Future Research Directions

As a paradigm shifting remarkable technology, VR service over wireless networks is now at the center of interests of telecommunication industries, mobile network operators and researchers. While the realm of VR research has witnessed a substantial surge in scholarly publications, the domain of supporting VR services over wireless networks remains nascent. Given the demanding QoE standards upheld by VR videos, groundbreaking innovations from diverse angles are imperative for the widespread and triumphant implementation of wireless VR applications. Crucially, conducting experimental research to unravel the tangible hurdles on the journey to delivering immersive and uninterrupted VR services is paramount. Delving into the practical challenges is instrumental. Below, we explore several avenues in the research landscape aimed at advancing wireless VR services.

A. THz Wireless Channel Modeling

As per various studies, wireless VR will most likely employ THz wireless communications, which has not been used in the past for such telecommunications. Thus, it is important to quantify the achievable latency, reliability, data rate and coverage range of THz links for VR services. On top of the traditional other issues of wireless links such as shadowing, small-scale fading and line-of-sight (LOS)/non-LOS (NLOS) path availability, THz communications brings new wireless link impairments, mainly molecular absorption loss and molecular absorption noise, which were not significant in sub-6GHz and mmWave channels. Thus, modeling the propagation characteristics of wireless THz links encompassing all these parameters under different mobility scenarios and network environments is extremely crucial for realistic analysis of wireless VR systems. These channel models will assist in determining the appropriate THz frequencies and channel bandwidth requirements, and network coverage planning for supporting the immersive experience of wireless VR.

B. Wireless Channel Impact

Investigating the impact of wireless channels on the performance of newly designed wireless VR schemes is a crucial area of research. However, there exists a huge research gap in this regard as most of the current works have assumed perfect communications. Understanding and quantifying the impact of wireless channels on various issues including latency, data rate and reliability of VR services is of profound importance. Optimal allocation of radio resources and computing resources among multiple users acting in a common VR space by taking into the loss of data due to wireless channel instability is essential. Design of adaptive streaming algorithms that can dynamically adjust the quality of VR content based on the characteristics of the wireless channel is also an open research issue.

C. User Mobility

The distinctive advantage of wireless VR lies in its mobility, allowing users to move within physical spaces while immersed in virtual environments. However, this mobility introduces numerous challenges, particularly in meeting the demanding QoE standards of VR services. Achieving a seamless user experience requires effective mobility management (e.g., handover management) to enable users' real-time movements without lag, buffering, or disruptions. Mobility brings dynamic changes to network conditions and wireless channels, posing significant hurdles in maintaining the essential QoE. In the context of wireless VR, mobility management must not only address these challenges but also optimize network resources and conserve energy in mobile devices. Additionally, VR applications utilize diverse wireless technologies like cellular networks (including 5G and beyond), WLAN, non-terrestrial networks, and OWC. Mobility management protocols play a critical role in ensuring smooth transitions between these technologies, allowing users to switch networks seamlessly and enhancing the mobility aspect of VR experiences. Despite its vital importance, the consideration of mobility in wireless VR system research and analysis remains notably scarce in the existing literature. This gap underscores the urgent need for extensive attention and exploration from the research community.

D. Energy Efficiency

Due to the transmission of large of volume of data, VR services are energy hungry, especially they put tremendous pressure on the energy consumption issue in VR user devices. High-quality VR experiences demand substantial processing power and constant communication with servers or other devices, putting a strain on batteries, which is even a greater issue for mobile VR devices. Optimizing the network and protocols designs for energy efficiency is thus vital for wireless VR networks. Although, there are some works on the energy efficiency as well as on energy-latency tradeoffs, extensive research in developing energy efficient network architectures, protocols and algorithms is required for minimizing the energy consumption of wireless communication modules, without compromising the immersive quality of VR content. This research will not only extend the usage time of VR devices, but will also contribute significantly to the overall sustainability of wireless VR technologies, making them more accessible and eco-friendly for users worldwide.

E. Security of Wireless VR

Data transmitted over wireless network is always more vulnerable and thus, ensuring the security of user data to protect against unauthorized access and data breaches is crucial. People are expected to adapt quickly to VR services for interacting with other people in virtual space, where privacy preservation poses unique challenges. For example, the way a user interacts with the surrounding environment is also a critical information itself, whereas FoV rendering also contains key information of VR users. If privacy of data cannot be ensured, individuals will not find confidence in using VR services. VR services deals with large amount of data with ultra low latency. Ensuring privacy for such huge volume of data at a super high speed is a mammoth task. There have been several works on the security and privacy of VR services [30]. Integration of blockchain for the security of VR services has also been investigated in several papers [197], [198]. However, these works have not considered the impact of wireless communications (e.g., lose of packets due to poor signal quality) in designing these security techniques. Not only that, utilization of blockchain in wireless VR services put extra burden on the ultra high data rate and ultra low latency requirements, and in turn to the effectiveness of blockchain-enabled security techniques. Thus, novel research initiatives are indispensable for developing privacy and security techniques for wireless VR services, while supporting QoE requirements.

F. Edge Computing and Caching

Designing effective caching schemes, determining the appropriate caching size, and implementing efficient cache management techniques pose significant challenges in harnessing the potential of edge computing. As the volume of VR videos is significantly large, which is increasingly becoming hungrier for storage, caching scheme is extremely vital for wireless VR. A proficient cache management strategy, when implemented, holds the potential to substantially decrease data transmission over wireless networks. Also, the unpredictable nature of the wireless channels can cause the loss FoV request packets and data packets as well. Caching schemes have to be robust against such packets losses. Also, because of the dense deployments of 5G and beyond networks, the capital and operational expenditures for cache devices can be exceptionally high. Consequently, the strategic placement of caching and computing resources for wireless VR systems remains an active area of research, necessitating innovative solutions.

G. Standardization and Interoperability

Numerous types of VR services with diverse QoE requirements are possible, some of which we don't even know now. On the other hand, VR services will be delivered to the end users over various types of heterogeneous networks having different architectures, RF spectrum, available channel bandwidth, user association policies, MAC protocols, traffic management policies and so on. VR users can even switch from one network type to another network type, e.g., from cellular to Wi-Fi and vice-versa, during the same VR session. On the other hand, heterogeneous end user devices varying in technical capabilities will also be used by the VR subscribers. Interoperability of heterogeneous systems for seamless VR user experience is a fundamental issue in such scenarios. Therefore, research should also focus on developing protocols and standards for VR data transmission over wireless networks to ensure compatibility and interoperability between different networks, devices and platforms.

H. Traffic Management

Traffic management in wireless VR networks is another major issue which has largely been ignored so far by the research community. Optimizing network resources including spectrum, APs and computing facilities to prioritize VR traffic for ensuring a consistent QoS for VR applications even in crowded network environments is vital for satisfying the users. Load balancing by distributing the VR processing tasks across the servers and devices of different hierarchical levels to prevent bottlenecks and maintain high performance should also be addressed. Tempo-spatial correlation of users' requests of VR services can also be exploited for load balancing across the wireless VR networks.

I. Media Access Control (MAC)

MAC protocols designed to support multiple VR users are pivotal in efficiently managing radio and computing resources for wireless VR services. These protocols are essential to meet the ultra-high demands of VR applications, including unparalleled data rates, lightning-fast responsiveness, and unmatched transfer reliability. Conventional MAC protocols that focus on optimizing the total capacity of all users with proportional fairness are inadequate for the complexities of wireless VR. VR services will be delivered across diverse wireless technologies. Often, these heterogeneous networking technologies will be deployed jointly for serving VR users. Additionally, the integration of cloud, fog, and edge computing introduces unique challenges, demanding meticulous scheduling of computing resources to ensure user satisfaction. Given these intricate requirements and diverse technological landscapes, MAC protocols must be meticulously crafted to guarantee the QoE for wireless VR users. These protocols should address the temporal, frequency and spatial dimensions as well as inter-user correlations. It is imperative to recognize that these cutting-edge MAC protocols are not just essential but indispensable in the realm of wireless VR services. Performance of wireless VR networks using the existing MAC techniques such as NOMA and OAM multiplexing should be explored under various network settings. Besides, considerable attention is required to develop and explore new generation multiplexing technologies. However, there is so far no significant research conducted on the development of MAC protocols for wireless VR services.

J. Leveraging ML

The power of ML is endless, which has to be explored for designing wireless VR systems. A growing number of research articles integrating various DNN based ML models for addressing different technical hurdles of wireless VR systems is being published. Addressed technical issues include mainly FoV prediction, mobility prediction of VR users and resource allocation for meeting QoE, which demand substantial investigations for diverse network environments and user requirements. Additionally, there is a need to delve into learning the future patterns of VR video requests, leveraging the temporal and spatial correlations of VR user locations and their demands, and predicting the eye and body movements of users for efficient delivery of VR services. Additionally, predicting the next AP for efficient handover management and forecasting wireless network behavior for adaptive streaming using ML models can significantly enhance VR experience and streamline network management for operators. Notably, a trend is observed in favor of employing conventional DNN models in published works. Researchers must think innovatively to devise new ML models tailored to the unique characteristics of wireless VR services, distinct from traditional video formats.

K. Application Specific Designs

Application-specific wireless network design including architectures and protocols is essential for wireless VR services due to the unique and demanding requirements of VR applications. Different VR applications may have varying QoE requirements. For instance, a multiplayer VR game might prioritize low latency and minimal packet loss, while a VR telemedicine application might prioritize reliability and security. Designing the network with QoE in mind ensures that these specific requirements are met, optimizing the performance of the VR service. Thus, tailoring the wireless network design to the specific needs of VR applications is crucial, which has not been the approach of existing research in wireless VR.

L. Quantum Communications

Emerging technologies such as the quantum computations and quantum communications have the potential to be the game changers for providing wireless VR system with stringent QoE demand. However, these technologies have not been explored yet for leveraging VR services over wireless networks. Thus, research on these areas can be the next frontier, which can unleash a number of frontiers for solving all the challenges towards enabling truly immersive VR services over wireless networks meeting the latency, data rate and reliability requirements.

XVII. Conclusions

Emerging VR technology is rapidly evolving, promising significant transformations in communications, service delivery, engineering designs, task execution, and daily life. Presently, VR services mainly operate offline, restricting our ability to fully explore its vast potential across various domains. Specifically, wireless VR services hold the key to unlocking its true capabilities, yet current wireless technologies fall short in supporting high-quality applications with satisfactory user experience. Extensive research is crucial to tackle these technical challenges and enhance the quality of wireless VR services. This survey paper has comprehensively explored all the technical issues of VR over wireless networks, covering the fundamental VR theory, its applications, VR content creation and processing methods, wireless VR system performance metrics, spectrum requirements, network architectures, and the key enabling technologies. It also has reviewed and summarized all the available research on wireless VR, and provided valuable insights into future research directions. Thus, this survey paper will serve as an excellent starting point for the researchers working in wireless VR systems.

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