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SURVEY

When Holographic Communication Meets Metaverse: Applications, Challenges, and Future Trends

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ABSTRACT Holographic communication represents a transformative technology for reshaping the digital interaction landscape by enabling the creation of realistic, immersive, and interactive 3D experiences. This survey overviews holographic communication and its integration with the Metaverse technologies' concepts, advantages, uses, and many applications. Furthermore, we examine a new paradigm for integrating holographic communication with the Metaverse, emphasizing how holography enhances immersive quality of virtual environments within the Metaverse, making interactions more lifelike and engaging. Extending the integration of holographic communication and Metaverse, we examine this combination's numerous uses in various applications across various industries, such as education where virtual classrooms and 3D simulations redefine remote learning, a business where virtual meetings and product demonstrations create more impactful customer engagements, entertainment where immersive gaming and 3D broadcasting transform user experiences, healthcare where remote consultations and surgical simulations enhance medical training and accessibility, and remote assistance where real-time holographic support improves technical troubleshooting. In addition, we discuss the challenges and prospects of integration of holographic communication into Metaverse ecosystems, emphasizing key approaches and technical developments emerging technologies such as AI-driven content optimization, advanced coding and compression techniques, and new paradigms like terahertz communication and quantum holography. This survey highlights the revolutionary potential of holographic communication and offers insightful information on how it will influence digital engagement and connectivity in the future, eventually opening up new avenues in the quickly changing Metaverse landscape.

INDEX TERMS Extended reality, digital interaction, immersive communications, holographic communication, Metaverse, connectivity, virtual environments, interaction, immersive experiences.

I. INTRODUCTION

The Metaverse is a significant force in the transformation of digital communication, entertainment, trade, and social interactions. It signifies a paradigm change toward persistent, networked virtual worlds where users may create, communicate, and work together in ways that were not previously possible due to physical limitations [1], [2]. Major firms are significantly investing in the creation of the Metaverse as interest in it grows, realizing that it has the potential to transform online engagement and human computer interaction [3]. In light of this, immersive technology such as holographic communication has become vital for augmenting the Metaverse experience. Holographic communication is a sophisticated type of multimedia interaction, that makes use of holographic displays to produce realistic, interactive 3D projections [1]. Holographic communication provides users with multimodal experiences that conflate the real

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and virtual worlds, allowing for hitherto unheard-of levels of engagement and immersion [4], [5]. The Metaverse ecosystem has seen a faster uptake of holographic communication due to advancements in both hardware and software. The technologies foster innovation in industries including healthcare, education, entertainment, and beyond by enabling people to engage with virtual information in more natural and intuitive ways [2], [3], [6]. Holographic communication meets the Metaverse has the potential to revolutionize digital commerce experiences, change conventional learning approaches, and improve distant collaboration [7].

Holographic communication represents a revolutionary multimedia technology that surpasses conventional audio-visual experiences by harnessing holographic displays to create lifelike 3D projections [8]. Holographic communication allows users to engage with virtual material in three dimensions, providing a more natural and intuitive experience than traditional multimedia, which is dependent on flat displays and stereo sound [9]. To recreate things as lifelike 3D projections, this technology uses holographic data transmission and display to capture spatial and light field information [10]. Users feel more immersed and more present in virtual worlds when they can see textures, depth, and parallax [11]. In addition, holographic communication allows for real-time interactions with avatars and virtual objects, enabling natural motions and behaviours that mimic interactions with real-world counterparts [5]. Holographic communication is a revolutionary technology with a wide range of applications in entertainment, healthcare, education, and other fields because it provides spatial awareness, natural interaction, and increased engagement above traditional multimedia [12], [13].

Based on visible-to-the-unaided eye holographic technology, the holographic communication service is an all-inclusive application solution that can manage any part of multi-dimensional, immersive interactive sceneries. It provides a natural and immersive type of engagement, covering the whole process from data acquisition to multi-dimensional sensory information restoration. Holographic communication architecture aims to make information flow between communicating parties more appealing, practical, and effective. To do this, capturing sensors continually track the motions of the face and body while using formatting and filtering methods to lower network bandwidth usage during data encoding. The compressed hologram that is produced is then sent to digital holographic devices via a dependable, low-latency network, like 6G. The digital holographic device receives the compressed hologram and processes it to make it ready for depiction in an aerial setting. The rendering engine also considers semantic information and device placement, which makes it possible to see the hologram in midair. High-performance computing workloads may be transferred to the network by integrating 6G technology, decreasing energy use and end-to-end latency on mobile devices.

Numerous recent reviews and surveys in the literature offer insights into immersive communications, ranging from presenting the current state-of-the-art to envisioning future advancements. While some papers delve into specific aspects like supporting 360-degree/holographic video streaming [14], [15], evaluating user immersive experiences [16], analyzing the impact of user movements on network performance in XR [17], enabling Metaverse use cases [18], [19], [20], or facilitating distributed implementation of Virtual Reality (VR) [21], our survey takes a different approach by providing a comprehensive survey of holographic communication network and architecture, focusing on holographic communication for empowering Metaverse applications. Prior studies have attempted to survey Metaverse opportunities and/or applications concerning specific industrial sectors [22], [23], [24], while others focused on identifying challenges, relevant security and privacy issues [25], [26], [27], [104]. A few studies have compiled and disseminated the technology behind the Metaverse [28]. However, to our knowledge, none of the existing surveys have addressed the combination of holographic communication and Metaverse and their applications.

A. MOTIVATIONS AND CONTRIBUTIONS

The driving forces behind this survey are the need to fill in gaps in holographic communication, its integration with the Metaverse, and the variety of applications. The survey aims to illustrate the wide range of industries including entertainment, education, healthcare, business, and remote assistance—where holographic communication might have revolutionary effects. The survey highlights holographic technology's potential influence and practical usefulness in several sectors. The survey also aims to fill in essential gaps in the knowledge and application of the combining technologies i.e., holographic communication and Metaverse, including how to optimize immersive experiences best, integrate holographic communication into Metaverse ecosystems, and use technology breakthroughs for scalable deployment. This study aims to fill the knowledge gaps and offer helpful advice to researchers, practitioners, and industry stakeholders who want to utilize holographic communication in virtual environments fully. The contributions are summaries as Fellow:

1) The survey paper provides a thorough examination of holographic communication and its intersection with the Metaverse, covering principles, requirements, architectures, benefits, and applications.
2) We Introduce a novel framework illustrating how holographic communication empowers immersive experiences within virtual environments, highlighting the transformative potential of holography in the Metaverse.
3) we explore a wide range of applications for the novel framework of integration of holographic communication and Metaverse across domains such as

TABLE 1. List of acronyms.

Acronym	Definition
3D	Three Dimension
6G	Sixth Generation
5G	Fifth Generation
B5G	Beyond Fifth Generation
AI	Artificial Intelligence
AR	Augmented Reality
DoS	Denial of Service
HMD	Head-Mounted Display
IRS	Intelligent Reflecting Surface
CAVs	Connected and Autonomous Vehicles
DT	Digital Twins
SDR	Software-Defined Radio
DSP	Digital Signal Processing
LIDAR	LIght Detection and Ranging
LFV	Light-Field Video
PoV	Persistence of Vision
HMIMO	Holographic Multiple Input Multiple-Output
HIRS	Holographic Intelligent Reflecting Surfaces
MR	Mixed Reality
QoE	Quality of Experience
QoS	Quality of Service
SDN	Software-Defined Networking
VLC	Visible Light Communication
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
LSTM	Long Short-Term Memory
NOMA	Non-Orthogonal Multiple Access
PT2DT	Physical to Digital
MEC	Mobile Edge Computing
JPEG	Joint Photographic Experts Group
VPCC	Video Point Cloud Compression
MVC	Multiview Coding
MPEG	Moving Picture Experts Group
COIN	Computing in the Network
VR	Virtual Reality
XR	Extended Reality
GANs	Generative Adversarial Networks
IoT	Internet of Things
ML	Machine Learning
THz	Terahertz Communication

entertainment, education, healthcare, business, and remote assistance.

4) This survey discusses the challenges and opportunities associated with integrating holographic communication into Metaverse ecosystems, offering insights into technological advancements needed for successful implementation.

B. PAPER STRUCUTURE

The rest of the paper is organized as follows. Section II focuses on the metaverse and its applications and benefits, while Holographic communication is discussed in detail in Section III. Section IV highlights when Holographic communication meets Metaverse while the use cases are discussed in Section V. Section VI highlights the challenges, opportunities, and future trends and the survey is concluded in Section VII. Figure 1 illustrates the paper structure including subsections of each section.

II. METAVERSE

A fully immersive virtual environment that smoothly combines components of the actual world with the virtual world is called a Metaverse [104]. Users can make avatars in the Metaverse to represent themselves digitally in fictitious or simulated contexts, including virtual towns or video games. Users can interact with virtual environments, other digital entities, and digital avatars via XR devices such as laptops or smartphones. Metaverses synchronize the digital and physical domains through two main information flows. First, information is transferred from the actual world into the digital domain, where sensors and actuators record human movements and represent them as virtual avatars. The second flow deals with digital interactions, such as digital items, avatars, and Metaverse services in virtual environments. Metaverses are positioned to provide user-centric content, enabling immersive social interactions, online collaborations, and more, thanks to improvements in networking technology, big data analytics, blockchain, and Artificial Intelligence (AI) [29].

Novel interface technologies have emerged mainly because of the COVID-19 epidemic and the ensuing limitations on social connections and daily activities. With the help of these technologies, social isolation should be lessened, and the idea of an integrated "Metaverse" that can replace routine everyday activities—even in situations where mobility is restricted and physical isolation is present—should be strengthened. The Metaverse has the potential to be applied in a wide range of sectors, including education [23], [30], [31], entertainment and social networking [32], business [26], healthcare [28], [33], [34], manufacturing [22], transportation [35].

The creation and operation of the Metaverse use various methods and tools explained [28]. These include technologies that create immersive and interactive virtual worlds, such as VR and Augmented Reality (AR). Furthermore, complex and realistic virtual environments and objects are made possible by 3D modelling and animation technology. Technologies related to AI and machine learning are essential for creating dynamic and interactive virtual worlds in the Metaverse. Future developments in Generative Adversarial Networks (GANs) may enable AI to produce (semi-)automatically and in large quantities of material. Moreover, speech recognition and natural language processing technologies improve how natural and easy-to-use interactions are in the virtual world.

Applications for VR and AR have grown in popularity because they provide a wealth of opportunities for both entertainment and education. Applications to cultural heritage sites are happening more frequently as technology advances. Cultural legacy can benefit significantly from the metaverse, especially regarding research, reconstruction, and display enhancement [36]. Nonetheless, although most implementations focus on visual experiences, the research acknowledges the importance of multimodal interaction. Research has shown that engaging in virtual experiences that stimulate several human senses may elicit a powerful sense of "being there" [37]. Humans perceive their surroundings through all five senses: aural, visual, gustatory, olfactory, and tactile [38]. As a result, efforts have been undertaken to understand the precision of each sensory signal. As a result, in addition to audiovisual material, tactile feedback [39] and

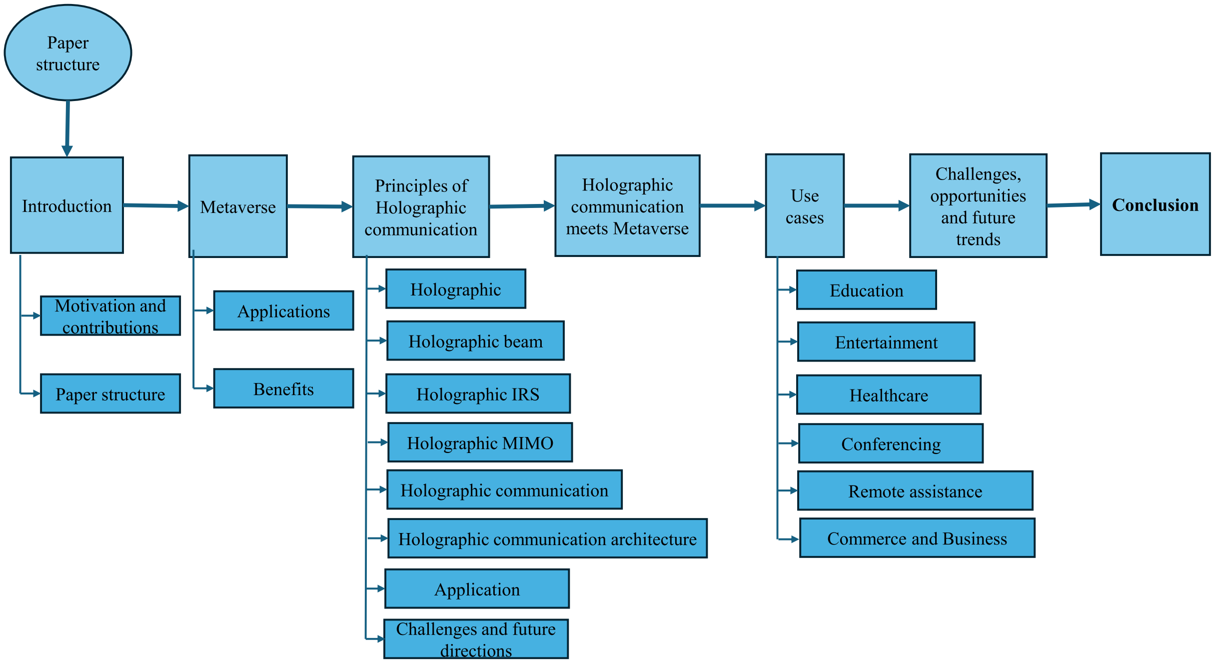

FIGURE 1. Survey structure .

scents [40], [41] are being explored more and more about Metaverse experiences.

The Metaverse architecture includes the immersive and real-time layer for physical-virtual world interaction powered by the Metaverse engine layer (As seen in Fig. 2). The auxiliary Metaverse ensures that the Metaverse is scalable, widely accessible, and has a trustworthy user base. The 6G networks, local and global computing, and edge-intelligent storage comprise the Metaverse infrastructure layer. The Metaverse layer employs user components to collect data: XR, Digital Twins (DT), haptic, Artificial Intelligence (AI), and blockchain. Metaverse inputs create, maintain, and improve the virtual environment. Virtual service providers create and manage the virtual worlds and run the physical infrastructure. At the same time, users engage with the virtual world through interaction with the Internet of Things (IoT) placed in the real world, which gathers data from the environment.

The seven levels of the Metaverse are human interface, infrastructure, decentralization, spatial computing, creator economics, discovery, and experience (As seen in Fig. 3). While still in the real world, users may interact with AR and obtain information about their surroundings. This capacity is made possible by developments in spatial computing and human interface technologies. A solid technical foundation is necessary for the Metaverse, and 6G computing must be used to reduce network congestion and increase network capacity. Microservices and distributed, decentralized ecosystems are essential for assisting companies and advancing the field of education. Characterized by integrating AR and VR technologies, spatial computing is best represented by features like

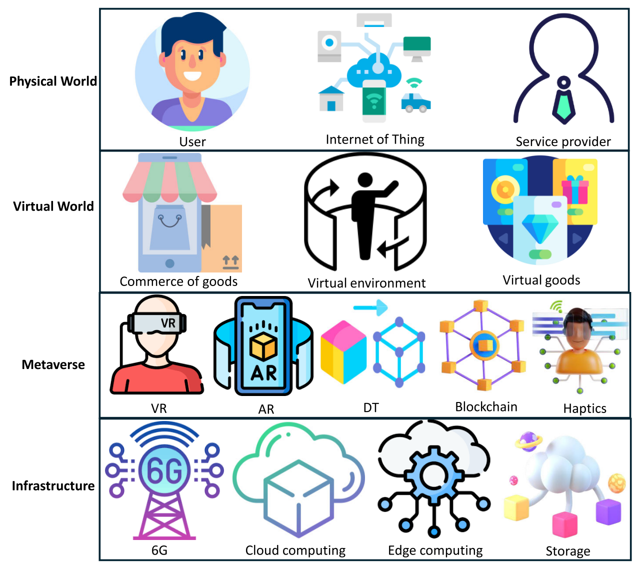

FIGURE 2. Metaverse-6G architecture enabling technologies and tool [6].

Instagram filters. Developing online tools and applications was difficult in the past, and programming knowledge was usually needed. However, while web application frameworks are now readily available, creating a Metaverse app requires high coding expertise due to technical improvements. As such, code complexity is no longer an obstacle to being the owner of a Metaverse learning platform. The Metaverse facilitates both outbound and inbound discovery systems. For instance, when a student experiments independently,

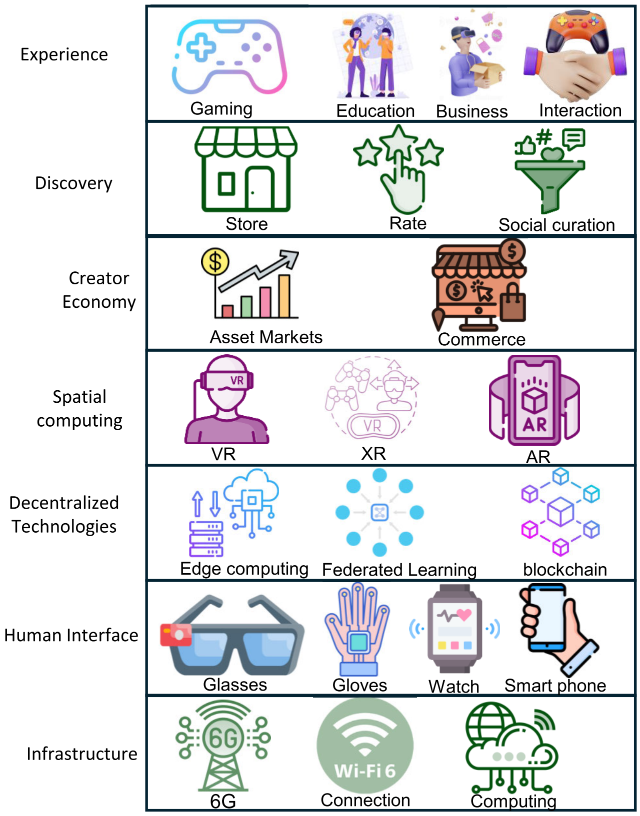

FIGURE 3. Metaverse layers [6].

it constitutes inbound discovery, whereas audio-video lessons a teacher provides represent outbound discovery for the student. Furthermore, the Metaverse offers a plethora of 3D visuals alongside traditional 2D experiences, a feature that was not feasible in conventional classroom settings.

A. METAVERSE APPLICATIONS

Table. 2 illustrated the summary of the descriptions of Metaverse applications across industries.

1) **Entertainment and Gaming:** The capacity to construct and explore virtual worlds that are completely imaginative or that closely mimic real-life locations is one of the Metaverse's distinguishing qualities. In virtual places, users may congregate to mingle, go to virtual concerts, and spend time with friends.
2) **Immersive Gaming:** Games are being revolutionized by metaverse apps, which offer incredibly immersive experiences. Gamers may join virtual worlds where they can interact with items, go on missions, and work in real-time multiplayer settings with other players. The experiences allow for hitherto unheard-of degrees of involvement and interactivity by obfuscating the distinctions between the physical and digital realities. The use of Metaverse features in games to generate dynamic and fascinating experiences is exemplified by games such as Roblox and Fortnite [42].
3) **Education and Training:** Applications for the metaverse are revolutionizing education by making it possible for instructors and students to participate in immersive, interactive learning environments virtually in classrooms. These online learning environments imitate traditional classroom environments, facilitating instantaneous communication, cooperation, and involvement. Students may take part in conversations, attend classes, and engage in highly interactive learning. Virtual classroom solutions that use the Metaverse to improve conventional educational models are provided by platforms such as Engage and AltspaceVR [43].
4) **Training Simulations:** Many different sectors are using training simulations that make use of the Metaverse. For example, pilots can receive hands-on training in realistic cockpit conditions without requiring actual aircraft by using flight simulators in aviation, which leverage Metaverse technology. Healthcare workers may rehearse intricate processes and scenarios in a risk-free virtual setting with the help of Metaverse-based medical simulators. In a similar vein, Metaverse apps are used by the manufacturing and construction sectors to instruct personnel in safety and operating processes. These simulations take advantage of the Metaverse's immersive qualities to improve learning objectives and skill development [44].
5) **Business and Commerce:** Because metaverse offers immersive virtual worlds, business and commerce have revolutionized the way corporations organize meetings, conferences, and trade exhibitions. The platforms are used by businesses to hold online conferences and meetings that allow attendees from all over the world to communicate, work together, and network virtually. Rich multimedia experiences like as customisable avatars, interactive presentations, and spatial audio are provided via metaverse-based events, which encourage more interactive and captivating interactions [3].
6) **Virtual Retail and Commerce:**Applications for the metaverse are transforming the retail sector by providing virtual shopping experiences. Consumers may browse virtual storefronts, engage with merchandise in three dimensions, and conduct transactions in a digital setting. Virtual commerce systems facilitate creative product showcases for businesses, offering customers customized and immersive purchasing experiences. To engage consumers and increase sales, brands are using the Metaverse to construct virtual showrooms, product demos, and interactive marketing campaigns [45].
7) **Healthcare and Telemedicine:** Telemedicine and remote consultations are being made possible via metaverse platforms, which are transforming the healthcare industry. With the use of immersive technology, medical personnel may interact and view patient data virtually during virtual visits. This improves

TABLE 2. Metaverse applications across industries.

Industry	Metaverse Applications
Entertainment	Virtual concerts, social gatherings, immersive gaming experiences, interactive storytelling
Education	Virtual classrooms, training simulations (e.g., flight simulators, medical training)
Business	Virtual meetings, conferences, trade shows, remote collaboration, virtual retail experiences
Healthcare	Remote consultations, telemedicine, medical training and simulations
Real Estate	Virtual property tours, architectural visualization, urban planning simulations
Retail	Virtual shopping experiences, digital showrooms, interactive product demonstrations
Automotive	Virtual vehicle showrooms, test drives, automotive design and customization
Tourism	Virtual travel experiences, destination previews, historical reconstructions
Art	Virtual art galleries, exhibitions, interactive art installations
Social Networking	Virtual social spaces, avatar-based interactions, online communities

accessibility to healthcare services by enabling clinicians to give diagnoses, treatment suggestions, and monitoring without needing to be physically present. Applications for the metaverse also enable professionals to consult together, facilitating interdisciplinary treatment and the exchange of expertise [34], [46].

8) **Medical Training:** The Metaverse is vital to medical training and education because it offers immersive environments where experts and students. Trainees can conduct diagnostic procedures, perform surgeries, and learn medical protocols in a safe and realistic environment by using virtual simulations in the Metaverse. By offering practical experience and enabling repeated practice without the hazards associated with conventional training techniques, the simulation improves learning outcomes [47].
9) **Architectural Visualization:** Architects and designers leverage the Metaverse for architectural visualization, enabling them to present building designs, urban planning projects, and construction concepts in virtual environments. Metaverse applications provide advanced visualization tools that facilitate the creation of interactive 3D models, walkthroughs, and simulations. These tools aid in communicating design ideas, assessing spatial relationships, and gathering feedback from clients and stakeholders before construction begins [48].

B. BENEFITS

Table. 3 illustrated the summary of the benefits of the Metaverse and its application.

1) **Immersive Experiences:** The Metaverse offers immersive and interactive experiences that go beyond traditional multimedia channels. Users can engage with virtual environments using avatars and interact with digital objects, enhancing realism and engagement [49].
2) **Enhanced Collaboration:** In business and education, the Metaverse enables remote collaboration in highly immersive settings. No matter where they are physically located, teams may collaborate, participate in virtual meetings, and hold training sessions, which promotes global cooperation and lowers travel expenses [50].
3) **Interactivity in Real Time:** Through the usage of metaverse apps, users may interact with content and modify things in real time as if they were there. This capacity is particularly useful in domains where precise interactions are crucial, such as engineering and healthcare [51].
4) **Enhanced Educational Results:** Educational establishments utilize the Metaverse to improve student learning. Pupils may work with classmates, engage in simulations, and picture difficult ideas in 3D, all of which enhance understanding and memory [52].
5) **Virtual Commerce and Retail:** Metaverse platforms enable virtual retail experiences where customers can browse products, interact with digital showrooms, and make purchases in immersive environments. This capability extends the reach of businesses and enhances customer engagement [3].
6) **Remote Assistance and Support:** In industries like healthcare and technical support, the Metaverse facilitates remote consultations and troubleshooting. Using 3D representations, experts may walk users through operations, increasing productivity and decreasing reaction times [53].
7) **Innovation and Creativity:** Artists, designers, and developers may push boundaries and experiment with new interactive media formats in the Metaverse, which acts as a playground for creative expression. As a result, creativity is encouraged and digital experiences continue to advance [54].
8) **Introduction to Society:** Within the Metaverse, virtual social spaces promote community formation and interpersonal relationships. By interacting, participating in shared experiences, and attending virtual events, users may foster inclusion and social engagement [55].

III. PRINCIPLES OF HOLOGRAPHIC COMMUNICATION

This section introduces holographic communication, discusses the idea and various forms of holography, then discusses the fundamental implementation process and concludes with requirements for data transmission rate and latency. The development of holography technology is at various stages. By preserving and recreating the optical wavefront, optical holography creates holograms. The associated holograms are interference patterns of an "object wave" and a "reference wave" that are recorded, for example, on photographic emulsions. Diffraction is used to reconstruct a 3D light field when the reference wave illuminates the recorded interference pattern.

TABLE 3. Benefits of the Metaverse.

Benefit	Application	Ref.
Immersive Experiences	Virtual worlds, social spaces, immersive gaming	[56]
Enhanced Collaboration	Virtual meetings, remote education , global teamwork	[57]
Real-time Interactivity	Healthcare simulations, engineering design,interactive storytelling	[58]
Improved Learning	Virtual classrooms, training simulations	[59]
Virtual Commerce	Virtual shopping, digital showrooms, retail experiences	[60]
Remote Assistance	Telemedicine, technical troubleshooting, customer support	[61]
Creativity and Innovation	Artistic expression, game development, digital media	[62]
Social Engagement	Virtual events, community building, social interactions	[63]

A. HOLOGRAPHY

The hologram concept was first developed in the 1940s, but the invention of the laser in the 1960s allowed for a genuine breakthrough [64]. Later, as electronic devices became more advanced, digital holography—which records interference patterns using image sensors—rose to prominence. Digital holography uses optomechanical recording, and numerical techniques like the Fourier transform are used to reconstruct a 3D image from light wave diffraction [65]. Computer-generated holography is the most recent advancement in holography, wherein a computer is used to digitally create the 3D picture on display and the interference pattern [66]. The item to be presented need not be physically present when using computer-generated holography, which offers significant flexibility at the expense of high computational complexity [67]. Based on the principle of interference, holography divides light into reference and object waves using a laser beam. A holographic plate or film records the interference pattern that is produced when the object wave and the subject interact. When the reference wave illuminates this medium, it replicates the interference pattern, producing a three-dimensional image that may be seen from different angles.

Early holographic displays were cumbersome and costly, but progress in optics, computing, and materials has rendered holography more accessible and practical [68]. Nowadays, holographic projectors that are small and portable may be easily integrated into communication systems to provide immersive virtual experiences and holographic teleconferencing [5]. Consider staying at home to watch a sporting event or concert. With the use of holographic technology, one may experience a live event virtually, with visuals and sounds that are similar to being there. This makes things more convenient and gives people who are limited by distance or movement more possibilities.

Therefore, holography empowers interaction face-to-face with the support of Holographic communication, in which colleagues anywhere exchange ideas, and presentations, and work together collaboratively. Without the need for special glasses or headsets, holography is a sophisticated imaging method that creates 3D images by using light interference [69]. Holographic teleconferencing enhances engagement and communication in telepresence by enabling remote collaboration with lifelike participant representations [70]. The technology is based on specialized holographic displays that project light fields to generate immersive and interactive 3D graphics, such as volumetric displays and light field displays [71]. Holographic technology has substantial effects and is applied in many different sectors. Medical practitioners utilize holography for imaging and surgical planning, while architects and designers use it for interactive design exploration and urban planning [72]. Holographic displays improve user immersion and narrative in entertainment and games by enabling interactive interactions [3]. Holographic technology is also used in retail, advertising, technical support, and remote help, which changes how products are showcased and services are provided [4].

Current limitations of holographic displays, including the restricted field of view (FoV), limited viewing zones (eyebox), and image quality degradation due to speckle noise, are acknowledged as factors that could undermine the effectiveness of face-to-face interaction and collaboration. While holographic communication holds potential, the paper now emphasizes that further technological advancements are necessary to fully realize this potential. It is acknowledged that conventional holographic displays typically rely on large optical systems, such as 4-f filtering, to remove noise, which contributes to their bulkiness. While there are ongoing efforts to miniaturize these systems and enhance wearability, it is premature to assert that such displays currently do not require additional hardware.Current holography aims to enable a wider acceptance and integration of holographic technology into daily life by overcoming issues like high bandwidth needs and difficult content development [73].

The methods produce the illusion of 3D pictures by using glass panes or other "tricks" [74], [75]. Volumetric display is one of the false holography methods that has garnered much interest in medical imaging and computer-aided design [76]. Volumetric display, a catch-all word for various methods, creates volume-filling 3D pictures by producing, absorbing, and dispersing light inside a small area, such as a cube or cone [77]. Exciting studies are being conducted in the field of volumetric display [78], and commercial devices are now available [79]. A human-size retroreflective cylinder and many projectors are two other methods to simulate 3D projection [80]. A circular multi-projector array can distinguish between seen pictures from various viewing angles for a light field cylindrical display.

B. HOLOGRAPHIC BEAM

Using holographic principles to improve signal transmission and reception, holographic beamforming is a state-of-the-art approach in wireless communications. Holography, a technology that records and reconstructs light waves to produce three-dimensional pictures, serves as its inspiration (as shown

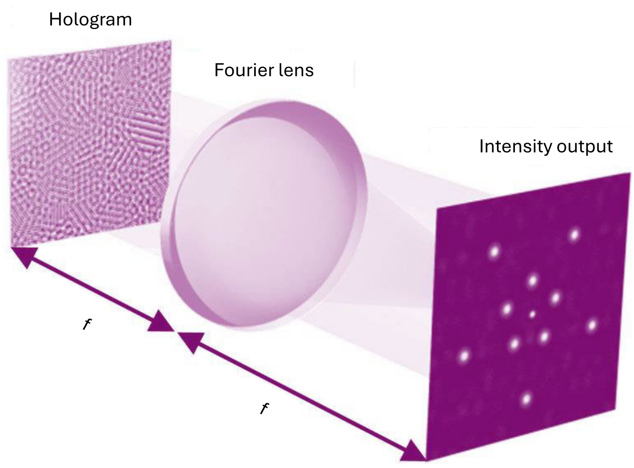

FIGURE 4. Holographic beam.

in Fig. 4). Similar to this, complex electromagnetic waves are created in holographic beamforming to maximize wireless communication. To overcome the drawbacks of conventional antenna systems in wireless networks, the idea of holographic beamforming was presented [81], [82]. Fixed beams are used by antennas in typical wireless communications to send and receive signals, which can lead to interference and ineffective coverage. On the other hand, holographic beamforming employs a more advanced method.

An array of antennas dynamically modifies the phase and amplitude of transmitted signals across many spatial dimensions in holographic beamforming. To maximize signal strength and minimize interference, this dynamic control enables the exact directing of signal beams towards certain directions or users [82], [83]. Holographic beamforming enables adaptive and effective signal transmission by utilizing holographic concepts, such as wavefront shaping and beam steering.

Holographic beamforming technology is based on sophisticated signal processing methods, which are frequently applied with software-defined radio (SDR) platforms and digital signal processing (DSP) algorithms [84]. These methods allow the signal qualities to be adjusted in real-time according to network needs and ambient circumstances. Applications for holographic beamforming may be found in a variety of wireless communication scenarios, including 5G and networks that are not wireless [85]. Holographic beamforming enhances network performance and user experience in contemporary wireless communication systems by increasing signal quality and spectrum efficiency.

C. HOLOGRAPHIC IRS

Holographic Intelligent Reflecting Surfaces (HIRS) is a novel way to improve wireless communication networks via the use of sophisticated beamforming and signal processing methods. Large arrays of programmable components, such as reconfigurable antennas or metamaterials, that can dynamically alter the phase and amplitude of incoming electromagnetic waves make up IRS devices. Holography, which uses patterns of light interference to produce 3D pictures, is the source of inspiration for the idea behind HIRS. IRS devices in wireless communication shape and guide signal beam toward certain directions or users by intelligent electromagnetic wave diffraction and reflection [83].HIRS's primary benefit is its capacity to increase signal quality, strength, and coverage by clever manipulation of reflected waves. IRS devices can alleviate signal blockage, decrease interference, and improve overall system performance by dynamically modifying the phase and amplitude of reflected signals [86], [87].

The use of HIRS in next-generation wireless networks, such as 5G and B5G, is among its most exciting uses. Operators may greatly increase coverage and capacity without requiring additional infrastructure by placing IRS elements in key areas, such as interior settings or building facades [88]. Fig. 5 illustrates how HIRS-aided HMIMO to target-oriented integrated services-based communication systems can simultaneously serve users with reflective beamforming, reflective beamforming, and extend the holographic communication coverage area. IRS-assisted integrated sensing and HMIMO can serve users with reflective beamforming and refractive beamforming for extending the coverage area. Therefore, HIRS capabilities can reflect and refract the holographic beams by activating the radiating element of IRS for serving heterogeneous users [89]. The users can access communication information and acquire beams generated by the HIRS to receive services. The authors of [90], extended the concept by considering the users receive combining, where the radiation amplitude of the grid-controlled holographic beamforming in a multi-user wireless communication system. However, this extension did not incorporate integrated sensing, localization, and communication for generating holographic beamforming. In [87], A proposed framework integrated sensing, localization, and communication within HMIMO, utilizing AI to enable location-based holographic beamforming to efficiently serve communication users with minimal power consumption. Like holographic imaging, holographic communication seeks to achieve complete EM wave control, which is expected to be made possible by RIS and mMIMO working together to provide deterministic spatial beam management from the Tx to the Rx [91]. Together with the well-established wireless channel's temporal and spectral control, this ambitious concept aims to improve the support for high-level applications like DT and connected and autonomous vehicles (CAVs) by offering incredibly fast, stable, and predictable wireless links even in complex environments.

D. HOLOGRAPHIC MIMO COMMUNICATION

The novel technology known as Holographic Multiple-Input Multiple-Output (HMIMO) communication improves wireless communication systems by fusing the concepts of MIMO with holography. Multiple antennas are used in MIMO technology to transmit and receive data, which can

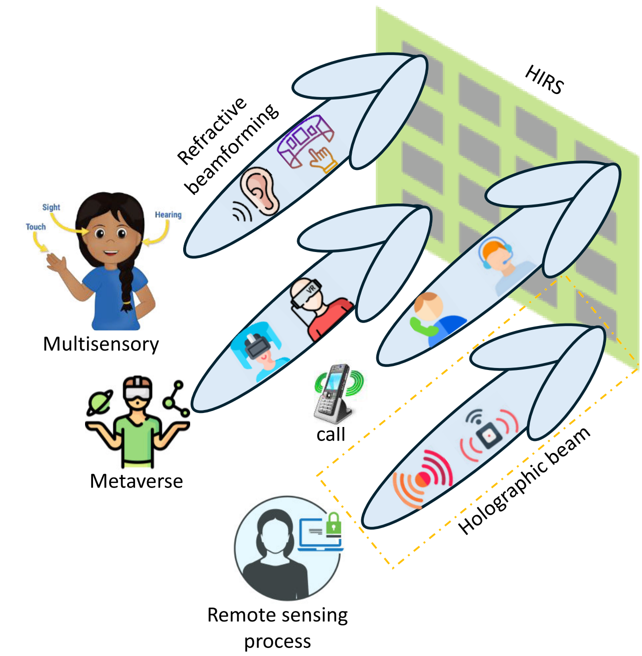

FIGURE 5. **HIRS assisted HMIMO communication.**

enhance system performance and spectral efficiency [83]. To shape and control electromagnetic waves for more effective and adaptable communication, HMIMO expands on this idea [89]. Spatial multiplexing allows antennas in classic MIMO systems to broadcast and receive data concurrently, improving data rates and dependability. HMIMO goes one step further, mimicking the way holography manipulates light waves to form three-dimensional pictures by dynamically altering the phase and amplitude of transmitted signals across several dimensions.

The main benefit of HMIMO is that it can adaptively focus signal beams toward certain users or directions (Fig. 5), improving signal quality and lowering interference [83]. Sophisticated signal processing methods that dynamically modify antenna parameters in response to network demands and ambient circumstances enable adaptive beamforming. Significant uses for HMIMO technology can be seen in 5G and other next-generation wireless networks. In a variety of communication settings, HMIMO improves network performance and user experience by increasing spectral efficiency and signal coverage [85], [87].

E. HOLOGRAPHIC COMMUNICATION

Holographic communication is an emerging technology with the potential to completely transform digital contact. Holography allows the production of immersive 3D virtual pictures that appeal to the senses using advanced imaging and projection techniques. This innovation enables lifelike talks with people over great distances, mimicking in-person encounters. Holographic communication usage opens up a world of possibilities in industries including business, education, healthcare, and more. Holographic communication integrates 3D data gathering, processing, transmission, and rendering, and is anticipated to open up attractive new services in 6G [92].

Holographic communication is data transfer for autostereoscopic 3D projection, or 3D pictures that are visible to the unaided eye without the need for glasses or headsets, changing depending on the location, angle, or tilt of the viewer. As long as the goal of the autostereoscopic 3D display is satisfied, the 3D display at the receiver can be generated using true holography, false holography, or other approaches. Like current multimedia communications, holographic communication can have broadcast, multicast, or unicast communication modes in addition to real-time or recorded material generation. Content distribution is revolutionized by holographic communication streaming for heterogeneous users, which caters to a wide range of audiences with different wants and tastes. By using holographic technology, broadcasters may send material in three dimensions, offering viewers of all technological skill levels and interests an immersive watching experience. By guaranteeing inclusion and engagement for a broad audience—from tech experts to regular consumers—this strategy promotes a more customized and interactive broadcasting environment.

While there are differences in the implementation process between different holographic communication approaches, Fig. 6 illustrates the overall data acquisition, processing, transmission, and rendering process. A capture system is needed to record 3D photographs of a physical item unless the object is computer-generated holographic. A perfect holographic communication capture system would record the target scene's light field—that is, every piece of information included in each light ray [93]. Visual sensors, such as a camera array [94] or LIght Detection and Ranging (LIDAR) sensors [95], are used in practice for capture. Directly (as in the case of a capture system with LIDAR sensors) or computationally (as in the case of a capture system with a camera array) is the depth information of the item of interest.

The first step in holographic communication is to use a variety of cameras or depth-sensing technology to take a live or recorded image of the target. Following processing, the visuals are transformed into holographic data. After being sent, the holographic data is decrypted and projected as a 3D image on the recipient's device. In real-time, the receiver can engage with this image as they would in a face-to-face exchange. Holographic communication may make use of gesture detection, haptic feedback, and spatial audio to enhance realism even further. As a result, a captivating and immersive virtual world is produced. Imagine using holographic communication to feel the weight and texture of an object or a piece of cloth. Haptic feedback technology allows users to feel tactile sensations, which improves the virtual world's realism and engagement. This creates new opportunities for sectors where feedback and physical contact are essential, such as manufacturing, design, and fashion.

A composite 3D representation of the collected scene is created by fusing the output from capture sensors and

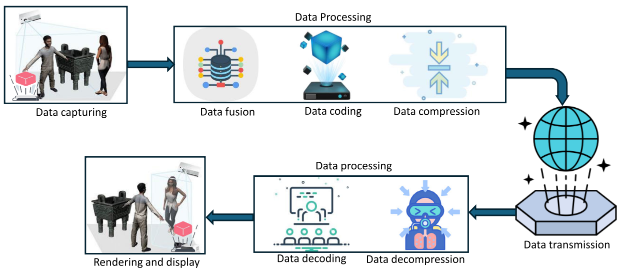

FIGURE 6. **Holographic communication procedures.**

computing the depth information of target objects in the image [96]. In digital holography, for instance, a computer may combine 2D pictures acquired by a camera array at various tilts and angles to create a single 3D depiction of the scene [97]. The fusion of pictures may be carried out either exclusively at the transmitter side or with the assistance of an edge server, and it may help accomplish visualization improvements in the produced 3D images, such as improvement in the resolution and contrast [96]. Furthermore, to expedite transmission and reconstruction and lower the necessary data transmission rate and storage in holographic communication, the data processing phase also compresses the fused data [98], [99]. After that, the 3D representation's compressed data is encoded and transferred via a network.

The received data is decoded and decompressed at the receiving end using one or more selected codecs. After that, the collected scene is displayed on a display device after being perhaps rebuilt with the aid of an edge server. To provide the impression that the user is in the scene, the perfect display device for holographic communication would renew the light field in the captured picture. It is challenging to create such an illustration as several light rays must radiate from each display device's point (i.e., pixel) in diverse directions. Nonetheless, considering the limits of human vision, devices like a static volumetric display device [100], a cylindrical light field display [80], or a Persistence of Vision (PoV) display [101] can all be used to simulate the sensation of visual immersion. The devices create the appearance of 3D pictures by, among other things, filling the user's field of view with a big curved display, using the phenomenon of a lingering afterimage on the retina, and dynamically turning on and off voxels in a limited 3D region. It is important to remember that audio data acquisition, processing, and rendering may also be necessary for holographic communication. In such a scenario, users may only fully engage in an immersive holographic communication experience by recording the sound field in the target scene and guaranteeing audio and visual synchronization [93].

There are two primary forms of holograms, i.e., image-based holograms and volumetric-based holograms. Different data speeds, from hundreds of Mbps to Tbps, are needed for the two forms of holograms to be sent [92]. An actual item is represented as a collection of 3D pixels, or voxels, in volumetric-based holograms, like a point cloud. Depending on the resolution of the 3D material, transmitting a point cloud that targets an object requires a transmission rate of several hundred megabits per second to several gigabits per second [102]. A human, for instance, requires 105–106 points in each frame to adequately display the point cloud, and each point requires 15 bytes of data to indicate its colour and 3D position [103]. The rate of data needed for 30 frames per second is between 300 Mbps and 3 Gbps [97], [104]. Photographs taken at various angles, tilts, and locations display objects for image-based holograms, such as Light-Field Video (LFV). When several pictures from multiple tilts, angles, and locations are utilized in each frame, an LFV-based hologram can be more accurate than a volumetric-based hologram, especially in high resolution [5]. If an item in 3D needs a different picture every 0.3°, for instance, a hologram with a 30° FoV angle range and a 10° tilt range would require 3,300 different 2D images. A 100 Gbps to 2 Tbps data rate is needed to broadcast an LFV-based hologram for a human-sized object [92], [105]. Table. 4 describes the comparison of holographic and 3D display technologies.

Real-time holographic communication requires a total latency of less than 100 ms, which includes the time required for data acquisition, analysis, transmission, and rendering [105]. Table. 5 presents an overview of the needs and possible solutions for immersive communication, which includes haptic, holographic, and XR communication. Typically, a hologram of an item or a person may be sampled by several sensors at various distances and angles. In this instance, data transmission from several sensors needs to be synced [106]. Using holographic teleconferences as an example, multisource synchronization is required for participants to have a high Quality of Experience (QoE) in holographic communication since they can join the teleconference from different places. Otherwise, some viewers may see a portion of the produced hologram that is marginally ahead or behind the remainder of the hologram, which would lead to a low-quality experience [107]. Additionally, multi-sensory information, such as haptic, audio, and visual information, may be included in holographic communication [108]. The synchronization of various sensory information in transmission is crucial in this scenario so that users may see the hologram, hear the speech, and get touch-sensory input from other users without experiencing a decrease in immersion owing to out-of-sync problems. For adequate QoE in holographic communication, including haptic and audiovisual data transmission, the acceptable variation in the latency of different data types should be less than 80 ms [109].

F. HOLOGRAPHIC COMMUNICATION ARCHITECTURE

Holographic data can be pre-recorded and stored on an external hard drive or other conventional device. Users may then select at any moment where to view the captured holographic

TABLE 4. Comparison of holographic and 3D display technologies.

Feature	Holographic Displays	Stereoscopic Displays	Autostereoscopic Displays
Field of View (FoV)	Limited	Typically wide	Wide, but limited by viewing angles
Eyebox	Narrow	Narrow with glasses	Wider without glasses, but varies by technology
Image Quality	Affected by speckle noise	High with proper glasses	Good, but can suffer from artifacts
Need Glasses/Headsets	Requires glasses or headsets	Requires glasses	Does not require glasses
Image Depth and Realism	High depth and realism	Moderate depth, depends on glasses	Moderate depth, less realistic than holographic
Bulkiness	Bulky due to optical systems	Glasses are bulky but manageable	Generally less bulky, depends on technology

TABLE 5. Comparison of immersive communication technologies: XR, Haptic, and holographic communication, including requirements and potential solutions.

Category	XR	Haptics	Holographic
	360° video playback	Telesurgery	Volumetric-based hologram
Required	Interactive applications (e.g., VR gaming)	Remote machine manipulation	Image-based hologram (e.g., LFV)
	Collaborative virtual applications	Haptic interaction-based rehabilitation	Real-time holographic teleconference
	20 ms delay [110], 2.35 Gbps data rate [111]	> 99.999% reliability, < 1 ms delay [114]	> 300 Mbps data rate [97], [104]
Objective	50 ms response time [112]	> 99.999% reliability, < 2 ms delay [115]	> 100 Gbps data rate [92]
Solutions	150 ms virtual feedback [113], 12.5 Tbps/km^2	> 99.999% reliability, < 50 ms delay [116]	< 100 ms delay [7]
	Require centralized online management	Increase interference management complexity	Require collaboration of multiple servers
Cost / Limitations	Require user state characterization	Increase resource consumption	Increase computing complexity
	Require data management	Require adaptive perception modeling	Require abundant data for flow control

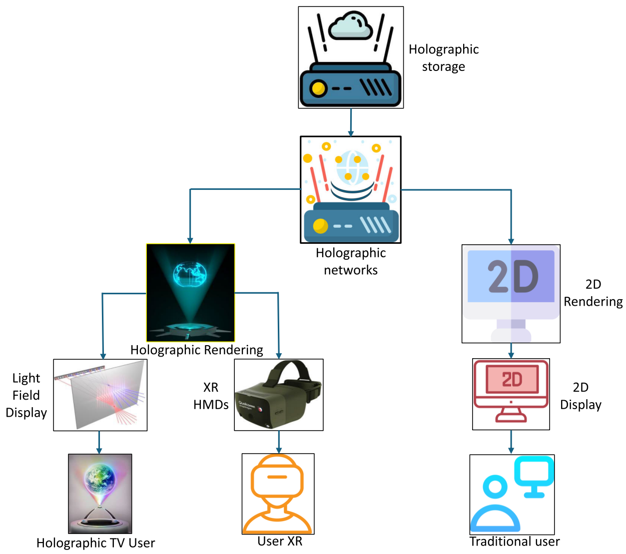

FIGURE 7. Holographic communication broadcasting for heterogeneous users.

data thanks to light field displays. In these scenarios, there are no problems with end-to-end communication. On the other hand, as seen in Fig. 7, our study concentrates on many situations in which holographic content is delivered from a source to one or more destinations or consumers. Holographic communication involves variable conditions that call for varying levels of participation and response in real-time. These circumstances can be divided into three categories.

The first scenario is the low-interactive holographic communication scenario, used in holographic remote education and other similar scenarios. In this instance, similar to a traditional presentation where slides are updated regularly, instructional materials are streamed from distant servers. This scenario may accept rather lengthy latency requirements without severely affecting user experience, as changes in holographic materials are often unnecessary. Second scenario, applications requiring ultra-low latency, broad bandwidth, and high reliability—such as live conferencing and remote control—benefit from high-interactive holographic communication. In these situations, rigorous latency and bandwidth requirements are required since immediate response ensures smooth user interactions.

In the third scenario, holographic communication broadcasting addresses situations where people watch live sporting events, attend public meetings, and passively take in holographic material without actively participating. Although this application can handle higher latency needs, effective networking resource management is necessary to guarantee seamless content delivery. holographic communication broadcasting situations can benefit from dynamic adaptive data packet transmission techniques, which maximize resource use and improve overall efficiency.

Figure 8 shows the three primary parts of a typical holographic communication system architecture: the networks, the source, and the destination. In this architecture, computational operations, including modulation, demodulation, encoding, decoding, and synchronization of aggregated data, mostly take place at the source and the destination. The link between the source and the destination is established via the network. Following that, we examine the main functions of holographic communication network architecture.

1) **Source:** The sources have three main roles. First, it uses sensors to record sensory inputs such as sound, pictures, haptic feedback, and even smell and taste

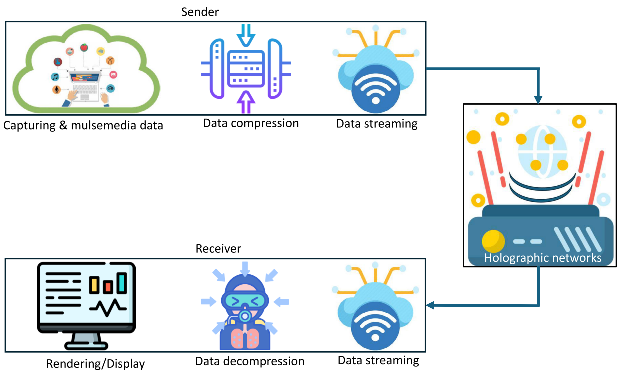

FIGURE 8. **Holographic communication network architecture.**

signals. Second, the source processes the combined data, carrying out operations like creating point clouds from pictures taken from different angles and making sure that the data from several sensors is synchronized to produce correct timestamps. The source is also responsible for encoding and compressing holographic data and multimedia to reduce network traffic. Finally, it transmits data packets using specific holographic communication networking protocols.

2) **Networks:** Both wireless and wired holographic communication networks effectively transfer large amounts of data from the source with a predictable and controlled end-to-end delay. To achieve these strict criteria, existing technologies like content caching, automated network slicing, Software-Defined Networking (SDN), and terahertz spectrum use must be modified. Furthermore, holographic communication networks can be reinforced and improved, becoming more resilient and effective, by incorporating cutting-edge technologies like deterministic networking, innovative transport layer solutions, semantic communications, and complex scheduling algorithms designed to control latency.

Computing: The holographic communication architecture necessitates significant computing capacity at both the source and destination, as seen in Fig. 8. Edge servers and high-performance PCs are good choices to meet these requirements. However, as Fig. 6, computational processes must be offloaded to the network using Computing in the Network (COIN) technologies to support low-cost devices at both ends [117], [118]. For example, sensors at the source can communicate directly with speakers, displays, and actuators at the destination. This configuration allows uncompressed source data to be sent while compression is performed dynamically in the network according to available bandwidth and congestion. Moreover, the network may transfer rendered data to the destination and perform decompression duties. This may be accomplished by utilizing edge servers, cloud servers, and routers with computing power, greatly reducing the computational load at the source and destination nodes.

Broadcasting: Holographic communication supports live and pre-recorded holographic content transmission in addition to end-to-end communication; these applications include asynchronous holographic education, holographic TV, and holographic video streaming. Holographic material is usually kept on a server or data centre, as Fig. 7 illustrates. Holographic communication acts as a bridge between these servers and end users. End users have access to a variety of devices, from conventional 2D displays to high-end light field displays and XR head-mounted displays. To serve a heterogeneous user base and take into account their unique quality of experience requirements, the holographic content must be produced uniquely for every end user.

3) **Destination:** The destination receives and outputs data for visualization, including actuators for gustation and smell, which are used to replicate the environment that was first recorded at the source. Synchronization is crucial even if the speakers, actuators, and holographic displays are placed in different places. Data packet delivery may be guaranteed at certain times using this synchronization, which can take place at the destination or inside the network architecture. Apart from its function of receiving and displaying material, the destination may also actively participate in error correction, improve the quality of holograms and multimedia using sophisticated methods like as super-resolution, and utilize motion detection to initiate service requests, therefore dynamically improving the user experience.

4) **Rendering and display:** The computational creation of a picture of a scene or model from a particular perspective is called rendering. A scene is an object within a scene that needs to be drawn, and it represents a volume and all of its components, including sources. The characteristics of a camera that define the viewpoint include position, focus, orientation, and resolution. Further methods are designed to optimize the rendering process, increasing rendering performance and QoE. The techniques include sharp edge smoothing, object quality enhancement, and AI algorithms to produce photorealistic representations, such as avatars.

More processing power is needed to render real-time data from a depth camera than avatar representations. For example, creating a hologram necessitates rendering every mesh frame, whereas updating an avatar model's facial emotions requires rendering the modifications. Split rendering assigns rendering duties to an edge cloud. It entails giving the edge real-time input while tracking an XR device's six degrees of freedom position and orientation within a scene. A 2D video is streamed back to the user's viewpoint based on their position after the 3D scene rendering occurs in the cloud. This strategy reduces the hardware end users need, but low-latency communication between the edge and the device is required for the best QoE. After being rendered, the stream is sent to gadgets that can provide holographic experiences, such as holographic displays, AR glasses, VR glasses, and handheld devices like smartphones and tablets. These tools allow people to place and communicate with holograms in their surroundings.

An edge cloud is assigned rendering duties through the use of split rendering. Order Providing real-time input to the edge entails tracking the six degrees of freedom position and orientation of an XR device within a scene. The rendering of the 3D scene takes place in the cloud, and a 2D video is streamed back to the user's perspective according to their position. While this strategy reduces the hardware that end users need, it requires low-latency communication between the edge and the device to provide the best experience. After the stream has been rendered, it is sent to devices that can provide holographic experiences, such as AR glasses, VR glasses, holographic displays, and handheld devices like smartphones and tablets. These devices allow users to position and interact with holograms in their surroundings.

Holographic communication is an advanced system incorporating knowledge from several technical fields, including computer networking, wireless communication protocols, sensors, actuators, data compression methods, and display technologies. We focus on describing the unique needs and challenges related to holographic communication coding, networking, and communications. The role of technologies in Holographic communication is illustrated in Table. 6.

1) **Data rate:** The data rates required for holographic displays are quite high—many terabytes per second. While distributed COIN and effective encoding techniques can reduce this need to terabytes per second or even several hundred megabytes per second, the computational cost. Consequently, holographic communication necessitates unprecedentedly high data rates, prompting the need to reevaluate and enhance current networking technologies to accommodate them. The anticipated data rates, frames-per-second, and communication distances for holographic communication are detailed in Table. 5. It is expected that the forthcoming 6G and advanced systems will be capable of supporting high-quality holographic communication across expansive geographical areas.
2) **End-to-end latency:** Holographic communication networks include several processes that are included in latency: data collecting, encoding, communication, networking, decoding, display, and actuation. Keeping the end-to-end latency under 20 ms is crucial to preventing motion sickness, especially for highly engaging applications like holographic gaming. There is still a stringent latency budget of less than 1 ms for networking and communication duties since procedures like data collecting, encoding, decoding, and display may already use up the allocated 20 ms. The restriction limits the maximum distance that may be travelled between the source and destination nodes since data packets can only travel at the speed of light.
3) **Lightweight computation:** Holographic communication requires significant processing power to improve transmission performance. It is necessary to create lightweight computing algorithms and frameworks to provide ubiquitous access via portable devices. For example, users' smartphones or tablets should be able to cast holographic content onto a light field display. Furthermore, lightweight processing helps maintain a good QoE and minimize end-to-end latency.

Holographic communication offers several compelling benefits that can revolutionize wireless systems and enable innovative applications in various domains (as shown in Table. 7).

G. APPLICATION

Holographic communication is poised to revolutionize various applications, offering new communication, training, and entertainment possibilities (as shown in Fig. 9.

1) **Healthcare:** Holographic communication improves telemedicine in the medical field by facilitating more immersive and lifelike remote patient assessments. Surgeons can work together virtually while providing knowledgeable assistance throughout complex surgeries. Imagine a situation where a patient with a unique ailment needs specialist care and lives in a remote place. By using holographic communication, a famous doctor may examine and discuss treatment alternatives in real-time with the patient in their room. This method guarantees that patients receive the best care possible wherever they are, all while saving time and money. Furthermore, holographic simulations that mimic actual patient scenarios are beneficial to medical students since they let them practice practical skills in a safe setting. Through the use of realistic simulations of various medical emergencies, students are given practical experience in making vital decisions and are better equipped to handle pressure-filled situations. By enabling remote patient inspections and surgical cooperation, holographic communication in healthcare improves telemedicine and gives medical practitioners a more realistic and immersive experience.
2) **Education:** Holographic communication has the potential to completely transform education. To promote dynamic and interesting learning experiences, students can take part in virtual classrooms where instructors and specialists from all over the world can appear as lifelike holograms. Imagine teaching a history lesson where students can watch historical events play out in front of them thanks to holographic simulations that replicate important historical occasions. In a manner that textbooks cannot, they may travel alongside ancient civilizations, discover historical sites,

TABLE 6. Role of technologies in holographic communication.

Technology	Description	Role in Holographic Communication
Holographic Displays	Use light field modulation to project 3D images with depth and parallax effects.	Enable visualization of holographic content in 3D space.
Depth Sensors	Measure distances to objects and capture spatial data for creating point clouds.	Aid in capturing real-world scenes and generating holographic content.
Multi-sensory Actuators	Provide tactile feedback, temperature changes, and scent reproduction.	Enhance immersion by engaging multiple senses in virtual environments.
Networking Protocols	High-speed, low-latency protocols optimized for transmitting large holographic data.	Ensure efficient transmission of holographic content over networks.
Compression Methods	Algorithms to reduce the size of holographic data for efficient transmission.	Minimize bandwidth requirements without compromising visual quality.

TABLE 7. Benefits of holographic communication in wireless systems.

Benefit	Description
Enhanced Spatial Multiplexing	Holographic communication enables advanced spatial multiplexing techniques by manipulating electromagnetic waves with IRS or other programmable elements.
Improved Coverage and Signal Quality	By deploying holographic elements strategically in wireless networks, such as in urban environments or indoor spaces, it is possible to enhance coverage and improve signal quality. Holographic communication can mitigate signal blockage and penetration issues, resulting in more reliable connectivity [119].
Dynamic Beam Steering	Holographic systems can dynamically steer beams towards specific users or areas by adjusting the phase and amplitude of reflected waves. This beamforming capability improves link reliability and enables adaptive communication tailored to changing network conditions [90].
Energy Efficiency	Utilizing holographic techniques in wireless communication can contribute to energy efficiency gains. By optimizing signal paths and reducing interference, holographic systems can minimize power consumption and extend battery life in devices.
Scalability and Flexibility	Holographic communication offers scalability and flexibility in network design. IRS devices can be deployed in a distributed manner, adapting to diverse environments and communication scenarios, which is beneficial for future network deployments.
Versatile Applications	The benefits of holographic communication extend to various applications, including but not limited to enhanced VR experiences, improved indoor localization, and efficient IoT connectivity. These applications leverage holographic techniques to deliver immersive, reliable, and efficient communication.

and engage with historical individuals. Subjects like physics and art may be made more engaging by visualizing and explaining complex ideas straightforwardly. For example, students studying physics can see 3D holographic simulations of complicated molecules, which helps them comprehend chemical structures. In art class, students can see the creative process of well-known artists and learn important insights into their methods and sources of inspiration.

3) **Entertainment and Gaming** Holographic communication is already being used by the gaming and entertainment sectors to provide audiences with immersive experiences. Fans may enjoy their favourite musicians and entertainers vividly and engagingly right from the comfort of their own homes with holographic concerts and shows. Imagine going to a holographic concert, where the stage is transformed into a holistic experience that surpasses typical live performances with breathtaking graphics and holographic effects. Each performance is a one-of-a-kind and amazing event since fans may dance with the hologram performers and engage with them directly. Holographic communication can also be advantageous to VR games since it allows players to engage more organically and authentically with virtual items and characters. Consider a VR game where players can physically touch and interact with items in the virtual world thanks to holographic projections that mix in perfectly with the game environment. As a result, it becomes harder to distinguish between the actual world and the virtual one, elevating gaming to new heights and offering previously unthinkable levels of immersion.

4) **Business** Holographic communication benefits companies looking to innovate and enhance their processes. By utilising holographic technology, businesses may have virtual meetings and conferences with a greater sense of presence, which promotes international cooperation and lowers travel expenses. Furthermore, holographic displays facilitate immersive marketing and product demos, allowing businesses to present their goods in interactive ways that better engage consumers. Holographic communication-enabled virtual retail experiences improve consumer engagement and offer tailored purchasing experiences. Holographic communication makes real-time help and troubleshooting possible in sectors that need remote support, increasing productivity and decreasing downtime. Additionally, holographic training and simulation technologies enable staff members to learn in fully immersive virtual settings, which promotes creativity and improves teamwork. Holographic communication is a game-changing technology companies can use to enhance consumer engagement, staff training, operational efficiency, and communication with one another and with other industries.

H. CHALLENGES AND FUTURE DIRECTIONS

The challenges and Proposed Solutions in Holographic Communication are summarised in Table. 8.

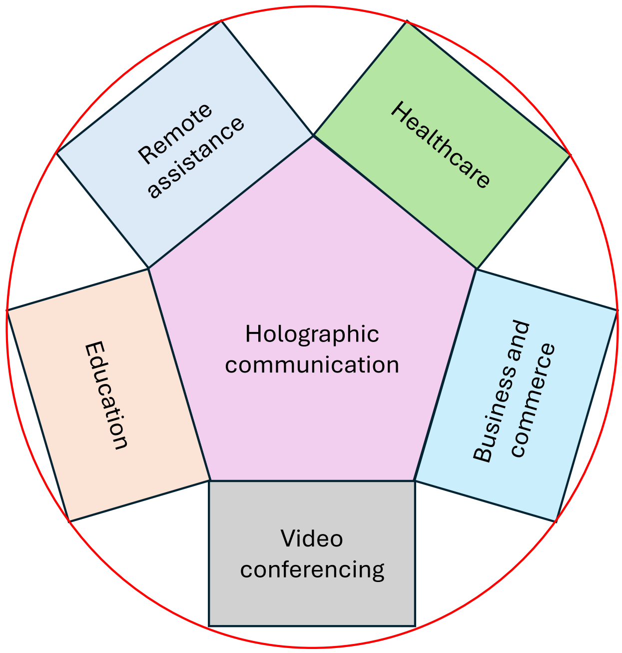

FIGURE 9. **Holographic Communication applications .**

1) COMPLEX SYSTEM DESIGN
The primary challenge in holographic communication is designing complex systems that can efficiently encode, transmit, and render holographic data. This involves addressing data acquisition, compression, and synchronization issues to ensure seamless communication [68].

2) BANDWIDTH AND DATA RATES
Holographic communication demands high data rates due to the nature of holographic content, which requires encoding detailed spatial information. Managing bandwidth-intensive data transmission poses significant challenges, especially in wireless environments [121].

3) REAL-TIME PROCESSING
Achieving real-time processing of holographic data is critical for interactive applications such as holographic telepresence and gaming. Processing holographic content in real-time involves overcoming computational bottlenecks and optimizing algorithms for efficient rendering [122].

4) NETWORK INFRASTRUCTURE
The deployment of holographic communication systems requires robust network infrastructure capable of supporting low-latency, high-bandwidth transmissions. This includes integrating IRS and advanced networking protocols to enhance coverage and reliability [5].

5) QoE
Ensuring a high-quality user experience is essential for the success of holographic communication. This encompasses factors such as resolution, frame rate, latency, and synchronization, which must be optimized to deliver immersive and engaging holographic content [121].

6) INTEROPERABILITY AND STANDARDS
Developing interoperable standards for holographic communication is crucial for enabling compatibility across different devices and platforms. Establishing common protocols and formats can facilitate widespread adoption and ecosystem development [3].

7) SECURITY AND PRIVACY
Holographic communication systems introduce new challenges related to security and privacy, particularly with the collection, transmission, and storage of sensitive multisensory data. Implementing robust encryption and authentication mechanisms is essential to protect user privacy and data integrity [1].

By creating practical algorithms designed explicitly for holographic data, advanced coding and compression techniques play a crucial part in holographic communication, lowering bandwidth requirements and improving transmission efficiency [121]. Furthermore, real-time processing, content optimization, and adaptive rendering are made possible by integration with AI and machine learning techniques, which enhances scalability and system performance [123]. Investigating cutting-edge technologies such as integrated photonics, quantum holography, and terahertz transmission presents viable paths to overcome existing constraints and open up new opportunities in holographic communication [124], [125]. Together, these developments propel the development of holographic communication systems, augmenting their potential and opening up revolutionary applications in various fields.

8) ADVANCED CODING AND COMPRESSION TECHNIQUES
Developing efficient coding and compression algorithms specifically tailored for holographic data to reduce bandwidth requirements and enhance transmission efficiency [126].

9) INTEGRATION WITH AI AND MACHINE LEARNING
Leveraging AI and machine learning techniques for real-time processing, content optimization, and adaptive rendering to improve the scalability and performance of holographic communication systems [122].

10) EMERGING TECHNOLOGIES
Exploring new technologies such as terahertz communication, quantum holography, and integrated photonics to address current limitations and unlock new possibilities in holographic communication [127].

Even though holographic communication has a lot of promise, challenges still need to be removed. The bandwidth requirements for real-time holographic data transmission are one of the primary obstacles. However, developments in

TABLE 8. Challenges and proposed solutions in holographic communication.

Challenge	Description	Proposed Solutions
Bandwidth Constraints	Holographic content requires high data rates, posing challenges for network bandwidth.	Use of advanced compression algorithms and network optimization.
Latency Issues	Real-time interaction demands low latency, which may be hindered by network delays.	Implementation of edge computing, 5G/6G networks, and CDN caching.
Hardware Limitations	Displaying high-quality holograms requires sophisticated and expensive hardware.	Development of cost-effective light field displays and XR devices.
Content Creation Complexities	Generating and rendering 3D holographic content can be complex and time-consuming.	Integration of AI-assisted content creation tools and workflows.
Interoperability with Existing Systems	Integration of holographic communication into current infrastructures and platforms.	Standardization efforts and APIs for seamless compatibility.

network infrastructure, including 5G technology, can assist in resolving this problem. Another challenge is the requirement for defined formats and protocols to guarantee compatibility across various holographic systems. Industry stakeholders may work together to create common standards and promote the use of holographic communication.

Three main components make up the Metaverse: apps, services (such as holographic communication, XR, and Multimedia), and auxiliary technologies (such as 6G wireless networks) [128]. XR and Holographic communication are the primary access technologies the Metaverse's apps and users use to create virtual environments that house social and economic activity. Multimedia communication combines numerous media types that appeal to multiple human senses. Conventional sensors and displays can show muffled media. However, the QoE will be diminished. One way to display holograms is using XR HMDs, which provide various angles to produce 3D effects. As such, there is a convergence between holographic communication and Metaverse, as Metaverse technologies enable the presentation of holograms, promoting interaction between them.

IV. HOLOGRAPHIC COMMUNICATION MEETS METAVERSE

The evolution from holography to holographic communication and its subsequent incorporation into immersive Metaverse experiences is demonstrated in framework paradigm Fig. 10. The four layers show how technology has evolved and come together to reinvent virtual presence and digital engagement. The comparison of Immersive Communication and Holographic Communication is described in Table. 9.

1) **Holography Layer:** The fundamental layer of holography consists of the fundamental ideas and technology that make holographic displays possible. The basis of holography's operation is the interference patterns produced when a laser beam is divided into reference and object waves. 3D views with parallax and depth may be recorded and reconstructed. Light modulation methods, such as phase-shifting components and spatial light modulators, are essential to producing holographic views and are among the key technologies. Holograms and multisensory media are sent over wired and wireless networks in holographic communication. A hologram is a light field recording that faithfully preserves the original parallax and depth of actual 3D objects. With six degrees of freedom (DoF), holographic movies provide immersive watching experiences that let viewers freely move forward, backward, up, down, or left and right to select their favorite viewing perspective [129]. This improves user interaction as opposed to traditional VR apps, which restrict user movement. Furthermore, multimodal data is captured at the source by holographic communication systems utilizing a variety of sensors and replicated at the destination through actuators, displays, and speakers. Users are free to choose which senses to use, taking into account the technology that is accessible as well as privacy and security concerns.
2) **Communication Layer:** Expanding on holography, the communication layer investigates how holographic technology might be used for distant and interpersonal communication. Experiences like holographic telepresence, in which people digitally meet and converse as though they are physically present in the same place, are made possible via holographic communication. In virtual meetings, holographic displays offer a more captivating and immersive experience than standard video conferencing. To improve cooperation and engagement, the communication layer offers interactive experiences that allow users to modify and interact with holographic objects in real-time.
The network infrastructure, the source, and the destination are the three main parts of a typical holographic communication system [1]. Several sensors are used at the source to record holographic material, synchronize multisensory data, encode holographic data, and send data packets according to holographic communication networking standards. To satisfy the needs of holographic communication-enabled applications, holographic communication networks provide source data with predefined performance parameters, including bandwidth, latency, and dependability. On the other hand, the received data is rendered for display at the destination, and other actuators are used to reproduce the original environment recorded at the source. Multisensory media are synchronized; the destination can give the source and network feedback when necessary. Light field displays enable

TABLE 9. Comparison of immersive communication and holographic communication.

Aspect	Immersive Communication	Holographic Communication
Definition	Involves technologies that deeply engage multiple senses to create a realistic experience. Examples include VR and AR.	Utilizes holographic displays and multisensory interactions to render 3D objects in physical space.
User Experience	Focuses on providing a virtual environment that surrounds the user, often with limited interaction with the physical world.	Offers a blend of virtual and physical elements, enabling interactions with 3D objects overlaid on real-world environments.
Display Technology	Relies on head-mounted displays (HMDs) or screens to immerse users in virtual environments.	Uses specialized holographic displays that project light fields to create 3D images visible without additional equipment.
Interactivity	Allows users to interact with virtual environments using controllers, gestures, and voice commands.	Supports natural interactions with holograms using gestures, touch, and voice, integrated with physical space.
Content Creation	Involves the development of virtual environments, often using 3D modeling software and game engines.	Focuses on creating holographic assets and experiences optimized for spatial interactions and real-time rendering.
Applications	Gaming, simulations, training, and entertainment industries.	Applied in telepresence, remote collaboration, education, healthcare, and retail to enhance real-world interactions with digital content.
Key Technologies	VR, AR, XR, spatial computing.	Holographic displays, light field technology, multisensory input/output devices.
Hardware Requirements	Requires HMDs, sensors, cameras, and powerful computing devices.	Relies on specialized holographic displays and sensors for capturing and rendering 3D content.
Use Case Examples	VR gaming, AR navigation apps, and immersive training simulations.	Holographic telepresence, interactive retail experiences, virtual product demonstrations.

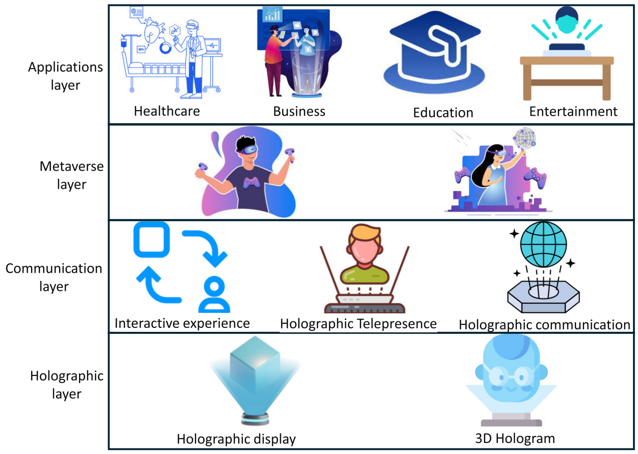

FIGURE 10. Holographic communication meets Metaverse framework.

users to observe genuine 3D holograms without needing specialist equipment, adding to the overall high-quality experience. holographic communication provides immersive experiences in addition to other multimodal media material.

3) **Metaverse Layer:** Through the Metaverse layer, holographic communication is included in the broader framework of virtual worlds and immersive experiences. Holographic technology improves several Metaverse applications in several fields. Section II provides a detailed description of the Metaverse.
4) **Applications layer:** Within the application layer, holographic technology is used to improve user experiences in several fields, including business and commerce, education, healthcare, and entertainment. Every application in the Metaverse layer demonstrates how holographic communication stimulates creativity and immersive interactions across conventional boundaries, empowering a wide range of sectors. the applications with more details are explained in section V.

Holographic communication for the Metaverse offers several benefits that can enhance user experiences and enable immersive interactions within virtual environments. Leveraging holographic communication within the Metaverse, the benefits (as shown in Table. 10) contribute to a more compelling, interactive, and realistic virtual environment that blurs the boundaries between the physical and digital worlds.

By streamlining data processing and cutting latency, edge computing significantly contributes to the Metaverse's holographic communication, improving immersive experiences [130]. Edge computing reduces latency for generating complex holographic material in real-time interactions by placing computational resources closer to end users and devices [5]. Furthermore, edge computing enhances responsiveness and minimizes network congestion by caching and saving holographic data close to consumers [131]. This method improves the sensation of presence and immersion by facilitating smooth real-time interactions and collaborative experiences in virtual environments [132]. Additionally, edge computing ensures optimal performance for producing holographic content and enabling interactive apps by dynamically allocating resources based on demand [5]. Edge computing reduces privacy hazards associated with centralized servers and improves data confidentiality by processing sensitive information locally [133]. Additionally, edge computing designs minimize infrastructure costs while providing scalable virtual experiences [134]. They are also very scalable and economical. The combination of edge computing with next-generation wireless technologies, such as 5G, allows for ultra-low latency and high bandwidth, which are essential for immersive Metaverse applications [135].

This paradigm for experimentation offers a systematic way to incorporate holography into the metaverse. This framework seeks to realize the full potential of holographic communication in the metaverse by emphasizing fundamental holographic technologies, effective communication techniques, and smooth integration into virtual surroundings. Iterative testing and improvement of this framework should

TABLE 10. Key aspects of holographic communication in the Metaverse.

Point	Description
Enhanced Immersion	Holographic communication enriches the Metaverse by providing users with realistic and immersive experiences.
Multi-sensory Engagement	Holographic communication extends beyond visual and auditory stimuli to incorporate other senses, such as touch, smell, and taste.
Spatial Awareness and Presence	Holographic representations in the Metaverse enable users to gain spatial awareness and presence within virtual environments.
Communication and Collaboration	Holographic communication facilitates more effective communication and collaboration in the Metaverse.
Personalized and Interactive	Holographic content in the Metaverse can be personalized and dynamically generated based on user preferences and interactions.
Real-time Interaction	Holographic communication supports real-time interactions and feedback, enabling synchronous collaboration and social interactions within virtual spaces.
Accessibility and Inclusivity	Holographic communication can improve accessibility and inclusivity in the Metaverse by accommodating diverse user needs and preferences.

be part of future efforts to handle new possibilities and problems in this quickly developing industry. Table. 11 illustrates the proposed experimental framework for integrating holography with the metaverse.

Human Factors in Holography and Metaverse Integration: To guarantee successful and immersive experiences, human aspects must come first when integrating holography with the metaverse. Comprehending user perception and interaction with holographic imaging is critical to optimize the technology and user experience. First and foremost, visual comfort and perceptual quality are essential factors. The resolution, depth perception, color correctness, and picture stability of holographic displays will all be evaluated using our experimental setup. We will also pay close attention to visual comfort to avoid problems like eye strain and tiredness. We will gather objective data using eye-tracking and gaze analysis to assess comfort, picture quality, and subjective feedback through questionnaires during user trials where people engage with holographic material under various circumstances.

Additionally significant is user interaction and cognitive burden. We will investigate user interaction with holographic content, analyzing the usability and intuitiveness of various input techniques, including wearables, voice commands, and gestures. To make sure that interactions go well and users are well-rested with cognitive demands, task-based tests will be carried out to assess efficiency, accuracy, and cognitive effort. Assessing holographic environments' sensation of presence and immersion in great detail is vital. We will simulate several holographic settings using VR headsets and other immersive technologies, monitoring the experience of presence through user input and physiological reactions such as skin conductance and heart rate. This will make it possible to guarantee that holography improves the immersiveness of virtual experiences.

Additionally, the framework will handle user population diversity adaptation. Various demographic groups, including those with impairments, will participate in usability research. This strategy will ensure that all users can make use of the technology by assisting in the identification of accessibility hurdles and providing direction for the creation of more inclusive holographic interfaces. Trials will adjust parameters, including reaction times, animation velocities, item dimensions, and motion, to identify ideal conditions that improve user awareness and lessen confusion. The holographic systems will be regularly improved and refined based on user study insights to satisfy user requirements and expectations.

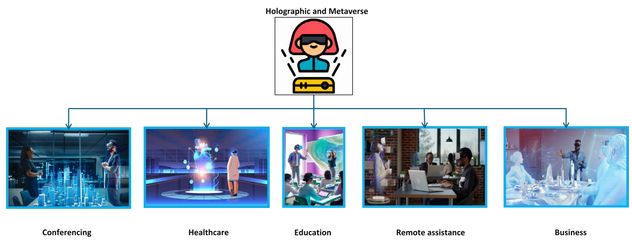

FIGURE 11. Use cases of holographic communication empowered Metaverse.

V. USE CASES

This section showcases a range of holographic communication-empowered use cases in the Metaverse, divided into six categories: education and training, healthcare, entertainment, business, conferencing, and Remote assistance (as shown in Fig. 11). The chosen use cases are emphasized because they have the most significant potential to drastically alter our way of life, even if it is unrealistic to include every possible holographic communication for Metaverse applications. Table. 12 describes the benefits of a framework for use cases and the role of Holographic communication in each use case.

A. EDUCATION

Immersion technologies are used in holographic communication-empowered education in the Metaverse to produce significant educational experiences. Immersion learning environments can be created by combining multimedia elements like music and film with sensory inputs like temperature, light, haptic feedback, and fragrance. For instance, students engage with virtual flowers with multimodal technology in biology and art courses within the Metaverse by touching, smelling, and viewing. The

TABLE 11. Proposed experimental framework for integrating holography with the Metaverse.

Layer	Objective	Components	Experimental Setup
Holography Layer	Establish foundational technologies for creating and rendering holograms.	• Holographic Displays: Light-field, volumetric, and other rendering technologies. • Interference and Light Modulation Techniques: Techniques like beam steering and spatial multiplexing. • Advanced Coding and Compression: Algorithms for efficient bandwidth usage and high-quality rendering.	• Controlled Environment Testing: Evaluate holographic displays in various conditions. • Optimization Trials: Experiment with coding and compression techniques.
Communication Layer	Facilitate real-time transmission and interaction of holographic content within the Metaverse.	• Edge Computing Infrastructure: Reduce latency with edge computing nodes. • Integration with AI/ML: Adaptive content rendering and optimization of holographic streams. • Network Protocols: Develop and test protocols for high-bandwidth, low-latency communication.	• Latency and Bandwidth Testing: Measure requirements for holographic applications. • Real-Time Interaction Trials: Test responsiveness and synchronization across locations.
Metaverse Layer	Integrate holographic communication seamlessly within the Metaverse to create immersive and interactive environments.	• Virtual Environment Integration: Design virtual spaces supporting holographic interactions. • User Interaction and Personalization: Implement gesture, voice, and input-based interactions with dynamic content generation. • Security and Privacy Protocols: Develop security measures to protect holographic data.	• User Experience Testing: Evaluate immersion and interactivity with real users. • Scalability Assessments: Test the framework's scalability and performance.

TABLE 12. Benefits of framework for use cases.

Metaverse Use Case	Description	Benefits of Holographic Communication
Holographic Telepresence	Users from different locations can meet virtually as holograms.	Facilitates immersive and realistic remote interactions.
Education and Training	Holographic materials enhance learning by providing 3D visualization of complex concepts.	Improves understanding and engagement in educational content.
Healthcare	Enables remote consultations and surgeries through holographic representations of patients.	Enhances communication and visualization in medical settings.
Entertainment	Delivers immersive experiences in gaming, sports broadcasting, and holographic television.	Enhances user engagement and realism in entertainment content.
Remote Assistance	Supports remote technical support by visualizing problems and demonstrating solutions in 3D.	Improves efficiency and accuracy in troubleshooting and repairs.

student's educational experiences in a variety of courses are expanded by holographic communication and Metaverse technology, which allow them to visually examine global weather conditions.

Professionals can benefit from multimedia-rich instruction made possible by holographic communication, which helps them understand crucial circumstances better. By mimicking real-world textures, sounds, and visual clues, this approach makes learning more realistic. By facilitating virtual interactions that transcend geographical boundaries, holographic communication in the Metaverse raises student participation in the classroom. For example, holographic simulations for nursing education are made possible by technologies such as Microsoft HoloLens, which enable students to carefully view and interact with virtual models. This creative method shows the revolutionary potential of holographic communication in Metaverse education by not only improving understanding but also enabling affordable access to otherwise expensive instruments and equipment.

The way children learn in schools is being revolutionized via holographic communication. With the use of holographic projectors in virtual classrooms, teachers may provide captivating lessons that make abstract concepts come to life. Pupils get access to real-time scientific experiments, lifelike avatars of historical figures, and virtual tours of ancient sites. Holographic communication presents new possibilities for distance learning for teachers. Instructors may present 3D models, diagrams, and simulations in virtual classrooms where students can participate. This experiential learning method improves understanding and memory retention while raising learning effectiveness and engagement.

B. ENTERTAINMENT

In the Metaverse, holographic communication-enabled entertainment is a revolutionary advancement over traditional forms of entertainment, especially in gaming, sports coverage, and television transmission. This technology allows immersion levels that go beyond those possible with conventional 2D panels. Holographic Television uses holographic communication technology to convey material like news, ads, and movies, offering a fresh way of broadcasting in the Metaverse. More sophisticated holographic displays—like light field displays—present remarkably lifelike 3D visuals in contrast to traditional 2D views, making them more user-friendly televisions. Holographic communication transforms the way people watch sports broadcasts by offering 3D views from several perspectives. Holographic projections, for example, may be used to display soccer matches on surfaces such as coffee tables, providing spectators with a 3D image of the whole game. Through virtual stadium watching, this immersive method improves the viewing experience.

Furthermore, non-immersive and immersive gaming experiences are included in the category of holographic gaming. Flat holographic displays provide visuals in non-immersive holographic gaming, while controllers or keyboards allow users to interact with holographic characters and objects. With XR HMDs, such as AR and Mixed Reality (MR) glasses, holographic components may interact with the human eye directly. On the other hand, immersive holographic gaming immerses users completely in virtual worlds where they may engage with holographic material like that of conventional gaming. VR equipment and occluded holographic displays augment this immersive experience by offering personalized near-eye displays. Immersion HMDs and light field displays, for example, enable holographic communication in entertainment inside the Metaverse, which promotes unprecedented realism and engagement.

C. HEALTHCARE

Online medical services are revolutionized by holographic communication-enabled healthcare in the Metaverse, which offers creative ways to improve patient-physician relations. There are clear benefits to this technology, especially when it comes to situations where there is restricted direct physical contact due to contagious illnesses. When holographic communication is used instead of typical video-based remote medical sessions, information accessibility is improved. Doctors may see more in-depth information about patient behaviour than just facial expressions with the use of holographic projections. With the aid of smart gloves, doctors can even evaluate the patient's physical state via haptic feedback. This remote evaluation is made possible by sensor and actuator arrays on the patient's end that capture and send haptic signals. Furthermore, remote surgical operations can be performed with the use of robotic aid. These movements are replicated on the patient's body by robots, which enables surgeons to operate remotely and see a holographic image of the patient.

Holographic communication has advanced much in telemedicine already. Holographic technology allows medical professionals to see scans and photos in three dimensions, confer with patients virtually, and even participate in surgery from a distance. In addition to increasing access to specialist healthcare services, this increases the standard of care by enabling medical professionals to diagnose and treat patients more accurately thanks to immersive holographic graphics.

D. CONFERENCING

Virtual conference experiences are revolutionized by holographic communication-enabled conferencing in the Metaverse, which seamlessly integrates technology to improve presence and participation. Holographic communication is one important use case that allows people in different places to virtually meet. Holographic displays and sensory booths are components of every holographic communication system. Human input is captured by cameras in the sensory booths, which creates a point cloud picture. The creation and playing of multimedia can be facilitated by additional sensors and actuators, which can project distant users' holograms onto holographic displays. Video conferencing became an essential tool for virtual meetings during the COVID-19 epidemic, allowing for distant communication and cooperation. But traditional video conferencing formats, with 2D screens that display people at a smaller size, do not have the same immersive features as in-person conversations. Holographic communication provides a more realistic substitute thanks to displays that faithfully depict people as they appear on the screen. Holographic conferences that are done well may create a sense of presence and participation by obfuscating the distinction between in-person and virtual meetings. Furthermore, holographic conferences can make physical interactions like handshakes easier by integrating smart gloves. The combination of conference and holographic communication shows how Metaverse-enabled technology might revolutionize virtual collaboration and communication.

E. REMOTE ASSISTANCE

In the Metaverse, holographic communication-enabled remote support is a game-changing tool for helping customers with appliances, cars, or machinery. Due to the limits of verbal descriptions, traditional technical support techniques like phone consultations sometimes face difficulties in successfully expressing solutions. Videos continue to have size and viewing angle limitations despite their better visualization. The specific location of the problem at a precise size may be visualized in three dimensions thanks to holographic communication. This feature greatly improves user experience by allowing technical support staff to walk customers through repair procedures and provide visual explanations of remedies. Therefore, by utilizing stronger visual signals, holographic communication enhances the efficacy of after-sales services, enhancing user comprehension and enabling effective issue resolution in the context of the Metaverse.

F. COMMERCE AND BUSINESS

The Metaverse's holographic communication-powered business and commerce provide a fresh way to approach online and in-store retail experiences. Because verbal descriptions and static photos or videos are the main components of traditional online purchase techniques, it can be difficult for buyers to effectively judge product qualities like colour, texture, and size. Customers may evaluate things precisely with holographic communication's visual inspection capability, which offers precise measurements, colours, and 3d geometry that nearly mimic reality. Furthermore, cutting-edge holographic communication technologies enhance the shopping experience by appealing to a variety of senses, including the sense of smell. Smart gloves interact with objects in a holographic shopping environment in virtual retail locations resembling enormous malls, thanks to enhanced holographic communication systems. The immersive experience exceeds standard retail methods within the context of the Metaverse by blending the lines between online and in-person commerce and offering a genuine virtual shopping experience.

VI. CHALLENGES, OPPORTUNITIES AND FUTURE TRENDS

Holographic communication allows users to see 3D holograms at various locations, tilts, and angles. A more realistic and immersive experience may be created for users by synthesizing information from several views to create holograms that provide continuous and comprehensive visual information [136]. However, to do this, many data must be sent. Stringent data rate and latency requirements are the primary hurdles in holographic communication. Within data processing, networking, and communication, we highlight possible approaches to address this difficulty in this subsection.

A. CONTENT SELECTION, COMPRESSION, AND PREDICTION

Depending on the kind of sent data (e.g., volumetric-based or image-based holograms), a high data rate is required for holographic communication. Requirement can range from hundreds of Mbps to several Tbps. Reducing the quantity of the data, for instance, by broadcasting just the most essential portions of a hologram using viewpoint-based content selection in holographic communication, is one method to ease the necessity for data rate [152]. Some aspects of the hologram might not need to be communicated since they might not be seen depending on the user's position, viewpoint, and obstructions. Even with the selective transmission, there are still two problems. First, when a user watches a hologram, 6 DoF (yaw, pitch, roll, up/down, left/right, forward/backwards) must be considered for an immersive holographic communication experience. This makes selecting material depending on the user's viewpoint a challenging task. Furthermore, tracking the location and viewpoint of the user is difficult without head-mount devices like VR headsets and calls for techniques like full-body tracking [137] or eye tracking [138].

Using data compression is another way to lower the needed data rate. Current media codecs may achieve compression ratios ranging from 250:1 to 1,000:1 for 2D real-time video [5]. Likewise, data compression and format conversion may be used to minimize the amount of data in holographic communication. The authors of [139] suggest a lossy real-time colour encoding technique that uses point clouds' interframe redundancy. Furthermore, multiview coding (MVC) for LFV-based streaming is offered in [140], considering the significant connection between various views in a hologram. MVC increases the compression rate by examining both horizontal and vertical correlations of pictures at nearby angles and tilts. Meanwhile, standards organizations have worked hard to condense holograms. Video point cloud compression (V-PCC), for instance, was developed by the Moving Picture Experts Group (MPEG) by splitting point clouds into two distinct video sequences that record the texture and geometry information, respectively [141]. For holographic communication, the Joint Photographic Experts Group (JPEG) aimed to offer a standard representation structure that would make it easier to compress material that was point cloud- or LFV-based [142]. In [143], the authors examine several codecs for holographic compression and the reorganization and compression of holograms.

Additional latency arises from retransmissions resulting from lost data packets. The lost data packets can be retrieved using anticipated data based on historical knowledge about an item, such as its trajectory, to prevent the retransmission delay. For instance, packets can be retrieved from a short-term forecast by examining user actions, gestures, or motions [144] or from an LSTM-based prediction of human actions and movements in 3D [145]. To minimize packet loss and shorten the holographic communication latency, data packets might be produced at the receiver side by anticipating content [71].

B. COMMUNICATION AND NETWORKING SOLUTIONS

Various communication and networking solutions, such as computer architectures, transport protocols, and physical layer technologies, have been studied to meet the delay and data rate requirements of holographic communication and data processing. Holographic communication requires processing input from various sensors to create a 3D model of the item, which is then rendered and recreated at the receiving end [1]. However, the heavy effort of data fusion and rendering may cause a lengthy processing delay because of the restricted computational power of local devices [146]. Cloud computing was established to handle heavy computer demands for data processing in holographic communication. However, massive data transfers to the cloud may cause a significant transmission latency [147], making them unsuitable for real-time holographic communication. Since MEC servers are situated close to consumers and have substantial processing power, assigning computing jobs to them for data processing seems like a viable approach [148]. Functions like data fusion, data compression, and data rendering may be virtualized and dynamically installed on MEC servers with the help of network function virtualization (NFV). Before rendering in this scenario, collected data from various sources may be combined, fused, and synchronized at a MEC server [18]. Furthermore, combining computing resources at cloud servers, MEC servers, and local devices proposes a multitier computing scheme for 6G networks that can be used for holographic communication. This allows for collaboration among various servers to achieve low latency for data transmission and high computing capacity for data processing [147], [149]. Flexible computer resource management should be created to enable multitier computing for holographic communication. By integrating computing resources on multiple tiers, material may be processed at separate servers to utilize computing resources efficiently. For instance, split rendering allows a local device and a MEC server to work together to jointly decode and generate holograms by the content [5].

Transport layer optimizations are also essential to meeting holographic communication's strict latency and high reliability requirements. The requirements of holographic communication are nearly impossible for current transport protocols, such as user datagram protocol (UDP) and transmission control protocol (TCP). To enhance real-time communication dependability and delay performance, new UDP-based protocols are proposed, namely QUIC over HTTP/3 [150]. While QUIC can be a viable solution for holographic communication, offering a quality-managed low-delay streaming alternative, most current research on the technology focuses on regular 2D video streaming services [122]. Furthermore, a hologram's broadcast might have several substreams representing several points of view, each with a distinct priority and QoS need. In this situation, priority must be given to transmitting the most essential substreams. To accomplish this goal, a new transport protocol for holographic communication is created in [151] that offers flow-level granular control to meet the various QoS needs of multiple flows. Furthermore, a TCP-based adaptive retransmission method is intended to minimize retransmissions by packet analysis and differentiation [152]. To minimize retransmissions, for instance, only crucial data—such as the information required to depict the portion of the hologram in the user's field of view—will be sent again if the corresponding packets are lost.

Supporting a high data rate for holographic communication depends on physical layer technologies. Holographic communication needs a data rate of several Tbps to transmit high-resolution LFV-based holograms, which existing 5G networks cannot provide [153]. THz communications have the potential to provide holographic communication with Tbps-level data rate as they have a higher frequency and a greater bandwidth than mmWave in 5G [154]. Dense deployment of access points and extremely tiny beams can increase connection density and communication reliability to offset the substantial propagation loss of Thaz communication [155]. To offer sustainable LoS networks for holographic communication, more research is needed on deploying THz base stations, predicting user movements, and the absorption and reflection characteristics in the THz regime [156]. Visible light communication (VLC), which has much accessible bandwidth, can offer an alternative to THz communications for holographic communication [157]. With its fast transmission data rate [71] and precise placement [158], VLC may be able to provide both indoor user monitoring and holographic communication. In [159], VLC and THz communication coordination are examined to deliver dependable service at a high data rate.

C. DATA PRIVACY

Because so much highly detailed personal data is collected and processed, holographic communication in the Metaverse creates serious data privacy issues. Biometric data such as speech, gestures, bodily movements, facial expressions, and even possible emotional states are included in this data. This data has a higher risk of misuse or unauthorized access since it is frequently transferred in real-time between networks inside the Metaverse. The Metaverse's immersive experience comprehensively monitors user interactions, preferences, and habits. This data may be compromised for even more malevolent reasons, such as profiling and targeted advertising. To safeguard their privacy and stop misuse, it is essential to ensure that users have control over their data and are well-informed about how it is used.

D. SECURITY

Holographic communication inside the Metaverse poses notable security obstacles, rendering these systems appealing to malevolent actors. Cyberattacks may entail spoofing or deepfaking holographic content, intercepting holographic feeds, or even impersonating users. These actions might have dire repercussions, especially in delicate industries like healthcare or business. Furthermore, because holographic communication is real-time, low-latency, high-bandwidth networks are necessary. However, these networks can be attacked if they are not well protected. The security and integrity of holographic communication inside the Metaverse are seriously threatened by weak encryption, unprotected communication channels, and other network weaknesses that might be used to interrupt services, intercept private information, or initiate denial-of-service assaults.

E. BANDWIDTH REQUIREMENTS

Holographic communication demands high bandwidth due to the complexity of transmitting 3D data in real-time. Meeting the requirements efficiently remains a challenge [1].

F. LATENCY AND REAL-TIME RENDERING

Achieving low latency for real-time rendering of holographic content is critical for immersive experiences. This requires optimizing network architectures and rendering techniques [121]. Content Compression and Transmission: Efficient compression and transmission of large holographic data sets pose technical hurdles. Developing robust encoding schemes for reducing data size without compromising quality is essential [160]. Integration with 5G and Beyond Seamless integration of holographic communication with advanced wireless networks like 5G and beyond requires addressing interoperability and standardization challenges [161].

The research directions and potential solutions to implement high-QoE holographic communication systems are discussed in this section. Our attention is directed towards the protocols and methods at the sources, networks, and destinations. The sources, networks, and destinations are cohesively related and impact each other even when considering them separately—for example, a high data compression rate at the source results in reduced network traffic. Additionally, edge intelligence at the network, source, and destination is a crucial technology that may work together to improve the holographic communication system to satisfy the technical specifications [162]. Conventional multimedia communications use a buffer to send or receive data to reduce jitter and network delay. Nevertheless, systems with limited memory cannot accommodate holographic communication's enormous data rates (up to several Tbps) and unprecedentedly massive buffers. The main challenges facing holographic communication systems are as follows:

1) **Create effective methods for encoding and decoding holograms:** Sending uncompressed holographic data directly might result in significant network traffic, which raises packet losses and end-to-end delay. However, there is a trade-off between calculation delay and the efficiency of encoding and decoding; a high encoding rate causes a lengthy computation latency, and vice versa. Jointly designing appropriate encoding and decoding algorithms while taking user QoE criteria and real-time network status into account is problematic.
2) **End-to-end latency:** Provide data packets with end-to-end latency that is bounded and guaranteed and that users or the system can define. It is preferable to transmit holographic communication data packets deterministically at a predetermined time since buffering holographic communication data is complex because of the big data size. Otherwise, it is possible to transmit several holographic communication data packets in a coordinated manner. Current networks employ best-effort delivery, which has a big tail in the probability density function of delay and does not allow users to adjust the latency. holographic communication networks must supply data packets with assured and limited end-to-end latency and let users and applications choose latency settings.
3) **Accurately synchronize several senses:** Holographic communication systems employ several human senses, necessitating the synchronization of several actuators, speakers, displays, and source sensors. Any asynchronous data can drastically lower the quality of experience. Additionally, precise synchronization raises computation cost, memory size, and end-to-end latency.
4) **Encourage highly engaging apps:** Motion capturing in high-interactivity holographic communication applications often requires a frame rate of more than 60 fps. Holographic data is vast in single frames. Therefore, a high frame rate can significantly increase the required data and network bandwidth. Also, these applications need minimal end-to-end latency—less than one millisecond, for example. Given that the end-to-end latency of the current network is more than 1 ms and that the encoding and decoding delay can reach several hundred milliseconds, enabling high-interactivity holographic communication applications is a significant difficulty.
5) **Heterogeneous technologies:** To satisfy the bandwidth requirements of the Metaverse, mobile-edge computing (MEC) can benefit from merging many technologies into a 6G network. However, because of this integration, there are difficulties in managing various communication resources and services, including higher queuing delays and network congestion. DT-assisted MEC can use AI models to identify overloaded networks and anticipate busy periods when offering Metaverse services. Once bottlenecks in the network are identified, other frequency bands can be requested for merging or multi-carrier switching, and the IRS reflection beams can be shifted toward more crowded locations. It is possible to assign NOMA clusters wisely to support many users or different types of data from a single user. Although theoretical research has optimized transmission throughput and latency in DT-assisted MEC, practical implementation and validation are still lacking. Prototypes of DT-assisted MEC should be deployed, thorough data-gathering pipelines should be put in place, and both directions of Physical to Digital (PT2DT) processes should be synchronized in future studies. It is crucial to look into how power synchronization is used and where DTs should be placed in the MEC network.
6) **experience of user:** Along with the QoS/QoE, taste and smell may be part of the Metaverse's sensory experiences. People differ in their preferences and sensitivity to sensory inputs, like in the real world. Therefore, the human five senses must be considered in the future Metaverse, which poses a significant challenge, i.e., precisely simulating user experience to define QoE, considering individual preferences, sensitivities, and cognitive reactions to various sensory inputs. Users in the same environment employ edge computation resources (such as cache memory and computation frequency) and communication resources (like spectrum) within the 6G mobile-edge empowered Metaverse framework. Ensuring fairness in QoE and resource distribution is crucial to preventing problems like network congestion, system failure, and user disengagement brought on by unjust resource allocation. The researcher should develop user models, machine learning techniques, and adaptive systems that can dynamically modify sensory stimuli to suit personal preferences. Furthermore, more research is required to determine how to use AI at the edge intelligence to provide personalized experiences and enable customized Metaverse services like suggestions for visual material.

7) **AI Generator:** AI-generated employs AI techniques to create digital material, such as music, photographs, and natural language. Through the use of AI models, it creates a variety of realistic virtual landscapes, people, and storylines that enhance the Metaverse experience. However, because of limitations in processing power and resources available on remote servers, the creation and display of such material in real-time pose challenges. Additionally, there is still a long way to go before data privacy, security, and interoperability across many platforms and devices are guaranteed. To meet the needs of AI-generated and numerous users in the Metaverse, a significant amount of computing power is required for effective data transmission and processing inside the 6G mobile edge architecture. Developing methods for protecting privacy in AI operations, safe protocols for sharing data, and encryption approaches that protect user data from various angles—such as algorithm design, 6G communications, and edge computation—may be the subject of research efforts.

VII. CONCLUSION

At the vanguard of disruptive technologies, holographic communication has the potential to completely change digital interactions and expand the definition of virtual reality. This review examined the fundamental ideas, uses, and incorporation of holographic communication with the Metaverse, emphasizing its significant influence in various fields. The meeting point of holographic communication and the Metaverse presented a new paradigm for immersive encounters, which opens up new avenues for commerce, education, healthcare, entertainment, and remote help. Users may participate in lifelike interactions and cooperative activities previously limited by physical constraints by utilizing holography in virtual worlds. However, there were drawbacks to integrating holographic communication into Metaverse ecosystems, such as requirements for data processing, latency, and scalability. To fully utilize the potential of holographic communication, new approaches, and technical developments will be needed to address these issues. Therefore, this survey highlighted the revolutionary potential of holographic communication and illustrated how it will revolutionize digital connection and participation. By synthesizing current scientific findings and business successes, we showed how holographic technologies enhance virtual worlds and revolutionize human interaction in the digital age.

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