Review

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A Survey on Real-Time Metaverse: Challenges and Opportunities

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A Survey on Real-Time Metaverse: Challenges and Opportunities

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Abstract: Metaverse represents a multifaceted digital universe integrating diverse technologies to create immersive, interconnected virtual environments. Key components foundational to a Metaverse structure include the infrastructure layer for hardware and network support, the human interface layer utilizing virtual reality (VR) and augmented reality (AR) devices, and a decentralized layer leveraging blockchain for secure digital asset management. Further components encompass spatial computing for realistic 3D environments, the creator economy for content generation and monetization, and discovery mechanisms for navigation within a Metaverse. VR, AR, blockchain, artificial intelligence (AI), the fifth-generation (5G) networks, and the Internet of Things (IoT) are central to Metaverse functionality, enabling real-time interactions and data integration. Real-Time Metaverse aims to replicate instantaneous real-world interactions, requiring advanced technological infrastructures for seamless data exchange. Critical challenges include ensuring low latency, high bandwidth, scalability, and robust security measures. Metaverse's potential spans various domains, promising to revolutionize social interactions, entertainment, workplaces, and education through dynamic, immersive experiences. Ongoing advancements in high-performance computing, cloud services, and AI-driven technologies are essential for addressing existing barriers and achieving a cohesive, secure, and inclusive Metaverse ecosystem. Future research must focus on enhancing user experience, accessibility, and standardized interoperability to fully realize the transformative capabilities of a Metaverse.

Keywords: metaverse; real-time metaverse; blockchain; artificial intelligence (AI); virtual reality (VR); augmented reality (AR); 5G networks

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1. Introduction

Metaverse is a complex, multi-component, hierarchical construct integrating various technologies and systems to create an immersive, three-dimensional (3D) interconnected virtual universe [1]. Figure 1 illustrates a seven-layer architecture of Metaverse. At its foundation, the *Infrastructure Layer* is the technical backbone that ensures the Metaverse operates smoothly and efficiently [2]. It includes the physical hardware like servers and data centers and the cloud computing resources that provide the necessary computational power. A robust infrastructure is essential for scalability, enabling the Metaverse to grow and accommodate increasing users and experiences.

The *Interface Layer* determines how users interact with the Metaverse [3], which includes the devices they use, such as VR headsets, AR glasses, and smartphones, as well as the software interfaces that make the Metaverse accessible and user-friendly [1]. A well-designed interface is key to ensuring that the Metaverse is easy to navigate and engaging, making it accessible to a wide range of users, regardless of their technical expertise.

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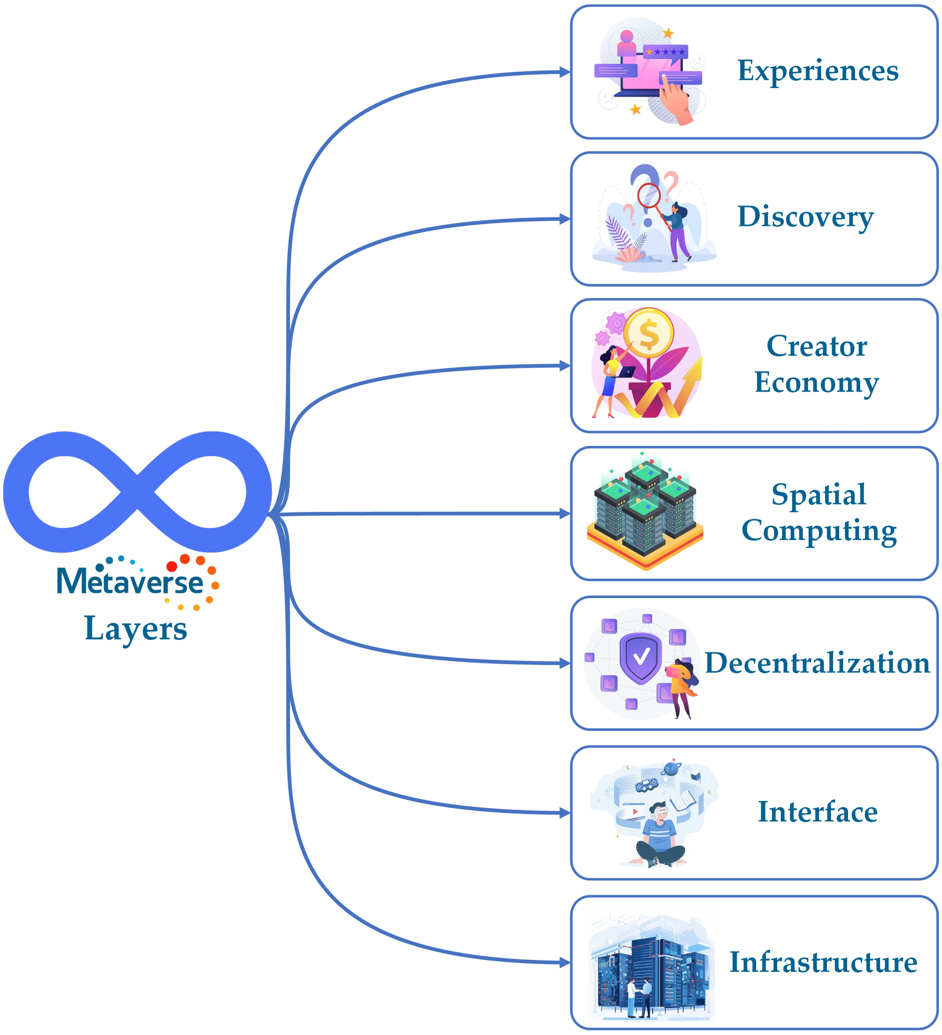

Figure 1. An Illustration of the 7-Layer Metaverse Architecture.

The core of the Metaverse is the *Decentralization Layer*, which ensures that the Metaverse operates without being controlled by a single entity. The decentralization layer is crucial for maintaining user autonomy, privacy, and security, often achieved through blockchain technology [4]. By distributing power and data across a network of users, decentralization enables true ownership of digital assets, allowing participants to engage in transactions and interactions with confidence that their data and property are secure [5].

Spatial Computing plays an essential role in a Metaverse, which merges the physical and digital worlds to create immersive experiences. The computing layer utilizes technologies like virtual reality (VR) [6], augmented reality (AR) [7], mixed reality (MR) [8], and haptic feedback systems [9] allowing users to interact with digital objects as if they were part of the physical world. Spatial computing makes the Metaverse more tangible and real, enabling users to experience and manipulate 3D environments in ways that go beyond the limitations of traditional computing interfaces [10].

Creator Economy is the engine that drives innovation and content within the Metaverse [11]. This layer supports the tools and platforms that allow users to create, distribute, and monetize digital content and experiences [12]. The creator economy fosters a vibrant, self-sustaining ecosystem where creativity is rewarded by empowering individuals to produce and profit from their creations [13]. The creator content fuels the diversity of experiences available and encourages continual growth and expansion of the Metaverse.

Discovery layer helps users navigate the vast expanse of the Metaverse [14]. It includes search engines, social networks, and recommendation systems that guide users towards content, experiences,

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and services that match their interests [15]. Effective discovery mechanisms are essential for helping users find and engage with what they are looking for, ensuring that the Metaverse remains a dynamic and accessible space.

Finally, the *Experiences layer* is where the true value of the Metaverse is realized [3]. It encompasses all the activities users can participate in, from socializing and gaming to education and commerce. The quality and variety of these experiences make the Metaverse an engaging and appealing place for users to spend their time. The Experences layer is constantly evolving, driven by the creativity of the community and the opportunities enabled by the other layers.

Metaverse is driven by several key technologies that collectively create the immersive, interactive, and interconnected nature [16], as conceptually shown in Figure 2. Blockchain technology underpins the decentralization and security aspects of the Metaverse [17]. Blockchain ensures that digital assets, including virtual currencies, property, and identities, are securely managed and owned by users without relying on centralized authorities [18]. Blockchain technology provides transparency, immutability, and trust, enabling users to engage in secure transactions and interactions within the Metaverse [19]. By leveraging blockchain, the Metaverse can maintain a fair and open economy where users have full control over their digital assets and data.

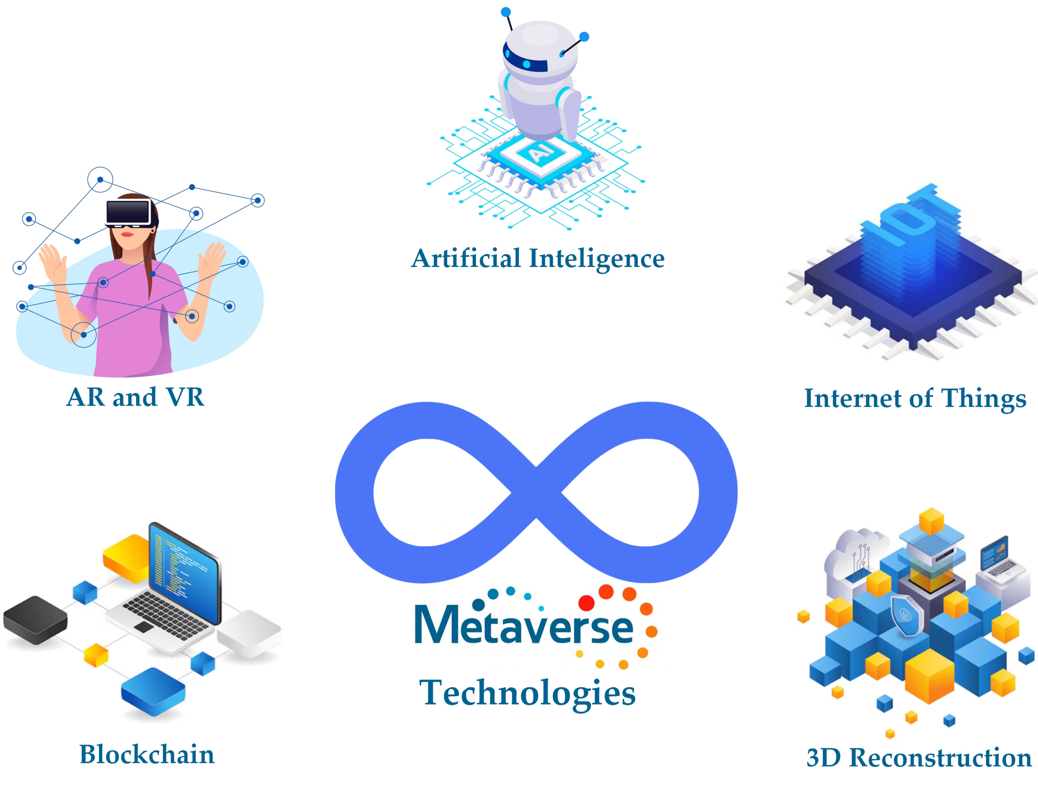

Figure 2. Metaverse technologies.

Augmented Reality (AR) and Virtual Reality (VR) are at the forefront of creating immersive experiences within the Metaverse [20]. VR creates fully digital environments that users can explore and interact with using devices like headsets and gloves, effectively transporting them to another world. AR, on the other hand, overlays digital content in the real world, enhancing users' perception and interaction with their surroundings [21]. Together, AR and VR provide the sensory and spatial components that make the Metaverse feel tangible and engaging, allowing users to interact with digital spaces in ways that mimic real-world experiences.

Artificial Intelligence (AI) technologies drive the intelligence and responsiveness of the Metaverse [22]. AI powers various aspects of the Metaverse, including creating realistic virtual characters to interact with users and generating dynamic and adaptive environments [23]. AI also plays a crucial role in personalization, learning from users' behaviors and preferences to tailor experiences that meet individual needs. By enabling complex decision-making and learning within the Metaverse, AI ensures that the digital world is not only immersive but also intelligent and responsive.

Internet of Things (IoT) technology bridges the gap between the physical and digital worlds by connecting real-world edge devices to the Metaverse [24]. IoT technology allows physical objects, from home appliances to vehicles, to communicate and interact with the digital environment. IoT integration enables real-time data exchange and interaction, making the Metaverse a more seamless extension of the physical world [2]. For instance, IoT can allow users to control real-world devices within a virtual environment or bring physical data into the Metaverse for analysis and visualization.

Similarly, 3D Reconstruction technology is vital in creating detailed and accurate digital representations of real-world environments [25]. This technology captures and digitizes physical spaces, objects, and people, bringing them into the Metaverse with high fidelity. 3D reconstruction allows for creating virtual replicas of real-world locations, enabling users to explore and interact with these spaces as if they were physically present [26]. 3D capabilities are particularly valuable for applications such as virtual tourism, real estate, and architecture within the Metaverse.

5G technology enables the metaverse's critical performance metrics, such as high-speed and low-latency internet connectivity, to function effectively. The 5G ensures that real-time data transfer occurs seamlessly, allowing for immersive interactions within virtual environments and minimizing the lag and buffering, allowing users to engage in real-time interactions. Furthermore, 5G promises better security features than its predecessors, making it more challenging for cybercriminals to exploit vulnerabilities in the network.

All these technologies, working together, form the backbone of Metaverse, enabling users to create, explore, and interact in a fully realized digital universe [2].

The rest of this paper is structured as follows. Section 2 gives a general overview of the real-time Metaverse concept. Section 3 introduces the key enabling technologies. The state-of-the-art real-time Metaverse is discussed thoroughly in Section 4, followed by the challenges and opportunities illustrated in Section 5. Finally, Section 6 concludes this survey with future directions.

2. The Real-Time Metaverse

Over the past few years, the idea of the "Metaverse" has transitioned from a theoretical concept to a rapidly growing reality, captivating the minds of technologists, futurists, and the general public [27]. The spike in interest is mainly driven by the rapid improvements in digital technology [28], together with a growing desire for immersive virtual and augmented experiences. As we approach the beginning of the digital transformation, the implications of the *Real-Time Metaverse* extend far beyond mere entertainment. In the realm of work, remote collaboration can be transformed into a more interactive and engaging experience [29]. Virtual offices and meeting rooms can offer a sense of presence, making remote interactions more natural and effective [30].

Similarly, education can benefit immensely from the Real-Time Metaverse [31]. Virtual classrooms and laboratories can provide immersive learning environments where students can explore complex concepts through interactive simulations and real-time collaboration with peers and instructors. These advancements can democratize access to high-quality educational resources and professional development opportunities, bridging geographical and socioeconomic gaps.

Social interactions within the Real-Time Metaverse can also be revolutionized [32], creating more affluent and more meaningful connections despite physical distances. Social platforms can offer immersive experiences that allow users to connect and communicate in more personal and engaging ways. In the entertainment industry, the potential is vast, ranging from virtual concerts [33] and events to fully interactive games [34] that blur the lines between the real and virtual worlds. The digital communication medium can provide unprecedented opportunities for creativity and storytelling. By blending the virtual and physical realms into a cohesive and interactive experience, the Real-Time

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Metaverse is poised to become a fundamental component of our future digital ecosystem, offering unparalleled opportunities for innovation, connectivity, and economic activity.

Metaverse is an integration of many technology advancements that have the potential to transform our interactions with both the digital and physical realms as the digital realm continues to grow [35]. The Real-Time Metaverse is a cutting-edge component of the ongoing digital revolution [36], serving as an advanced expansion of the broader Metaverse concept. The Real-Time Metaverse attempts to emulate the immediacy of real-world interactions [32], in contrast to conventional virtual environments that may encounter latency or delayed interactions [37]. To achieve this ambitious reality objective, it is necessary to flawlessly incorporate state-of-the-art technology to establish an ecosystem where users interact with one another and their surroundings instantaneously. Metaverse can significantly revolutionize social interactions, entertainment, business, and education [27].

Achieving such instantaneous interactions within the Real-Time Metaverse demands a complex and highly advanced technological infrastructure [38], which includes the development of robust and low-latency networks, powerful processing capabilities, and sophisticated software that can handle the dynamic nature of real-time data exchange. High-speed networks such as the fifth-generation (5G) provide the necessary bandwidth and low latency to support real-time interactions [39], while edge computing significantly reduces latency by processing data closer to the user [40]. Innovations in VR and AR technologies enhance the realism and immersion of these virtual environments, allowing users to experience a level of presence and engagement that closely mimics the physical world [41]. Additionally, AI enhances the Real-Time Metaverse by enabling intelligent and responsive virtual environments and characters [22], while blockchain technology ensures security, transparency, and ownership of digital assets [5]. Together, these advancements form the backbone of Metaverse, enabling users to create, explore, and interact in a fully realized digital universe.

3. Related Works

Metaverse represents a burgeoning frontier where the digital and physical worlds converge, offering immersive experiences through advancements in virtual reality (VR), augmented reality (AR), and other cutting-edge technologies. This section delves into the critical aspects of Metaverse, including blockchain integration, artificial intelligence (AI), edge computing, and the myriad challenges and implications of these innovations.

Blockchain technology is foundational for establishing a decentralized, secure, and interoperable Metaverse [42]. Blockchain enhances Metaverse functionalities such as data acquisition, storage, sharing, interoperability, and privacy preservation. Blockchain ensures the trustworthiness of transactions and interactions by providing a transparent and tamper-proof ledger, essential for managing digital assets and identities in a virtual world [1]. Blockchain can facilitate the creation of interoperable virtual worlds, allowing users to seamlessly transition and securely interact across different platforms, which is crucial for realizing a unified Metaverse [43].

In Metaverse, *AI* is pivotal in enhancing user experiences by enabling more natural and intuitive interactions [42]. AI applications such as natural language processing, computer vision, and neural interfaces are instrumental in creating responsive and adaptive virtual environments [44]. AI-driven avatars, capable of understanding and reacting to user inputs, significantly enhance the realism and immersion of Metaverse [45]. *Edge computing* complements AI by providing the computational power and low-latency communication required for real-time interactions in Metaverse [46]. Edge computing is crucial in supporting AR and VR applications by reducing latency and ensuring a high-quality user experience. Edge computing brings data processing closer to the user, essential for applications that demand immediate feedback and minimal delay.

The deployment of Metaverse faces several technological and infrastructural challenges [21]. The role of *5G/6G technology* in overcoming these hurdles by providing ultra-low latency, high data rates, and enhanced reliability. The proposed layered architecture for integrating 6G with Metaverse addresses the need for scalable and efficient network infrastructure to handle the vast amounts

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of data generated by Metaverse applications. Network scalability, data privacy, and security are identified as key challenges [36]. The advanced cryptographic algorithms and robust security protocols protect user data and ensure secure transactions within Metaverse are required [47]. Additionally, developing interoperability standards is critical to facilitate seamless interactions across different virtual environments [48].

VR and AR are core technologies driving the immersive experiences of Metaverse. Integrating *haptic feedback* in AR shows how tactile sensations can enhance user interactions in virtual environments [9,49]. Innovations such as the FingerTac haptic gloves provide real-time haptic feedback and improve the realism of AR applications. The infrastructure supporting Metaverse must handle compute- and data-intensive tasks efficiently. Edge computing is essential for Metaverse, particularly in enhancing the performance and scalability of virtual environments. The role of edge-enabled technologies in managing the real-time demands of VR and AR applications is crucial. By processing data closer to the user, edge computing reduces latency and improves the overall user experience [50]. In addition, integrating advanced queue management algorithms and edge computing can optimize network performance for data-intensive applications [51]. The network integration is paramount for maintaining the high levels of responsiveness and interaction fidelity required by Metaverse.

Metaverse holds significant potential for transforming education by creating immersive and interactive learning environments [52]. Metaverse can enable virtual classrooms where students and teachers interact in a shared virtual space, enhancing the learning experience through interactive simulations and collaborative projects. The flexibility and accessibility of Metaverse can democratize education, making high-quality learning resources available to a global audience.

Beyond technological advancements, Metaverse presents several social and ethical considerations [53]. Some issues, such as user addiction, digital harassment, and equitable representation of avatars, are highlighted. The immersive nature of Metaverse can exacerbate these issues, necessitating the development of guidelines and regulations to protect users and promote a healthy virtual environment [54]. Additionally, integrating AI and blockchain raises data privacy and security concerns, which must be addressed to ensure user trust and safety in Metaverse.

Security and *privacy* are among the top concerns in Metaverse, where vast amounts of personal data and digital assets are exchanged. The importance of advanced cryptographic algorithms and robust security protocols to protect user data and ensure secure transactions is a fundamental requirement. The decentralized nature of Metaverse, facilitated by blockchain technology, offers a layer of security by eliminating the need for a central authority [17,55]. However, decentralization also challenges ensuring data integrity and preventing unauthorized access. The role of blockchain in providing secure data acquisition, storage, and sharing within Metaverse is inevitable. Blockchain's immutable ledger can help prevent data tampering and ensure transparency [56]. Yet, blockchain integration also raises concerns about user data privacy, as transactions are publicly recorded on the ledger. Therefore, finding a balance between transparency and privacy is crucial for the widespread adoption of blockchain in Metaverse.

The findings showed that *quality of user experience* is another critical factor in the success of Metaverse [57]. The immersive nature of VR and AR technologies can significantly enhance user engagement, but they also come with challenges. Integrating haptic feedback in AR can improve the realism of virtual interactions [9]. However, the technical difficulties in delivering consistent and intuitive haptic feedback are due to network latency and resource allocation issues [58]. AI can enhance user interaction by making virtual environments more responsive and adaptive. AI-driven avatars, capable of understanding and reacting to user inputs, can create more engaging and personalized experiences. Nonetheless, ensuring these AI systems operate seamlessly across different platforms and devices remains a significant challenge.

Some research highlighted that *scalability* is another major challenge in the development of Metaverse [59]. The current social VR platforms struggle to support large numbers of concurrent users. The bandwidth requirements for transmitting high-resolution 3D content and real-time interactions can be immense, necessitating advanced networking techniques to ensure scalability. The potential of 6G technology is to address these scalability issues by providing ultra-low latency, high data rates, and enhanced reliability. The proposed layered architecture for integrating 6G with Metaverse could help manage the massive data traffic and support large-scale user interactions. However, deploying such infrastructure poses significant technical and economic challenges. Recently, researchers proposed *Microverse* [60], a task-oriented, scale-down Metaverse instance, as a practical approach to current technologies [61,62].

Data integration is essential for creating seamless and coherent virtual experiences in Metaverse, expressed by some research [21,63]. The role of the edge is to compute and manage the real-time demands of data integration by processing data closer to the user. This approach reduces latency and improves the quality of experience. However, ensuring consistent and accurate data synchronization across distributed edge nodes is complex. Integrating diverse data sources, including IoT devices, digital twins, and AI systems, into Metaverse is essential. Integrating devices enables the creation of rich and dynamic virtual environments but requires robust frameworks to manage data interoperability and consistency.

In addition, *data compatibility* is another major challenge for the interoperability of different systems within Metaverse [63]. The lack of standardized data formats and protocols can hinder seamless interactions between virtual environments. Ensuring data compatibility involves developing common standards and protocols that can be adopted across various platforms and technologies. Cross-platform compatibility is essential for allowing users to access Metaverse from different devices and platforms [64]. The main challenge is achieving cross-platform compatibility, particularly in delivering consistent user experiences across devices with varying capabilities. Ensuring that applications and content are accessible and functional on different platforms requires significant effort in standardization and optimization.

Interoperability is another area of research of Metaverse, enabling seamless transitions and interactions across different virtual worlds [65]. Also, AI and machine learning can facilitate interoperability by enabling systems to understand and adapt to different environments [66]. However, achieving true interoperability requires collaboration between developers, platform providers, and standardization bodies to establish common frameworks and protocols. Ensuring a cohesive experience of interoperability in Metaverse is crucial. To enable seamless interactions, it is required to integrate diverse technologies, such as blockchain, AI, and edge computing, and the need for standardized interfaces to enable seamless interactions [19]. Without interoperability, Metaverse risks becoming fragmented, with isolated virtual environments that cannot communicate with each other.

4. State-of-the-Art Real-Time Metaverse

The latest advancements and cutting-edge technologies are shaping the development and functionality of Metaverse [67]. Figure 3 presents a detailed view of the architecture for integrating physical, virtual, and metaverse layers within a digital ecosystem. The *physical layer* comprises four main components: users, IoT/sensors, virtual service providers, and physical service providers. Users engage with the virtual world using various devices, and IoT/sensors facilitate the synchronization between the physical and virtual worlds [15]. Virtual service providers offer digital goods and services. In contrast, physical service providers handle tangible goods and services transactions, highlighting the importance of interaction and synchronization between physical and virtual entities for a seamless user experience.

The *virtual layer* includes avatars for virtual navigation, virtual environments for constructing the virtual world, and virtual goods/services such as virtual workspace and education [21]. The virtual layer bridges the gap between the physical and virtual worlds by providing immersive and interactive experiences. The Metaverse engine focuses on creating an immersive, real-time, and intelligent environment by integrating advanced technologies. This includes physics simulations, animations, AR/VR, human-machine and human-human communication, haptic feedback, and AI-

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driven graphic enhancements. Additionally, it encompasses modeling/simulation optimization, data processing, digital twins, recommendation systems, and blockchain applications for secure data storage, decentralized trading, and interoperability.

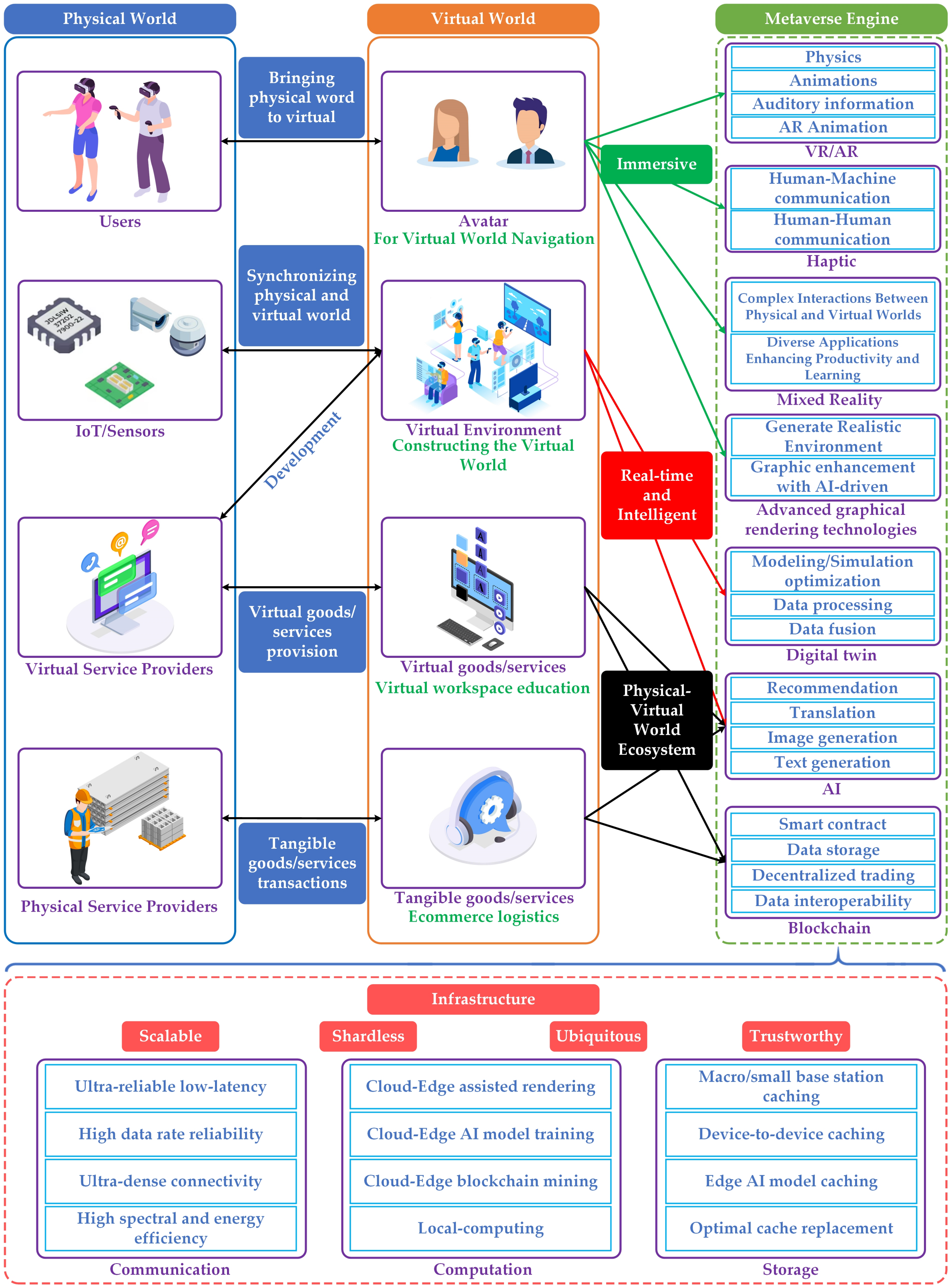

Figure 3. Metaverse architecture.

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The *infrastructure layer* supports this ecosystem through scalable, shardless, ubiquitous, and trustworthy communication, computation, and storage solutions. These include ultra-reliable low-latency communication, cloud-edge assisted rendering, AI model training, blockchain mining, local computing, macro/small base station caching, device-to-device caching, edge AI model caching, and optimal cache replacement, ensuring efficient and effective performance across the entire digital ecosystem.

Figure 4 presents an advanced real-time metaverse architecture that integrates various sensors, robotics, and haptic control technologies to create a highly immersive and interactive virtual experience. The system's core relies on diverse sensors, including thermal cameras, RGB (red, green, and blue) cameras, multispectral sensors, Lidar sensors, and hyperspectral sensors [23,68]. Each sensor plays a critical role in capturing comprehensive environmental data. For instance, thermal cameras detect temperature variations, RGB cameras provide standard color images, multispectral sensors capture images in specific wavelength bands [69], Lidar sensors measure distances using laser light [70]. Hyperspectral sensors gather detailed spectral information across many narrow wavelength bands [71].

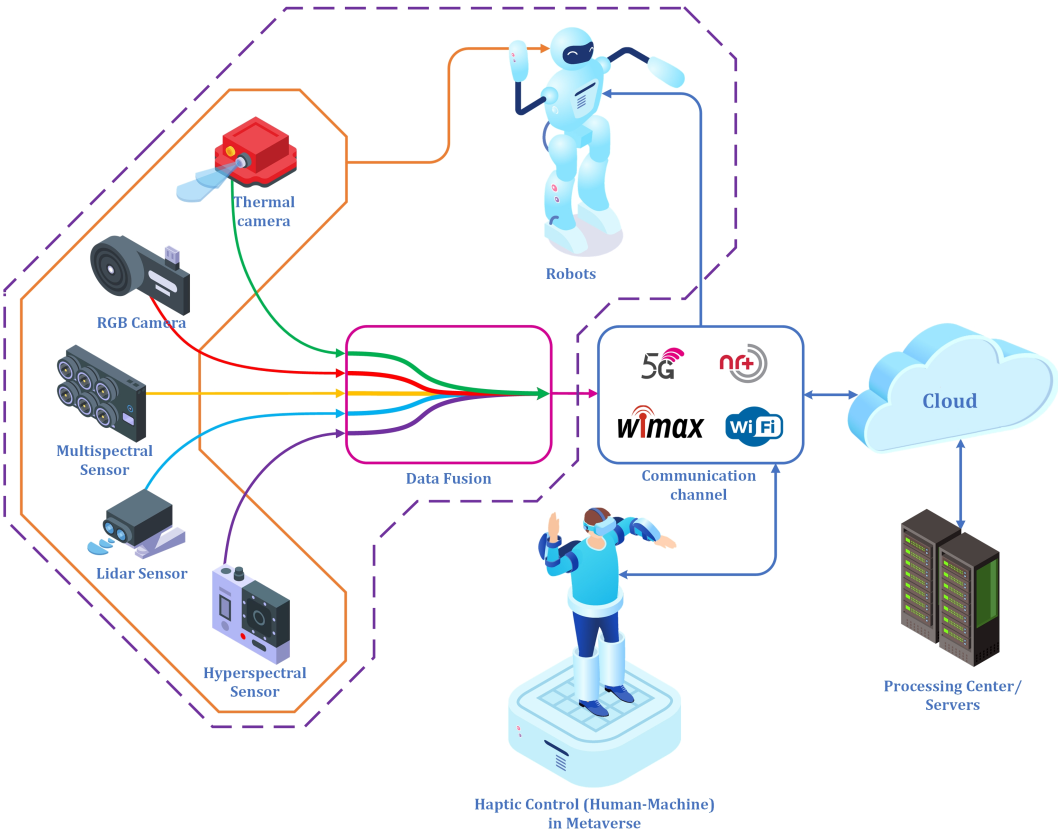

Figure 4. Real-time metaverse in a closed-loop system.

The data collected from these sensors are then processed in a data fusion module [72–74]. The data fusion module integrates the diverse data streams to generate a unified and comprehensive understanding of the environment. Such data fusion is crucial for enhancing the accuracy and reliability of the information used within Metaverse. The fused data supports various applications, particularly in robotics and haptic control. Robots within this system, which can be either autonomous or remotely controlled, use the integrated data for navigation, executing tasks, and interacting within Metaverse. Additionally, haptic control devices allow users to interact with the virtual environment through tactile feedback, significantly enhancing the immersive experience by providing a sense of touch.

To ensure seamless operation, the Metaverse system should employ high-speed communication technologies like 5G [75]. These communication technologies facilitate real-time data transmission and

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control signals between sensors, robots, and user interfaces, ensuring low latency and high reliability. The real-time connectivity is essential for maintaining the interactive nature of Metaverse, allowing users to experience immediate responses to their actions. Data and commands are processed in centralized servers or cloud-based processing centers. This setup supports complex computations and large-scale data storage, enabling the system to handle vast amounts of information and deliver real-time responses. The system benefits from scalable processing power and robust data management capabilities by leveraging cloud integration.

The benefits of a sophisticated metaverse system are manifold. Firstly, it offers an enhanced immersive experience by combining various sensors and haptic feedback, making users feel as though they are physically present in the virtual environment. Secondly, real-time data integration ensures a comprehensive and accurate environment representation, which is critical for applications like virtual simulations, user training, and remote operations. Thirdly, the high-speed connectivity of advanced communication technologies ensures that data transmission and control signals are rapid and reliable, maintaining the system's responsiveness.

Moreover, the versatility of a Metaverse system allows it to be used in a wide range of fields, including gaming, remote surgery, virtual training, and disaster management. It supports the simulation of complex scenarios and the remote manipulation of objects, providing valuable training and operational capabilities. Lastly, the integrated data from various sensors enhances decision-making processes by providing a rich source of information, which is particularly beneficial in fields like robotics, where accurate and real-time data is crucial for effective operations.

4.1. Technological Infrastructure

The technological infrastructure of Metaverse comprises a sophisticated and interconnected ecosystem of advanced technologies designed to support immersive, real-time virtual experiences. The hardware includes high-speed and low-latency networks like 5G and fiber optics, powerful computing hardware such as graphics processing units (GPUs) and cloud computing resources, and robust data storage solutions. Together, these components ensure Metaverse is a seamless, scalable, and interactive digital universe capable of supporting various applications from gaming and social interactions to professional and educational environments. Key enablers include high-performance computing, cloud and fog architectures, and edge devices as shown in Figure 5.

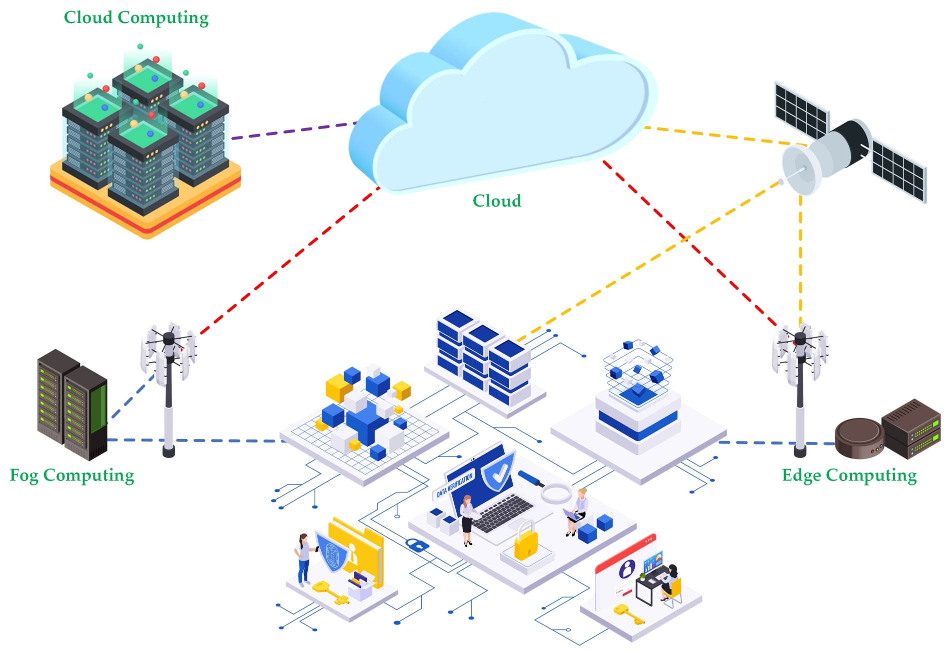

Figure 5. Structures of computing in the network.

4.1.1. High-Performance Computing (HPC)

High-Performance Computing (HPC) leverages the combined power of supercomputers, cluster centers, and parallel processing techniques to tackle complex computational problems beyond standard desktop computers' capabilities [76]. HPC systems are essential in various domains, such as scientific research, design engineering, and data analysis, enabling large-scale simulations, systems modeling, and processing of massive datasets. Supercomputers and HPC clusters of interconnected nodes perform calculations at incredible speeds by dividing tasks into smaller sub-problems solved simultaneously. Advanced data centers equipped with high-performance servers and GPUs are essential for processing the vast amounts of data required for real-time metaverse interactions [77]. Specialized software and tools, like MPI (Message Passing Interface), OpenMP (Open Multi-Processing), and CUDA (Compute Unified Device Architecture), support the development and execution of HPC applications, ensuring efficient use of the vast computing resources available [78]. Applications range from climate modeling and molecular dynamics in scientific research to computational fluid dynamics and structural analysis in engineering, as well as big data analytics and machine learning in data-intensive fields.

Despite the immense capabilities of HPC for a real-time Metaverse, it faces several challenges, including scalability, energy consumption, cost, and complexity [79]. Scaling applications across thousands of processors efficiently requires optimizing code to minimize communication overhead. The significant power consumption of supercomputers and large clusters necessitates the development of energy-efficient designs. The high costs of HPC infrastructure and the specialized knowledge required for developing and maintaining applications further complicate its adoption. However, the future of HPC is promising, with advancements in exascale computing, quantum computing, and AI integration. Exascale systems will enable even more complex simulations and data analyses, while quantum computing could revolutionize fields like cryptography and material science [80]. Combining HPC with AI and machine learning will drive innovations across various domains, and research into energy-efficient technologies aims to reduce the environmental impact of HPC.

4.1.2. Cloud Computing

Cloud computing is a transformative technology that allows individuals and organizations to access and store data, applications, and computing power over the Internet rather than relying on local servers or personal devices [81]. Cloud technology offers several key advantages, including scalability, flexibility, cost-efficiency, and accessibility [82]. Cloud services are typically categorized into three main types: Infrastructure as a Service (IaaS) [83], which provides virtualized computing resources over the internet; Platform as a Service (PaaS) [84], which offers hardware and software tools for application development; and Software as a Service (SaaS) [85], which delivers software applications over the internet on a subscription basis [86]. Major cloud service providers like Amazon Web Services (AWS), Microsoft Azure, and Google Cloud Platform (GCP) offer robust solutions that cater to a wide range of needs, from startups requiring minimal resources to enterprises needing extensive infrastructure and advanced services.

Cloud computing has revolutionized various industries by enabling more efficient and innovative business models. For instance, in the healthcare sector, cloud computing facilitates the secure storage and sharing of patient data, supports telehealth services, and enhances collaborative research through data analytics [87]. In finance, it allows for real-time transaction processing and advanced fraud detection. Additionally, cloud computing supports the growing field of remote work by providing seamless access to applications and data from any location, fostering collaboration and productivity [88]. Despite its many benefits, cloud computing also poses challenges such as data security, privacy concerns, and dependency on internet connectivity. However, ongoing advancements in cloud security protocols and hybrid cloud solutions, which combine private and public cloud resources, are addressing these issues and enhancing the reliability and security of cloud services.

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4.1.3. Edge and Fog Computing

Edge and Fog computing are paradigms that enhance data processing and analysis capabilities closer to the source of data generation, reducing latency and improving efficiency [89]. Edge computing involves processing data directly on devices or near the data source, such as sensors, IoT devices, or local servers [90]. The edge approach minimizes the need to send data to centralized cloud servers, reducing latency and bandwidth usage. Edge computing applications include real-time analytics, autonomous vehicles, and smart cities, where immediate data processing is crucial. For instance, in autonomous vehicles, edge computing allows for rapid decision-making based on real-time data from sensors, enhancing safety and performance.

Fog computing, on the other hand, extends the concept of edge computing by providing a distributed computing infrastructure that includes edge devices, local servers, and potentially the cloud [91]. The fog architecture acts as an intermediary layer that processes data before it reaches the cloud, providing additional storage and computational resources closer to the data source [92]. The fog-edge layered approach benefits applications requiring real-time processing and more substantial computational power or data aggregation. Fog computing is particularly useful in scenarios like industrial IoT, where data from numerous devices needs to be aggregated and analyzed swiftly to optimize operations and maintenance. By distributing resources across multiple layers, fog computing improves overall system efficiency, scalability, and reliability.

Figure 5 illustrates a comprehensive architecture that integrates cloud computing, fog computing, and edge computing. At the center of the diagram is the cloud, symbolizing the centralized and extensive data processing capabilities of cloud computing. Cloud computing is depicted with multiple connections, including data centers and satellites, highlighting its broad reach and ability to handle significant computational tasks and data storage. Fog computing is represented by servers and network infrastructure placed closer to the data sources, such as IoT devices and sensors. The fog layer aims to reduce latency by processing data near its origin before sending it to the cloud. Edge computing, depicted with smaller, decentralized servers and network nodes, is even closer to the end-users and devices. It emphasizes real-time data processing and immediate response actions, crucial for applications requiring low latency and high reliability. Integrating these computing paradigms ensures a balanced and efficient data handling from the core cloud to the network's edge, optimizing performance and resource utilization.

4.1.4. 5G Communication Technology

The fifth generation (5G) communication technology represents a significant leap in mobile communications, offering faster data speeds, lower latency, and more excellent connectivity compared to previous generations [93].

With theoretical speeds of up to 10 Gbps and latency as low as 1 millisecond, 5G enables a wide range of applications that require real-time data transmission and high bandwidth. These include enhanced mobile broadband, ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC) [94]. Industries such as healthcare, automotive, and entertainment are poised to benefit immensely from 5G. For example, 5G supports telemedicine and remote surgeries in healthcare by providing reliable, high-speed connections necessary for transmitting high-definition video and large medical data files in real-time.

Beyond 5G, the focus is on developing technologies like 6G, which aims to provide even higher speeds, lower latency, and more extensive connectivity [46]. 6G is expected to integrate advanced technologies such as artificial intelligence, machine learning, and blockchain to enhance network management, security, and efficiency. Potential applications of 6G include holographic communications, advanced AR and VR, and ubiquitous IoT connectivity, enabling smart environments and autonomous systems to operate seamlessly [95]. Research and development in 6G technology are exploring new spectrum bands, such as terahertz frequencies, to achieve these ambitious goals. As

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society moves toward 6G, the focus will also be on sustainable and energy-efficient solutions to support the ever-growing demand for data and connectivity.

Figure 6 shows a 5G network architecture, integrating various components and technologies to create a robust communication system. The core is a massive multiple-input multiple-output (MIMO) network that connects to resources and wireless and wired links. The cloud provides extensive data processing and storage capabilities, connected to the core network and servers via wired links. The Internet is crucial, linking the core network and servers to broader online resources. The mobile small cell network, including 5G-enabled devices, ensures coverage and connectivity for mobile users. The edge network includes sensors, IoT devices, and connected appliances, receiving and sending data through wireless links. A residential setup is also included, demonstrating the network's ability to provide high-speed internet access to homes.

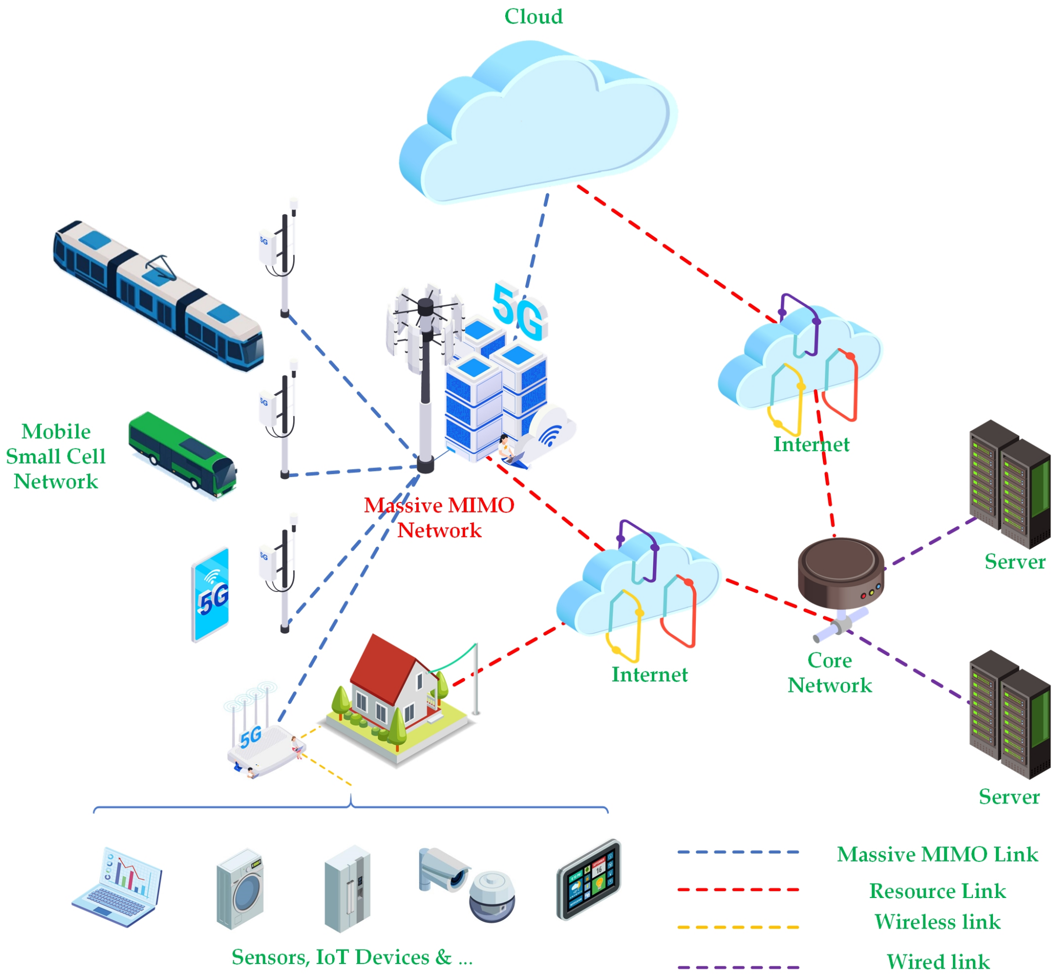

Figure 6. A general 5G cellular network architecture.

4.2. Immersive Technologies

Immersive technologies for the real-time Metaverse encompass a range of advanced tools and systems designed to create deeply engaging and interactive virtual experiences [77,96,97]. These technologies include VR, AR, Mixed Reality (MR) [41], haptic feedback [9], and advanced graphical rendering techniques [23], all of which work together to blur the lines between the physical and digital worlds. Figure 7 showcases the integration of VR/AR, Haptic, and Advanced Graphical Rendering Technologies to enhance virtual and augmented reality experiences. VR/AR creates immersive environments using physics, animations, and auditory information. Haptic enhances human-machine communication and provides tactile feedback for real-life interactions. Advanced Graphical Rendering

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uses AI-driven techniques to generate realistic environments and enhance graphics, resulting in more immersive and interactive virtual experiences.

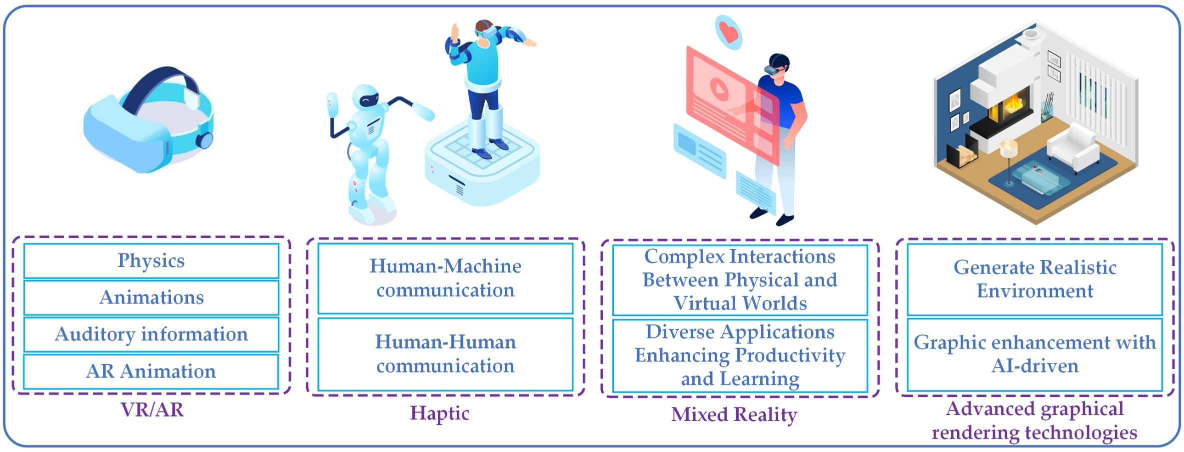

Figure 7. Metaverse immersive technologies.

4.2.1. Virtual Reality (VR)

Virtual Reality (VR) is a technology that immerses users in a computer-generated environment, providing a simulated experience that can be similar to or completely different from the real world [98]. VR typically involves headsets equipped with displays, sensors, and controllers that track the user's movements and interactions within the virtual environment. VR technology is widely used in gaming and entertainment, creating immersive experiences that engage users in new and exciting ways. Beyond entertainment, VR has significant applications in education, where it enables interactive learning experiences, such as virtual field trips or simulations of complex scientific concepts, allowing students to explore and understand subjects more deeply.

In addition to its impact on gaming and education, VR is transforming industries like healthcare, real estate, and training [99]. In healthcare, VR is used for surgical simulations, allowing surgeons to practice procedures in a risk-free environment and for therapeutic purposes, such as exposure therapy for patients with anxiety disorders. In real estate, VR provides virtual tours of properties, giving potential buyers a realistic sense of space without needing to visit in person. In professional training, VR offers a safe and controlled environment for employees to practice skills and scenarios, such as emergency response or complex machinery operation. As VR technology advances, with improvements in display resolution, motion tracking, and user interfaces, its applications are expected to expand further, offering increasingly sophisticated and practical uses across various fields.

4.2.2. Augmented Reality (AR)

Augmented Reality (AR) is a technology that overlays digital information and virtual objects onto the real world, enhancing the user's perception and interaction with their environment [100]. Unlike Virtual Reality, which creates an entirely simulated experience, AR blends virtual elements with the physical world, often through smartphones, tablets, or AR glasses. AR technology has gained widespread popularity in applications such as mobile gaming, with games like Pokémon GO allowing users to interact with virtual characters in real-world locations. AR also enhances navigation and location-based services by providing real-time information and directions overlaid on the physical environment, improving user convenience and engagement.

Beyond entertainment and navigation, AR is making significant strides in many fields, such as retail, education [101], and healthcare. In retail, AR applications allow customers to visualize products in their own space before purchasing, such as seeing how furniture would look in their home or trying on virtual clothing. AR not only enhances the shopping experience but also reduces return rates and increases customer satisfaction. In education, AR brings learning materials to life

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by enabling interactive and immersive experiences, such as 3D visualizations of historical events or scientific phenomena, which can deepen student understanding and engagement. In healthcare, AR assists surgeons by providing real-time overlays of critical information during procedures, improving precision and outcomes. As AR technology continues to evolve, its integration into everyday life and various professional fields is expected to grow, offering increasingly innovative and practical applications.

4.2.3. Mixed Reality (MR)

Mixed Reality (MR) is an advanced technology that seamlessly blends the physical and digital worlds, creating environments where real and virtual elements coexist and interact in real time [102]. Unlike VR, which immerses users in a completely virtual environment, or AR, which overlays digital information in the real world, MR allows for more complex interactions between physical and virtual objects. MR is typically achieved using advanced sensors, cameras, and displays, often incorporated into headsets like Microsoft's HoloLens or Magic Leap. These devices track the user's position and surroundings, enabling virtual objects to be anchored in the real world and interact with them naturally and intuitively [103].

The potential applications of Mixed Reality span numerous fields, enhancing productivity, creativity, and learning [8]. MR can be used in industry and manufacturing for remote collaboration, allowing engineers to visualize and manipulate 3D models of equipment or structures as if they were physically present [104]. This can improve design accuracy and speed up problem-solving processes. MR can provide immersive learning experiences in education, such as virtual laboratories where students can conduct experiments without the risk or expense associated with physical setups. MR can assist in medical training in the healthcare sector by simulating complex surgical procedures with real-time feedback and guidance. As MR technology continues to evolve [105], it promises to revolutionize how we interact with both the digital and physical worlds, providing a more integrated and interactive experience.

4.2.4. Haptic Feedback

Haptic feedback is a technology that simulates the sense of touch by applying forces, vibrations, or motions to the user [9,49]. Haptic sensory feedback enhances the immersive experience in virtual environments by allowing users to feel interactions with virtual objects as if they were real. In the context of Metaverse, haptic feedback is delivered through various devices such as gloves, vests, and other wearables, which can replicate sensations like texture, resistance, and impact. For instance, when a user picks up a virtual object or feels a virtual breeze, haptic devices provide physical sensations corresponding to those actions, making the virtual experience more realistic and engaging.

Integrating haptic feedback into Metaverse has significant implications for various applications, including gaming, training, and remote collaboration [106]. In gaming, haptic feedback enhances immersion by allowing players to physically feel in-game actions, such as holding equipment or surface texture. In training simulations, particularly in fields like medicine and engineering, haptic technology can provide realistic practice scenarios, helping users develop practical skills without real-world risks. For remote collaboration, haptic feedback can bridge the gap between digital and physical interactions, enabling more effective and intuitive communication. Overall, haptic feedback enriches the user experience in Metaverse by adding a critical layer of sensory interaction that deepens engagement and realism.

4.2.5. Advanced Graphical Rendering Technologies

Advanced graphical rendering (GR) technologies are crucial for creating highly realistic and visually stunning virtual environments in Metaverse [23]. One of the key advancements in GR is real-time ray tracing, a technique that simulates the way light interacts with objects in a scene to produce highly accurate reflections, refractions, and shadows [77,107]. This level of detail enhances

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the realism of virtual worlds, making them more immersive and visually engaging. Real-time ray tracing requires significant computational power, but recent advances in GPUs and optimization techniques have made it feasible for real-time applications, allowing users to experience lifelike visuals in interactive settings such as gaming, virtual tours, and social interactions within Metaverse.

Another significant development in advanced graphical rendering is using artificial intelligence (AI) to enhance graphics quality and performance [22,108]. AI-driven techniques, such as deep learning-based upscaling (e.g., NVIDIA's Deep Learning Super Sampling (DLSS)), can improve frame rates and image quality by predicting and generating high-resolution frames from lower-resolution inputs. High resolution not only ensures smoother performance but also allows for more detailed and complex scenes without compromising on speed. AI is also used in procedural content generation, enabling the creation of vast and diverse virtual landscapes with minimal manual effort. By leveraging these advanced rendering technologies, Metaverse can offer visually rich, dynamic, and interactive environments that push the boundaries of what is possible in digital experiences, making them more compelling and lifelike for users.

4.3. Interoperability Standards

Interoperability standards ensure that different systems, devices, and applications can work together seamlessly, exchanging data and functionality without compatibility issues [42,63]. These standards facilitate communication and integration across various platforms, enhancing efficiency and user experience. Interoperability is particularly important in industries where disparate systems, such as healthcare, finance, telecommunications, and information technology, need to interconnect. By adhering to common protocols and formats, interoperability standards enable diverse systems to interoperate, reducing the need for costly custom integrations and minimizing the risk of data silos.

Figure 8 illustrates the concept of metaverse interoperability, depicting how users in the physical world can access a unified virtual world through various devices. The physical layer showcases the interoperability across these devices, allowing seamless transitions into the virtual world. Once in the virtual world, represented by avatars, users can interact and navigate across different platforms and activities in the virtual layer.

Open standards play a crucial role in achieving interoperability. These are publicly available specifications developed and maintained by consensus-driven processes, often involving multiple stakeholders from industry, academia, and government [109]. Open standards are designed to be vendor-neutral, ensuring that any organization can implement them without restrictive licensing terms. Open infrastructure promotes competition and innovation, as developers can build interoperable products without being locked into proprietary technologies. Examples of open standards include HTTP and HTML for web technologies, TCP/IP for internet communications [27], and Health Level 7 (HL7) for healthcare data exchange [110].

The adoption of open standards offers several significant advantages. First, it enhances compatibility and integration, allowing different systems to communicate and share data more easily [111]. Data compatability is particularly beneficial in complex environments such as smart cities, where various technologies must work together to deliver seamless services. Second, open standards support long-term sustainability and flexibility. Since they are not tied to a single vendor, organizations can avoid vendor lock-in and more easily adapt to changing technological landscapes. Third, open standards foster a collaborative ecosystem where communities of developers and organizations can contribute to and benefit from shared advancements and improvements.

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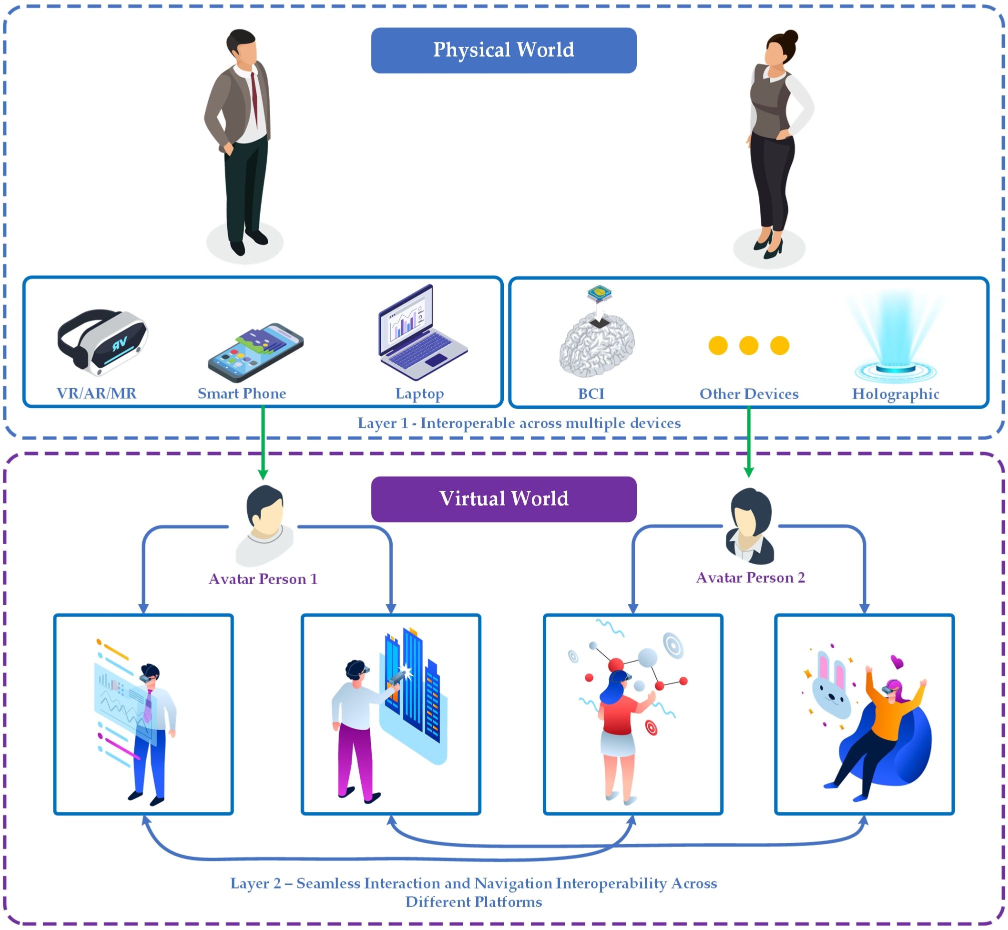

Figure 8. Interoperability of Metaverse.

4.3.1. OpenXR

OpenXR is an open standard for VR and AR that aims to streamline the development of applications across different hardware platforms [112]. Managed by the Khronos Group, a consortium of industry-leading companies, OpenXR provides a unified framework for VR and AR runtime interfaces. This allows developers to write code that can run on various devices without tailoring their applications to each specific hardware configuration. By abstracting the hardware details, OpenXR significantly reduces the complexity and cost of developing cross-platform VR and AR experiences, fostering more significant innovation and broader adoption in the immersive technology space.

The benefits of OpenXR extend beyond simplifying development. For end users, it ensures a more consistent and reliable experience across different VR and AR devices [113]. Since applications built with OpenXR can operate on multiple platforms, users are not limited to specific hardware when accessing their favorite VR and AR content. This interoperability also encourages competition among hardware manufacturers, as it levels the playing field and allows new entrants to support a rich content ecosystem without the barrier of proprietary software constraints. Ultimately, OpenXR plays a crucial role in the growth of the VR and AR industries by promoting a more open, inclusive, and efficient development environment.

4.3.2. WebXR

WebXR is a robust application programming interface (API) that brings VR and AR experiences to the web, enabling developers to create immersive content accessible directly through web browsers [114]. Managed by the World Wide Web Consortium (W3C), WebXR is a standardized framework for integrating VR and AR capabilities into web applications, allowing users to experience immersive environments without downloading specialized software. The accessibility is crucial for broadening the reach of VR and AR technologies, as it leverages the ubiquity of web browsers to deliver content to a broad audience across various devices, from desktops and laptops to smartphones and dedicated VR headsets.

4.4. Artificial Intelligence (AI) and Machine Learning (ML)

AI-driven avatars represent a remarkable fusion of artificial intelligence and digital animation, poised to revolutionize how we interact in virtual environments [108]. These avatars are sophisticated digital representations of individuals designed to mimic human behavior, appearance, and communication with high realism and responsiveness. At the core of these avatars is advanced AI technology, enabling them to learn, adapt, and respond to users naturally and intuitively [115]. The AI-driven avatars are integral in enhancing the user experience within Metaverse, providing a seamless and immersive interaction that bridges the gap between humans and machines.

One of the most significant aspects of AI-driven avatars is their ability to understand and process natural language [116]. Using natural language processing (NLP) algorithms, these avatars can interpret spoken or written language, allowing for fluid and dynamic conversations with users. Machine learning models further enhance this capability, enabling avatars to learn from interactions and improving their responses over time. As a result, users can engage in meaningful and personalized dialogues with their avatars, making virtual interactions more engaging and lifelike.

In addition to linguistic capabilities, AI-driven avatars are equipped with advanced facial recognition and emotion detection technologies [117]. These technologies allow avatars to read and respond to human emotions, adapting their behavior and expressions accordingly. For instance, an avatar can recognize when a user is happy, sad, or frustrated and tailor its responses to provide appropriate emotional support or feedback. This emotional intelligence adds another layer of depth to virtual interactions, making AI-driven avatars not just functional tools but empathetic companions in the digital world.

The applications of AI-driven avatars extend far beyond entertainment and social interactions. These avatars can serve as personalized tutors in educational settings, offering tailored instruction and feedback to students [118]. They can provide efficient and empathetic support in customer service, handling inquiries, and resolving issues with a human touch [119]. In healthcare, AI-driven avatars can act as virtual companions for patients, providing comfort and monitoring their well-being [120]. By integrating AI-driven avatars into various sectors, the Metaverse can unlock new possibilities for enhancing user experiences and improving the quality of services across multiple domains.

4.4.1. Artificial Intelligence (AI)

Artificial Intelligence (AI) content generation plays a pivotal role in developing and enhancing Metaverse, a virtual universe where users can interact with each other and in digital environments in real-time [22]. The use of AI in content creation within a Metaverse encompasses various technologies, including procedural generation, natural language processing (NLP) [121], and large language models (LLMs) [122]. These technologies collectively create more immersive, interactive, and personalized user experiences. Procedural generation is a method in which content is created algorithmically rather than manually, allowing for the creation of vast and diverse virtual worlds within Metaverse. The procedural technique can generate everything from complex landscapes to intricate architecture and even entire ecosystems. Procedural generation ensures that Metaverse remains dynamic and expansive, offering users new and unique experiences each time they log in. The ability to automatically generate content also significantly reduces the time and resources needed for manual creation, enabling developers to focus on other aspects of Metaverse.

4.4.2. Natural Language Processing (NLP)

NLP is another critical component in the AI content generation for Metaverse [121]. NLP enables more natural and intuitive interactions between users and virtual entities, including non-player characters (NPCs) and digital assistants [22]. By understanding and processing human language, NLP allows these virtual entities to respond appropriately to user inputs, facilitating more engaging and meaningful conversations. The NLP capability fosters a seamless and immersive user experience [123], as it bridges the gap between human communication and digital interaction.

4.4.3. Large Language Models (LLMs)

LLMs, such as GPT-4, further enhance the capabilities of NLP in Metaverse [122]. These models are trained on vast datasets and can generate human-like text based on contextual understanding. LLMs can create complex narratives, generate dialogue for NPCs, and even assist in real-time translation between users of different languages. The integration of LLMs into Metaverse ensures that the virtual world is rich in content and can adapt to the diverse linguistic needs of its global user base.

The combination of procedural generation, NLP, and LLMs in Metaverse leads to a highly dynamic and personalized user experience. For instance, users can explore unique environments tailored to their preferences, engage in meaningful conversations with virtual entities, and enjoy evolving narratives based on their interactions [124]. The advanced level of personalization not only enhances user engagement but also fosters a sense of connection and immersion within the virtual world. The AI-driven content generation ensures that Metaverse remains a vibrant and evolving space, continuously offering new experiences.

5. Challenges and Opportunities

5.1. Latency and Bandwidth

Latency and bandwidth are critical factors in the performance and user experience of Metaverse [125]. Latency refers to the delay between a user's action and the system's response, which is crucial for real-time interactions in virtual environments. High latency can result in lag, making movements and communications appear delayed or out of sync, thus disrupting the immersive experience [37]. Bandwidth, on the other hand, refers to the amount of data that can be transmitted over a network in a given period. Sufficient bandwidth is necessary to support the high data transfer rates required for high-resolution graphics, real-time interactions, and seamless streaming of virtual content [126]. Together, low latency and high bandwidth ensure smooth, responsive, and immersive experiences in Metaverse, allowing users to interact in real time without interruptions or delays. Figure 9 illustrates the critical relationship between bandwidth and latency for various applications [127], focusing on a Metaverse system.

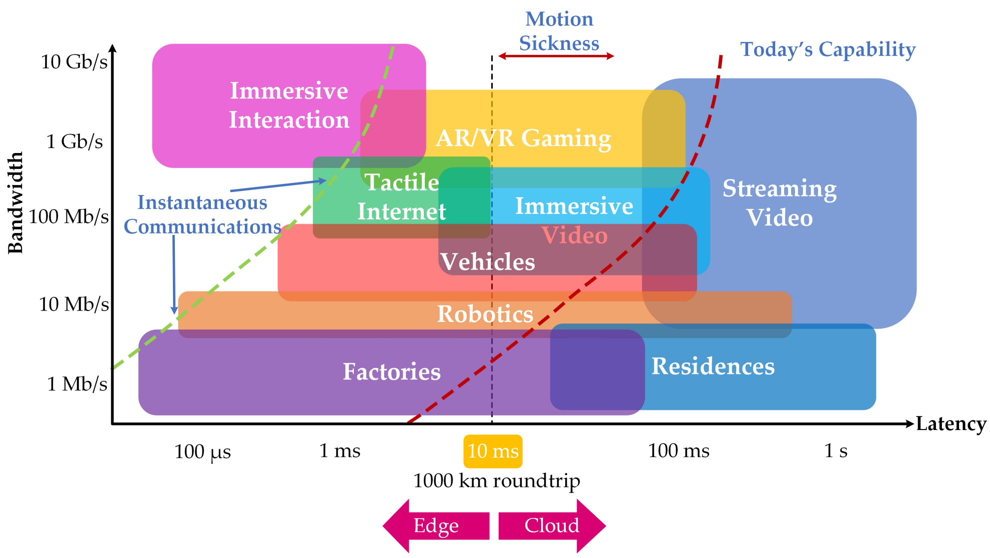

Figure 9. Mean-time-to-Cloud – Bandwidth & Latency

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5.1.1. Network Latency

Network latency refers to the delay between a user's action and the response from the network in a digital environment [128]. In the context of Metaverse, which relies heavily on real-time interactions and seamless connectivity, latency can significantly impact user experience. High latency can cause noticeable delays in data transmission, leading to lagging or choppy movements, delayed responses from virtual entities, and disrupted interactions between users. These delays can break the immersion and fluidity of Metaverse, making it difficult for users to enjoy a smooth and interactive experience.

The effects of network latency on Metaverse are particularly pronounced in activities that require real-time synchronization [129], such as multiplayer gaming, live events, and social interactions. When latency is high, users may experience out-of-sync movements, communication breakdowns, and inconsistencies in the virtual environment. Lack of synchronization can lead to frustration and disengagement, undermining Metaverse's overall effectiveness and appeal. Ensuring low latency is critical for maintaining the real-time responsiveness and immersive quality essential for a compelling Metaverse experience. To address these challenges, advancements in network infrastructure, such as 5G technology and edge computing, are being leveraged to reduce latency and enhance the reliability of real-time interactions in Metaverse.

5.1.2. Bandwidth Limitations

Bandwidth limitation is the maximum rate at which data can be transmitted over a network. In Metaverse, bandwidth determines how much data can be exchanged between users and servers at any given time [130]. High-quality virtual experiences in Metaverse require transmitting large volumes of data, including high-resolution graphics, audio, and real-time interactive elements. When bandwidth is limited, these data transmissions can become bottlenecked, leading to slower loading times, reduced graphical fidelity, and overall degraded user experience.

The impact of bandwidth limitations on Metaverse is particularly significant during peak usage times or in areas with poor network infrastructure [131]. Users may experience lag, buffering, and disconnections, disrupting the immersive experience and hindering interactions within the virtual world [132]. Bandwidth constraints can also limit the scalability of Metaverse, as the infrastructure may struggle to support many concurrent users. To mitigate these issues, advancements in network technologies, such as fiber optics and 5G, are being deployed to increase bandwidth capacity [133]. Additionally, data compression and content delivery networks (CDNs) optimize data transmission and reduce the strain on bandwidth, ensuring a smoother and more reliable Metaverse experience.

Table 1 highlights the progression of VR technologies by comparing bandwidth requirements, latency, and supported resolutions based on the latest published research. Wi-Fi 6E supports up to 8K resolution with bandwidth of up to 2.4 Gbps and approximately 20 ms latency, leveraging the 6 GHz band for enhanced performance in crowded environments [134]. Wi-Fi 7 further improves, offering bandwidth of up to 46 Gbps and latency of around 10 ms, also supporting up to 8K resolution with multi-link operation and enhanced spectrum efficiency [135]. Wi-Fi 8 is expected to advance these capabilities significantly, incorporating millimeter-wave technology to achieve data rates up to 100 Gbps and latency below 1 ms, supporting 8K and beyond with features like multiple Access Point (AP) coordination and beamforming [136,137]. 5G networks provide ultra-fast speeds of 1-10 Gbps and latency between 1-10 ms, capable of smoothly streaming up to 8K VR content, especially in mobile environments [138]. The combination of NGCodec with 5G optimizes bandwidth usage through advanced video compression, reducing latency to under 5 ms while supporting up to 8K resolution [139]. Lastly, FPGA-based VR streaming utilizes reconfigurable hardware for efficient video encoding and decoding, achieving latency below 1 ms and supporting up to 8K resolution, ensuring real-time interactivity and smooth performance [140,141].

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Table 1. Progression of VR compare bandwidth and latency across different technologies.

Technology	Bandwidth Requirement	Latency	Resolution
Wi-Fi 6E	Up to 2.4 Gbps	∼20 ms	HD, 2K, 4K 8K with strong signal strength and minimal interference
Wi-Fi 7	Up to 46 Gbps	∼10 ms	Up to 8K Potential to support 16K video resolution
Wi-Fi 8	Up to 100 Gbps	<1 ms	Up to 8K Potential to support 16K video resolution
5G Network	1-10 Gbps	1-10 ms	Up to 4K 8K depends on network conditions and coverage
NGCodec + 5G	∼1-10 Gbps (optimized)	<5 ms	Up to 8K
FPGA-based VR Streaming	Depends on setup	<1 ms	Up to 8K

5.2. Interoperability and Standards

Interoperability and standards pose significant challenges in the development and functionality of Metaverse [142]. Interoperability refers to the ability of Metaverse systems, platforms, and applications to work seamlessly together. The diversity of virtual environments, avatars, digital assets, and interaction mechanisms created by various developers and organizations makes achieving interoperability complex. Users might face difficulties transferring digital identities, assets, and experiences without common standards across virtual worlds. Digital fragmentation can hinder Metaverse's vision of a unified, cohesive digital universe, limiting user engagement and stifling innovation.

5.2.1. Universal Standards

Establishing universal standards for Metaverse is another formidable challenge. Standards are essential to ensure consistency, security, and compatibility across various platforms and technologies that constitute Metaverse [54]. However, reaching a consensus on these standards involves coordination among numerous stakeholders, including tech companies, developers, regulatory bodies, and users. Each group may have different priorities and interests, making it difficult to agree on a unified set of rules and protocols. Additionally, rapid technological advancements and the evolving nature of Metaverse further complicate standardization efforts. Metaverse risks becoming a collection of isolated ecosystems without robust interoperability and standardized frameworks rather than a seamless, interconnected digital reality. This major challenge is divided into two parts: Fragmentation and Data Compatibility.

5.2.2. Fragmentation

Fragmentation refers to multiple, incompatible systems and protocols within Metaverse, leading to isolated digital environments that cannot seamlessly interact with each other [43]. Product fragmentation arises when different developers and platforms adopt unique standards for creating and managing virtual worlds, avatars, digital assets, and user interactions. Without a unified approach, users face significant challenges when navigating between different parts of Metaverse, as their digital identities, assets, and experiences may not be transferable across these isolated ecosystems.

The fragmentation issue severely impacts the user experience and the overall potential of Metaverse [143]. For instance, a user might create an avatar and acquire virtual assets in one platform, only to find that these cannot be used or recognized in another platform. The lack of interoperability discourages users from investing time and resources into Metaverse, as they may be concerned about the portability and longevity of their digital assets. Moreover, developers are also hindered by fragmentation, as they must choose which standards to support or face the burden of trying to make their platforms compatible with multiple systems. The lack of universal standards stifles innovation and growth, preventing Metaverse from becoming the interconnected and expansive digital universe it aspires to be. Addressing fragmentation requires concerted efforts to establish and adopt common standards, ensuring that all parts of Metaverse can work together harmoniously.

5.2.3. Unified Standards

Unified standards are an asset of agreed-upon protocols, formats, and guidelines that ensure compatibility and interoperability across different systems and platforms within Metaverse [54]. These standards aim to eliminate the barriers created by fragmentation, allowing for seamless integration and interaction between diverse virtual environments, digital assets, avatars, and user experiences [144]. By adopting unified standards, developers and platforms can ensure that users can move fluidly between different parts of Metaverse without losing functionality or having to recreate their digital presence.

Implementing unified standards is crucial for Metaverse to achieve its vision of a cohesive and interconnected digital universe [65,145]. These standards would cover various aspects such as data formats, communication protocols, security measures, and user interface guidelines. For example, a standardized avatar format would allow users to maintain the same digital identity across different virtual worlds. In contrast, standardized asset formats would ensure that digital goods purchased or created in one environment can be used in another. Unified standards thus foster a more inclusive and expansive Metaverse, enhancing user experience, encouraging innovation, and promoting collaboration among developers and platforms.

5.2.4. Cross-Platform Compatibility

Cross-platform compatibility is the ability of different virtual environments, systems, and applications within Metaverse to work together seamlessly, regardless of the underlying platform or technology [146]. This means that users can access and interact with various parts of Metaverse using different devices (such as PCs, VR headsets, mobile phones, etc.) and still have a consistent and unified experience. Cross-platform compatibility ensures that digital assets, avatars, user data, and interactions can be transferred and recognized across different systems without losing functionality or user experience.

Addressing cross-platform compatibility is essential for overcoming fragmentation in Metaverse. It allows users to navigate between different virtual worlds and applications without encountering barriers or needing to adapt to different interfaces or standards [147]. For example, a user should be able to purchase a digital item in one virtual world and use it in another, regardless of which platform each world is built on. Cross-platform compatibility involves adopting common standards and protocols that enable different systems to communicate and share data effectively. Cross-platform integration enhances the user experience by providing continuity and coherence across Metaverse, fostering greater engagement and participation from a broader audience.

5.2.5. Data Compatibility

Data compatibility ensures that different systems, platforms, and applications can effectively share, interpret, and use data across various environments [148]. These issues arise when there is no common format or protocol for data representation, storage, and exchange, leading to difficulties in integrating and synchronizing data across different virtual worlds and applications.

In Metaverse, data compatibility is essential for a seamless user experience [18]. Users create and interact with various digital assets, including avatars, virtual goods, and user-generated content. When these assets are created in one environment but incompatible with others, users face significant barriers in transferring or utilizing their data across different platforms [10]. For instance, an avatar designed in one virtual world might not be recognized, or digital assets purchased in one marketplace might not be usable in another due to differences in data formats and structures.

The lack of data compatibility hampers Metaverse's potential as a unified and interconnected digital universe [149]. To address these issues, there needs to be a concerted effort to develop and adopt common data standards and protocols. These standards would define how data should be formatted, stored, and exchanged, ensuring that it can be seamlessly interpreted and used across different systems. By achieving data compatibility, Metaverse can provide a more cohesive and integrated experience, allowing users to move fluidly between different environments and fully leverage their digital assets across the entire ecosystem. Common formats and data integration are the most important factors of data compatibility [144].

Common formats in data compatibility within Metaverse are essential for ensuring seamless interoperability across various platforms, applications, and virtual environments [27,150]. These standardized formats facilitate the consistent representation, storage, and exchange of data, allowing different systems to interpret and use the same data efficiently. Common formats are critical in avatars and digital identities, digital assets and virtual goods, user data and profiles, virtual currency and transactions, communication and interaction data, and environment and world data.

Common formats like FBX (Filmbox), OBJ (Wavefront Object), and glTF (GL Transmission Format) are widely used for 3D models and animations for avatars and digital identities. These formats ensure that avatars created in one virtual world can be rendered and animated correctly in another [151]. Metadata formats such as JSON (JavaScript Object Notation) and XML (Extensible Markup Language) are essential for including information about avatars, such as appearance, accessories, and customizations, ensuring consistent interpretation across platforms. Standardizing these formats helps maintain the visual and functional integrity of avatars and digital identities as they move across different virtual environments.

In the realm of digital assets and virtual goods, standardized formats for textures and materials, such as PNG (Portable Network Graphics) and JPEG (Joint Photographic Experts Group) for textures and PBR (Physically Based Rendering) materials, ensure that the visual quality of digital assets is maintained across various platforms [152]. Asset bundles packaged in standard formats like Unity Asset Bundles or Unreal Engine's asset format facilitate the transfer and usage of digital assets across different virtual worlds. Additionally, blockchain standards like ERC-20 or ERC-721 for tokens ensure that virtual currencies and digital collectibles can be managed and exchanged securely and interoperably [153].

5.2.6. Data Integration

Data integration is equally important for user data and profiles, virtual currency and transactions, and communication and interaction data [154]. Standard formats for user profiles, preferences, and settings (e.g., JSON or XML) enable consistent user experiences across different platforms. Adopting blockchain protocols like ERC-20 or ERC-721 for virtual currencies and transactions ensures secure and interoperable management of digital assets [153]. In terms of communication and interaction data, standardized protocols like XMPP (Extensible Messaging and Presence Protocol) or WebRTC (Web Real-Time Communication) ensure that text, voice, and video communication services are interoperable across different platforms [155]. Using standard formats for describing virtual environments, such as XML-based X3D or JSON-based Scene Graphs, also ensures that different platforms can render and interact with these environments consistently [156].

By adopting these common formats and data integration standards, Metaverse can achieve a higher level of interoperability, enabling a more cohesive and integrated user experience. This approach not only facilitates the seamless transfer of digital assets and data across different virtual environments but also enhances user engagement and satisfaction. As Metaverse continues to evolve, the importance of standardized data formats and integration protocols will only grow, ensuring that users enjoy a unified and immersive digital universe.

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5.3. Scalability

Scalability is a significant issue in Metaverse [59], as it needs to support an ever-growing number of users, vast virtual environments, and a wide range of activities and interactions. As Metaverse expands, the infrastructure must handle increased loads without degrading performance. Challenges include maintaining low latency and high bandwidth for real-time interactions, managing large volumes of data generated by users, and ensuring consistent user experiences across diverse devices and locations.

Addressing resource management involves optimizing computational and network resources for efficiency and performance. Resource management can be achieved through techniques such as load balancing, which distributes traffic across multiple servers to prevent any single server from becoming a bottleneck [157]. Edge computing, which processes data closer to the user's location, can reduce latency and improve response times by offloading tasks from centralized servers. Additionally, scalable cloud [158] and edge [159] infrastructure allows for dynamic allocation of resources based on demand, ensuring that the system can handle peak loads without compromising performance.

Global accessibility ensures that users from different regions can access and enjoy Metaverse without facing disparities in performance or availability [160]. This involves deploying a distributed network infrastructure, such as content delivery networks (CDNs), to cache and deliver content from servers geographically closer to users, thereby reducing latency. Investing in robust network infrastructure, including the latest 5G and fiber-optic technologies, can enhance connectivity and support high data transfer rates worldwide. Moreover, adopting standard protocols and ensuring cross-platform compatibility allows users on various devices and network conditions to have a consistent and inclusive experience in Metaverse.

5.4. User Experience

User experience (UX) is a critical issue in Metaverse, as it directly impacts user engagement and satisfaction [161]. A seamless and intuitive UX is essential for making virtual environments enjoyable and accessible to a wide audience. However, creating an optimal UX in Metaverse is challenging due to the complexity of immersive technologies, the diversity of user needs, and the potential for adverse effects such as motion sickness [20]. Ensuring that users can navigate, interact, and communicate effectively within Metaverse requires careful design and continuous improvement based on user feedback.

Motion sickness, also known as cybersickness in virtual environments, is a significant UX issue in Metaverse [162]. It occurs when there is a disconnect between the visual input from the virtual environment and the user's physical sensations, leading to symptoms such as nausea, dizziness, and disorientation. To address motion sickness, developers can implement several strategies. These include optimizing frame rates to reduce lag and visual inconsistencies, minimizing latency to ensure responsive interactions, and designing smooth and predictable motion paths. Additionally, allowing users to control their movements, such as allowing for gradual acceleration and deceleration, can help mitigate motion sickness. Implementing comfort settings, such as adjustable field of view (FOV) and customizable motion controls, allows users to tailor their experience to their comfort levels [163].

Accessibility in Metaverse is another crucial aspect of UX that ensures inclusivity for users with diverse abilities and needs. Addressing accessibility involves implementing features that accommodate various physical, sensory, and cognitive disabilities [164]. For example, providing options for text-to-speech and speech-to-text can assist users with visual or hearing impairments. Ensuring that virtual environments are navigable with various input devices, such as adaptive controllers or voice commands, can make Metaverse more accessible to users with motor disabilities. Additionally, incorporating customizable interfaces, adjustable text sizes, and color contrast settings can enhance usability for users with cognitive or visual challenges. By prioritizing accessibility, developers can create a more inclusive Metaverse that offers meaningful and enjoyable experiences for all users, regardless of their abilities.

5.5. Security and Privacy

Security and privacy issues in Metaverse are significant concerns due to the vast amount of personal and sensitive data generated and exchanged within virtual environments [165]. Users' interactions, transactions, and personal information, including biometric data from VR/AR devices, are vulnerable to breaches and misuse. The immersive nature of Metaverse adds complexity to security challenges, as it involves real-time data exchange and extensive user tracking to deliver personalized experiences. Ensuring the security and privacy of this data is critical to maintaining user trust and safeguarding against potential threats.

Addressing *data security* in Metaverse requires robust encryption methods to protect data in transit and at rest. Enhancing security involves using advanced cryptographic techniques to ensure that data exchanged between users and servers is secure and cannot be intercepted or altered by malicious actors [166]. Employing multi-factor authentication (MFA) and secure login protocols can prevent unauthorized access to user accounts. Regular security audits and vulnerability assessments are essential to identify and address potential weaknesses in the system. Developers must also establish protocols for incident response to quickly mitigate the effects of any security breaches.

Privacy concerns in Metaverse can be addressed by giving users greater control over their data and ensuring transparency in data handling practices [167]. Implementing privacy settings that allow users to manage what information is shared and with whom can empower users to protect their data. Developers should adhere to privacy-by-design principles, embedding privacy considerations into the development process from the outset. Compliance with global data protection regulations like the European Union's General Data Protection Regulation (GDPR) and the California Consumer Privacy Act (CCPA) ensures user data is handled responsibly and ethically [168]. Educating users about best practices for protecting their privacy, such as avoiding sharing sensitive information and recognizing phishing attempts, can further enhance Metaverse's overall security and privacy posture.

The Real-Time Metaverse represents a transformative frontier in digital interaction, offering unprecedented opportunities for immersive and interactive experiences. While significant progress has been made in technology, infrastructure, and interoperability, numerous challenges remain. Addressing these issues requires collaborative efforts across industries, academia, and government bodies to create a seamless, inclusive, and secure metaverse experience. As technology evolves, the real-time metaverse will increasingly become integral to our digital lives, reshaping how we interact, work, and play in the virtual world.

Figure 10 depicts various security challenges associated with Metaverse, focusing on the interactions between the physical and virtual worlds and the cloud infrastructure. In the physical world, users use VR headsets, smartphones, and laptops to access the virtual world. Data transmission between these devices and the cloud, which supports Metaverse, is vulnerable to packet loss and cyber-attacks. Hackers can exploit these vulnerabilities through methods like "Man in the Middle" attacks, where they intercept and potentially alter data being transmitted, and Denial of Service (DoS) attacks, which can disrupt services by overwhelming the network. These security threats can lead to compromised user experiences and data integrity in the virtual world, emphasizing the need for robust security measures to protect metaverse interactions.

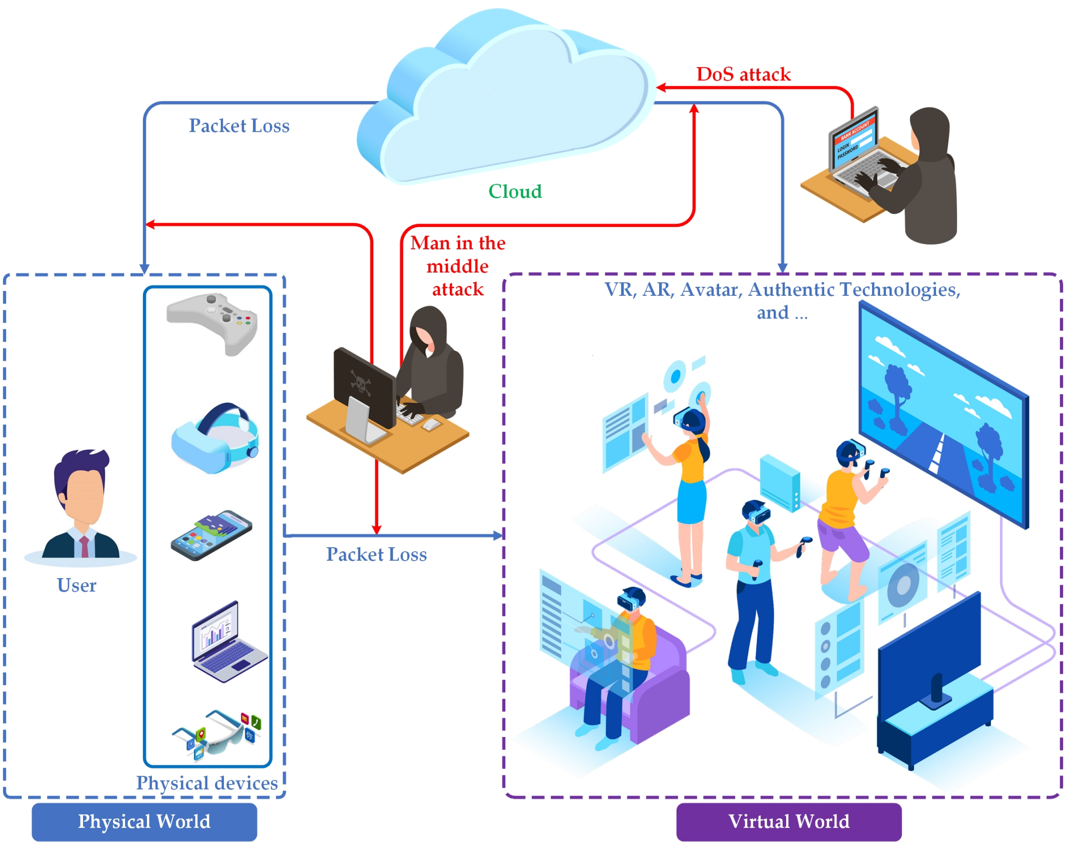

Figure 10. Security challenges associated with Metaverse.

6. Conclusions

The real-time metaverse represents a significant leap in integrating digital and physical realms, driven by technological advancements such as AI, VR, AR, blockchain, and high-speed networks. The technology convergence facilitates immersive, interactive experiences that span various sectors, including education, healthcare, entertainment, and business. The potential of Metaverse lies in its ability to provide seamless, real-time interactions that closely mimic the immediacy of the real world. However, achieving an interactive Metaverse requires overcoming substantial challenges related to latency, bandwidth, scalability, and security.

Efforts to enhance Metaverse's infrastructure are crucial for its success. Incorporating edge computing is one such effort, as it brings data processing closer to the user, thereby reducing latency and improving response times. Additionally, developing robust interoperability standards is essential to ensure seamless communication and integration across different platforms and devices. These advancements will enable a more cohesive and efficient digital ecosystem, allowing users to transition smoothly between virtual environments and experiences.

Addressing social and ethical concerns is equally important in fostering a safe and inclusive virtual environment. User privacy, data security, and equitable representation must be at the forefront of metaverse development. Ensuring that users' data is protected and interactions within Metaverse are secure will help build trust and encourage broader adoption. Furthermore, creating guidelines and regulations to prevent digital harassment and ensure equitable representation of avatars will contribute to a healthier and more welcoming digital space.

As Metaverse evolves, industry, academia, and government collaborative efforts will be necessary to realize its transformative capabilities fully. Such collaboration will drive innovation and address existing barriers, ensuring Metaverse becomes a vibrant, user-friendly, and secure digital ecosystem. By focusing on these social, technical, and governance issues, the real-time metaverse can revolutionize how we interact, work, and learn, creating new opportunities for innovation and connectivity in the digital age.

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Abbreviations

The following abbreviations are used in this manuscript:

3D	Three Dimensional
5G	the fifth-generation
AI	Artificial Intelligence
AP	Access Point
API	Application Programming Interface
AR	Augmented Reality
AWS	Amazon Web Services
CCPA	California Consumer Privacy Act
CDN	Content Delivery Networks
CUDA	Compute Unified Device Architecture
DoS	Denial of Service
DLSS	Deep Learning Super Sampling
FBX	Filmbox
FOV	Field of View
GCP	Google Cloud Services
GDPR	General Data Protection Regulation
glTF	GL Transmission Format
GPU	Graphics Processing Unit
GR	Graphical Rendering
HPC	High Performance Computing
HL7	Health Level Seven
HTML	Hyper Text Markup Language
HTTP	Hypertext Transfer Protocol
IaaS	Infrastructure as a Service
IoT	Internet of Things
JPEG	Joint Photographic Experts Group
JSON	JavaScript Object Notation
LLM	Large Language Models
MFA	Multi-Factor Authentication
MIMO	Multiple-Input Multiple Output
ML	Machine Learning
mMTC	massive Machine-Type Communications
MPI	Message Passing Interface
MR	Mixed Reality
NLP	Natural Language Processing
NPC	Non-Player Characters
OBJ	Wavefront Object
OpenMP	Open Multi-Processing
PaaS	Platform as a Service
PBR	Physically Based Rendering
PNG	Portable Network Graphics

RBG	Red, Green and Blue)
SaaS	Software as a Service
TCP/IP	Transmission Control Protocol/Internet Protocol
URLLC	Ultra-Reliable Low-Latency Communications
UX	User eXperience
VR	Virtual Reality
W3C	World Wide Web Consortium
WebRTC	Web Real-Time Communication
XML	Extensible Markup Language
XMPP	Extensible Messaging and Presence Protocol

References

1. Wang, Y.; Su, Z.; Zhang, N.; Xing, R.; Liu, D.; Luan, T.H.; Shen, X. A survey on metaverse: Fundamentals, security, and privacy. *IEEE Communications Surveys & Tutorials* **2022**, *25*, 319–352.
2. Li, K.; Cui, Y.; Li, W.; Lv, T.; Yuan, X.; Li, S.; Ni, W.; Simsek, M.; Dressler, F. When internet of things meets metaverse: Convergence of physical and cyber worlds. *IEEE Internet of Things Journal* **2022**, *10*, 4148–4173.
3. Setiawan, K.D.; Anthony, A.; others. The essential factor of metaverse for business based on 7 layers of metaverse–systematic literature review. 2022 international conference on information management and technology (ICIMTech). IEEE, 2022, pp. 687–692.
4. Tyagi, A.K. Decentralized everything: Practical use of blockchain technology in future applications. In *Distributed Computing to Blockchain*; Elsevier, 2023; pp. 19–38.
5. Truong, V.T.; Le, L.; Niyato, D. Blockchain meets metaverse and digital asset management: A comprehensive survey. *Ieee Access* **2023**, *11*, 26258–26288.
6. Zhu, H.Y.; Hieu, N.Q.; Hoang, D.T.; Nguyen, D.N.; Lin, C.T. A human-centric metaverse enabled by brain-computer interface: A survey. *IEEE Communications Surveys & Tutorials* **2024**.
7. Park, S.M.; Kim, Y.G. A metaverse: Taxonomy, components, applications, and open challenges. *IEEE access* **2022**, *10*, 4209–4251.
8. Liu, S.; Xie, J.; Wang, X. QoE enhancement of the industrial metaverse based on Mixed Reality application optimization. *Displays* **2023**, *79*, 102463.
9. Yang, Y.; Ma, M.; Van Doan, T.; Hulin, T.; Fitzek, H.F.; Nguyen, G.T. Touch the Metaverse: Demonstration of Haptic Feedback in Network-Assisted Augmented Reality. 2024 IEEE International Conference on Pervasive Computing and Communications Workshops and other Affiliated Events (PerCom Workshops). IEEE, 2024, pp. 379–381.
10. Mystakidis, S. Metaverse. *Encyclopedia* **2022**, *2*, 486–497.
11. Singla, B.; Shalender, K.; Singh, N. *Creator's Economy in Metaverse Platforms: Empowering Stakeholders Through Omnichannel Approach: Empowering Stakeholders Through Omnichannel Approach*; IGI Global, 2024.
12. Park, S.; Kim, S. Identifying world types to deliver gameful experiences for sustainable learning in the metaverse. *Sustainability* **2022**, *14*, 1361.
13. Mancuso, I.; Petruzzelli, A.M.; Panniello, U. Digital business model innovation in metaverse: How to approach virtual economy opportunities. *Information Processing & Management* **2023**, *60*, 103457.
14. Xu, M.; Ng, W.C.; Lim, W.Y.B.; Kang, J.; Xiong, Z.; Niyato, D.; Yang, Q.; Shen, X.; Miao, C. A full dive into realizing the edge-enabled metaverse: Visions, enabling technologies, and challenges. *IEEE Communications Surveys & Tutorials* **2022**, *25*, 656–700.
15. Dwivedi, Y.K.; Hughes, L.; Baabdullah, A.M.; Ribeiro-Navarrete, S.; Giannakis, M.; Al-Debei, M.M.; Dennehy, D.; Metri, B.; Buhalis, D.; Cheung, C.M.; others. Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. *International Journal of Information Management* **2022**, *66*, 102542.
16. Ng, D.T.K. What is the metaverse? Definitions, technologies and the community of inquiry. *Australasian Journal of Educational Technology* **2022**, *38*, 190–205.
17. Gadekallu, T.R.; Huynh-The, T.; Wang, W.; Yenduri, G.; Ranaweera, P.; Pham, Q.V.; da Costa, D.B.; Liyanage, M. Blockchain for the metaverse: A review. *arXiv preprint arXiv:2203.09738* **2022**.
18. Ersoy, M.; Gürfidan, R. Blockchain-based asset storage and service mechanism to metaverse universe: Metarepo. *Transactions on Emerging Telecommunications Technologies* **2023**, *34*, e4658.

19. Huang, H.; Wu, J.; Zheng, Z. *From Blockchain to Web3 and Metaverse*; Springer, 2023.
20. Dincelli, E.; Yayla, A. Immersive virtual reality in the age of the Metaverse: A hybrid-narrative review based on the technology affordance perspective. *The journal of strategic information systems* **2022**, *31*, 101717.
21. Wang, H.; Ning, H.; Lin, Y.; Wang, W.; Dhelim, S.; Farha, F.; Ding, J.; Daneshmand, M. A survey on the metaverse: The state-of-the-art, technologies, applications, and challenges. *IEEE Internet of Things Journal* **2023**, *10*, 14671–14688.
22. Huynh-The, T.; Pham, Q.V.; Pham, X.Q.; Nguyen, T.T.; Han, Z.; Kim, D.S. Artificial intelligence for the metaverse: A survey. *Engineering Applications of Artificial Intelligence* **2023**, *117*, 105581.
23. Zhao, Y.; Jiang, J.; Chen, Y.; Liu, R.; Yang, Y.; Xue, X.; Chen, S. Metaverse: Perspectives from graphics, interactions and visualization. *Visual Informatics* **2022**, *6*, 56–67.
24. Aloqaily, M.; Bouachir, O.; Karray, F.; Al Ridhawi, I.; El Saddik, A. Integrating digital twin and advanced intelligent technologies to realize the metaverse. *IEEE Consumer Electronics Magazine* **2022**.
25. Grande, R.; Albusac, J.; Vallejo, D.; Glez-Morcillo, C.; Castro-Schez, J.J. Performance Evaluation and Optimization of 3D Models from Low-Cost 3D Scanning Technologies for Virtual Reality and Metaverse E-Commerce. *Applied Sciences* **2024**, *14*, 6037.
26. Singh, A.; Mishra, S.; Jain, S.; Dogra, S.; Awasthi, A.; Roy, N.R.; Sodhi, K. 8 Exploring practical use-cases of augmented reality using photogrammetry and other 3D reconstruction tools in the Metaverse. *Augmented and Virtual Reality in Industry 5.0* **2023**, *2*, 163.
27. Ball, M. *The metaverse: and how it will revolutionize everything*; Liveright Publishing, 2022.
28. Bibri, S.E. The social shaping of the metaverse as an alternative to the imaginaries of data-driven smart Cities: A study in science, technology, and society. *Smart Cities* **2022**, *5*, 832–874.
29. Alpala, L.O.; Quiroga-Parra, D.J.; Torres, J.C.; Peluffo-Ordóñez, D.H. Smart factory using virtual reality and online multi-user: Towards a metaverse for experimental frameworks. *Applied Sciences* **2022**, *12*, 6258.
30. Chen, Z. Metaverse office: Exploring future teleworking model. *Kybernetes* **2024**, *53*, 2029–2045.
31. Lin, H.; Wan, S.; Gan, W.; Chen, J.; Chao, H.C. Metaverse in education: Vision, opportunities, and challenges. 2022 IEEE International Conference on Big Data (Big Data). IEEE, 2022, pp. 2857–2866.
32. Hennig-Thurau, T.; Aliman, D.N.; Herting, A.M.; Cziehso, G.P.; Linder, M.; Kübler, R.V. Social interactions in the metaverse: Framework, initial evidence, and research roadmap. *Journal of the Academy of Marketing Science* **2023**, *51*, 889–913.
33. Turchet, L. Musical Metaverse: vision, opportunities, and challenges. *Personal and Ubiquitous Computing* **2023**, *27*, 1811–1827.
34. Kiong, L.V. *Metaverse Made Easy: A Beginner's Guide to the Metaverse: Everything you need to know about Metaverse, NFT and GameFi*; Liew Voon Kiong, 2024.
35. Venugopal, J.P.; Subramanian, A.A.V.; Peatchimuthu, J. The realm of metaverse: A survey. *Computer Animation and Virtual Worlds* **2023**, *34*, e2150.
36. Aslam, A.M.; Chaudhary, R.; Bhardwaj, A.; Budhiraja, I.; Kumar, N.; Zeadally, S. Metaverse for 6G and beyond: The next revolution and deployment challenges. *IEEE Internet of Things Magazine* **2023**, *6*, 32–39.
37. Warburton, M.; Mon-Williams, M.; Mushtaq, F.; Morehead, J.R. Measuring motion-to-photon latency for sensorimotor experiments with virtual reality systems. *Behavior Research Methods* **2023**, *55*, 3658–3678.
38. Cai, Y.; Llorca, J.; Tulino, A.M.; Molisch, A.F. Compute-and data-intensive networks: The key to the metaverse. 2022 1st international conference on 6G networking (6GNet). IEEE, 2022, pp. 1–8.
39. Mei, L.; Gou, J.; Cai, Y.; Cao, H.; Liu, Y. Realtime mobile bandwidth and handoff predictions in 4G/5G networks. *Computer Networks* **2022**, *204*, 108736.
40. Wang, Y.; Zhao, J. A survey of mobile edge computing for the metaverse: Architectures, applications, and challenges. 2022 IEEE 8th International Conference on Collaboration and Internet Computing (CIC). IEEE, 2022, pp. 1–9.
41. Familoni, B.T.; Onyebuchi, N.C. Augmented and virtual reality in us education: a review: analyzing the impact, effectiveness, and future prospects of ar/vr tools in enhancing learning experiences. *International Journal of Applied Research in Social Sciences* **2024**, *6*, 642–663.
42. Gadekallu, T.R.; Wang, W.; Yenduri, G.; Ranaweera, P.; Pham, Q.V.; da Costa, D.B.; Liyanage, M.; others. Blockchain for the metaverse: A review. *Future Generation Computer Systems* **2023**, *143*, 401–419.

43. Lee, L.H.; Braud, T.; Zhou, P.; Wang, L.; Xu, D.; Lin, Z.; Kumar, A.; Bermejo, C.; Hui, P. All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystem, and research agenda. *arXiv preprint arXiv:2110.05352* **2021**.
44. Górriz, J.M.; Ramírez, J.; Ortiz, A.; Martinez-Murcia, F.J.; Segovia, F.; Suckling, J.; Leming, M.; Zhang, Y.D.; Álvarez-Sánchez, J.R.; Bologna, G.; others. Artificial intelligence within the interplay between natural and artificial computation: Advances in data science, trends and applications. *Neurocomputing* **2020**, *410*, 237–270.
45. Saxena, A.C.; Ojha, A.; Sobti, D.; Khang, A. Artificial Intelligence (AI)-Centric Model in the Metaverse Ecosystem. In *Handbook of Research on AI-Based Technologies and Applications in the Era of the Metaverse*; IGI Global, 2023; pp. 1–24.
46. Duong, T.Q.; Van Huynh, D.; Khosravirad, S.R.; Sharma, V.; Dobre, O.A.; Shin, H. From digital twin to metaverse: The role of 6G ultra-reliable and low-latency communications with multi-tier computing. *IEEE Wireless Communications* **2023**, *30*, 140–146.
47. Seo, J.; Park, S. SBAC: Substitution cipher access control based on blockchain for protecting personal data in metaverse. *Future Generation Computer Systems* **2024**, *151*, 85–97.
48. Hyun, W. Study on standardization for interoperable metaverse. 2023 25th International Conference on Advanced Communication Technology (ICACT). IEEE, 2023, pp. 319–322.
49. Sun, Z.; Zhu, M.; Shan, X.; Lee, C. Augmented tactile-perception and haptic-feedback rings as human-machine interfaces aiming for immersive interactions. *Nature communications* **2022**, *13*, 5224.
50. Yu, J.; Alhilal, A.; Hui, P.; Tsang, D.H. Bi-directional digital twin and edge computing in the metaverse. *IEEE Internet of Things Magazine* **2024**, *7*, 106–112.
51. Karunarathna, S.; Wijethilaka, S.; Ranaweera, P.; Hemachandra, K.T.; Samarasinghe, T.; Liyanage, M. The role of network slicing and edge computing in the metaverse realization. *IEEE Access* **2023**, *11*, 25502–25530.
52. Lee, H.; Hwang, Y. Technology-enhanced education through VR-making and metaverse-linking to foster teacher readiness and sustainable learning. *Sustainability* **2022**, *14*, 4786.
53. Kaddoura, S.; Al Husseiny, F. The rising trend of Metaverse in education: Challenges, opportunities, and ethical considerations. *PeerJ Computer Science* **2023**, *9*, e1252.
54. Yang, L. Recommendations for metaverse governance based on technical standards. *Humanities and Social Sciences Communications* **2023**, *10*, 1–10.
55. Karaarslan, E.; Yazici Yilmaz, S. Metaverse and Decentralization. In *Metaverse: Technologies, Opportunities and Threats*; Springer, 2023; pp. 31–44.
56. Nikouei, S.Y.; Xu, R.; Nagothu, D.; Chen, Y.; Aved, A.; Blasch, E. Real-time index authentication for event-oriented surveillance video query using blockchain. 2018 IEEE International Smart Cities Conference (ISC2). IEEE, 2018, pp. 1–8.
57. Lee, H.J.; Gu, H.H. Empirical research on the metaverse user experience of digital natives. *Sustainability* **2022**, *14*, 14747.
58. Mourtzis, D.; Angelopoulos, J.; Panopoulos, N. Smart manufacturing and tactile internet based on 5G in industry 4.0: Challenges, applications and new trends. *Electronics* **2021**, *10*, 3175.
59. Cheng, R.; Wu, N.; Chen, S.; Han, B. Will metaverse be nextg internet? vision, hype, and reality. *IEEE network* **2022**, *36*, 197–204.
60. Qu, Q.; Hatami, M.; Xu, R.; Nagothu, D.; Chen, Y.; Li, X.; Blasch, E.; Ardiles-Cruz, E.; Chen, G. The microverse: A task-oriented edge-scale metaverse. *Future Internet* **2024**, *16*, 60.
61. Qu, Q.; Chen, Y.; Li, X.; Blasch, E.; Chen, G.; Ardiles-Cruz, E. Low-cost collision avoidance in microverse for unmanned aerial vehicle delivery networks. Sensors and Systems for Space Applications XVII. SPIE, 2024, Vol. 13062, pp. 215–226.
62. Sun, H.; Qu, Q.; Chen, Y.; Ardiles-Cruz, E.; Blasch, E. Senior Safety Monitoring in Microverse using Fuzzy Neural Network Enhanced Action Recognition. *Authorea Preprints* **2024**.
63. Yang, L.; Ni, S.T.; Wang, Y.; Yu, A.; Lee, J.A.; Hui, P. Interoperability of the Metaverse: A Digital Ecosystem Perspective Review. *arXiv preprint arXiv:2403.05205* **2024**.
64. Mangrulkar, R.S.; Chavan, P.V. *Blockchain Essentials*; Springer, 2024.
65. Ritterbusch, G.D.; Teichmann, M.R. Defining the metaverse: A systematic literature review. *Ieee Access* **2023**, *11*, 12368–12377.

66. Blasch, E.; Pham, T.; Chong, C.Y.; Koch, W.; Leung, H.; Braines, D.; Abdelzaher, T. Machine learning/artificial intelligence for sensor data fusion–opportunities and challenges. *IEEE Aerospace and Electronic Systems Magazine* **2021**, *36*, 80–93.
67. Tyagi, A.K. *Automated Secure Computing for Next-Generation Systems*; John Wiley & Sons, 2023.
68. Braud, T.; Fernández, C.B.; Hui, P. Scaling-up ar: University campus as a physical-digital metaverse. 2022 ieee conference on virtual reality and 3d user interfaces abstracts and workshops (vrw). IEEE, 2022, pp. 169–175.
69. He, X.; Liu, Y.; Ganesan, K.; Ahnood, A.; Beckett, P.; Eftekhari, F.; Smith, D.; Uddin, M.H.; Skafidas, E.; Nirmalathas, A.; others. A single sensor based multispectral imaging camera using a narrow spectral band color mosaic integrated on the monochrome CMOS image sensor. *APL Photonics* **2020**, *5*.
70. Li, N.; Ho, C.P.; Xue, J.; Lim, L.W.; Chen, G.; Fu, Y.H.; Lee, L.Y.T. A progress review on solid-state LiDAR and nanophotonics-based LiDAR sensors. *Laser & Photonics Reviews* **2022**, *16*, 2100511.
71. Tang, Y.; Song, S.; Gui, S.; Chao, W.; Cheng, C.; Qin, R. Active and low-cost hyperspectral imaging for the spectral analysis of a low-light environment. *Sensors* **2023**, *23*, 1437.
72. Munir, A.; Aved, A.; Blasch, E. Situational awareness: techniques, challenges, and prospects. *AI* **2022**, *3*, 55–77.
73. Munir, A.; Blasch, E.; Kwon, J.; Kong, J.; Aved, A. Artificial intelligence and data fusion at the edge. *IEEE Aerospace and Electronic Systems Magazine* **2021**, *36*, 62–78.
74. Tang, Q.; Liang, J.; Zhu, F. A comparative review on multi-modal sensors fusion based on deep learning. *Signal Processing* **2023**, p. 109165.
75. Fernández-Caramés, T.M.; Fraga-Lamas, P. Forging the Industrial Metaverse-Where Industry 5.0, Augmented and Mixed Reality, IIoT, Opportunistic Edge Computing and Digital Twins Meet. *arXiv preprint arXiv:2403.11312* **2024**.
76. Yin, F.; Shi, F. A comparative survey of big data computing and HPC: From a parallel programming model to a cluster architecture. *International Journal of Parallel Programming* **2022**, *50*, 27–64.
77. Cheng, S. Metaverse and immersive interaction technology. In *Metaverse: Concept, Content and Context*; Springer, 2023; pp. 47–81.
78. Hamid, N.A.W.A.; Singh, B. High-Performance Computing Based Operating Systems, Software Dependencies and IoT Integration. In *High Performance Computing in Biomimetics: Modeling, Architecture and Applications*; Springer, 2024; pp. 175–204.
79. Navaux, P.O.A.; Lorenzon, A.F.; da Silva Serpa, M. Challenges in high-performance computing. *Journal of the Brazilian Computer Society* **2023**, *29*, 51–62.
80. Pyzer-Knapp, E.O.; Curioni, A. Advancing biomolecular simulation through exascale HPC, AI and quantum computing. *Current Opinion in Structural Biology* **2024**, *87*, 102826.
81. Sunyaev, A.; Sunyaev, A. Cloud computing. *Internet computing: Principles of distributed systems and emerging internet-based technologies* **2020**, pp. 195–236.
82. Karunamurthy, A.; Yuvaraj, M.; Shahithya, J.; Thenmozhi, V. *Cloud Database: Empowering Scalable and Flexible Data Management*; Quing: International Journal of Innovative Research in Science and Engineering, 2023.
83. Santana, M. Infrastructure as a Service (IaaS). In *Cloud Computing Security*; CRC Press, 2020; pp. 65–70.
84. Bharany, S.; Kaur, K.; Badotra, S.; Rani, S.; Kavita.; Wozniak, M.; Shafi, J.; Ijaz, M.F. Efficient middleware for the portability of paas services consuming applications among heterogeneous clouds. *Sensors* **2022**, *22*, 5013.
85. Nadeem, F. Evaluating and ranking cloud IaaS, PaaS and SaaS models based on functional and non-functional key performance indicators. *IEEE Access* **2022**, *10*, 63245–63257.
86. Ara, R.; Rahim, M.A.; Roy, S.; Prodhan, U.K. Cloud computing: Architecture, services, deployment models, storage, benefits and challenges. *International Journal of Trend in Scientific Research and Development (IJTSRD)* **2020**, *4*, 837–842.
87. Aceto, G.; Persico, V.; Pescapé, A. Industry 4.0 and health: Internet of things, big data, and cloud computing for healthcare 4.0. *Journal of Industrial Information Integration* **2020**, *18*, 100129.
88. Wang, Y.; Zhu, M.; Yuan, J.; Wang, G.; Zhou, H. The intelligent prediction and assessment of financial information risk in the cloud computing model. *arXiv preprint arXiv:2404.09322* **2024**.
89. Hazra, A.; Rana, P.; Adhikari, M.; Amgoth, T. Fog computing for next-generation internet of things: fundamental, state-of-the-art and research challenges. *Computer Science Review* **2023**, *48*, 100549.

90. Kong, X.; Wu, Y.; Wang, H.; Xia, F. Edge computing for internet of everything: A survey. *IEEE Internet of Things Journal* **2022**, *9*, 23472–23485.
91. Mann, Z.A. Decentralized application placement in fog computing. *IEEE Transactions on Parallel and Distributed Systems* **2022**, *33*, 3262–3273.
92. Munir, A.; Kwon, J.; Lee, J.H.; Kong, J.; Blasch, E.; Aved, A.J.; Muhammad, K. FogSurv: A fog-assisted architecture for urban surveillance using artificial intelligence and data fusion. *IEEE Access* **2021**, *9*, 111938–111959.
93. Hazarika, A.; Rahmati, M. Towards an evolved immersive experience: Exploring 5G-and beyond-enabled ultra-low-latency communications for augmented and virtual reality. *Sensors* **2023**, *23*, 3682.
94. Sefati, S.S.; Halunga, S. Ultra-reliability and low-latency communications on the internet of things based on 5G network: Literature review, classification, and future research view. *Transactions on Emerging Telecommunications Technologies* **2023**, *34*, e4770.
95. Qadir, Z.; Le, K.N.; Saeed, N.; Munawar, H.S. Towards 6G Internet of Things: Recent advances, use cases, and open challenges. *ICT express* **2023**, *9*, 296–312.
96. Murala, D.K.; Panda, S.K. Metaverse: A study on immersive technologies. *Metaverse and Immersive Technologies: An Introduction to Industrial, Business and Social Applications* **2023**, pp. 1–41.
97. Bibri, S.E.; Jagatheesaperumal, S.K. Harnessing the potential of the metaverse and artificial intelligence for the internet of city things: Cost-effective XReality and synergistic AIoT technologies. *Smart Cities* **2023**, *6*, 2397–2429.
98. Korkut, E.H.; Surer, E. Visualization in virtual reality: a systematic review. *Virtual Reality* **2023**, *27*, 1447–1480.
99. Raji, M.A.; Olodo, H.B.; Oke, T.T.; Addy, W.A.; Ofodile, O.C.; Oyewole, A.T. Business strategies in virtual reality: a review of market opportunities and consumer experience. *International Journal of Management & Entrepreneurship Research* **2024**, *6*, 722–736.
100. Dargan, S.; Bansal, S.; Kumar, M.; Mittal, A.; Kumar, K. Augmented reality: A comprehensive review. *Archives of Computational Methods in Engineering* **2023**, *30*, 1057–1080.
101. Liu, D.; Huang, R.; Metwally, A.H.S.; Tlili, A.; Lin, E.F. *Application of the Metaverse in Education*; Springer, 2024.
102. Buhalis, D.; Karatay, N. Mixed reality (MR) for generation Z in cultural heritage tourism towards metaverse. Information and communication technologies in tourism 2022: Proceedings of the ENTER 2022 eTourism conference, January 11–14, 2022. Springer, 2022, pp. 16–27.
103. Nleya, S.M.; Velempini, M. Industrial Metaverse: A Comprehensive Review, Environmental Impact, and Challenges. *Applied Sciences* **2024**, *14*, 5736.
104. Cardoso, L.F.d.S.; Kimura, B.Y.L.; Zorzal, E.R. Towards augmented and mixed reality on future mobile networks. *Multimedia Tools and Applications* **2024**, *83*, 9067–9102.
105. El Koshiry, A.; Eliwa, E.; Abd El-Hafeez, T.; Shams, M.Y. Unlocking the power of blockchain in education: An overview of innovations and outcomes. *Blockchain: Research and Applications* **2023**, p. 100165.
106. Mitra, S. Metaverse: A potential virtual-physical ecosystem for innovative blended education and training. *Journal of Metaverse* **2023**, *3*, 66–72.
107. Tan, Y.W.; Low, S.E.; Chow, J.; Teo, J.; Bhojan, A. DHR+ S: distributed hybrid rendering with realistic real-time shadows for interactive thin client metaverse and game applications. *The Visual Computer* **2024**, pp. 1–11.
108. Chamola, V.; Bansal, G.; Das, T.K.; Hassija, V.; Sai, S.; Wang, J.; Zeadally, S.; Hussain, A.; Yu, F.R.; Guizani, M.; others. Beyond reality: The pivotal role of generative ai in the metaverse. *IEEE Internet of Things Magazine* **2024**, *7*, 126–135.
109. Quek, H.Y.; Sielker, F.; Akroyd, J.; Bhave, A.N.; von Richthofen, A.; Herthogs, P.; van der Laag Yamu, C.; Wan, L.; Nochta, T.; Burgess, G.; others. The conundrum in smart city governance: Interoperability and compatibility in an ever-growing ecosystem of digital twins. *Data & Policy* **2023**, *5*, e6.
110. Song, Y.T.; Qin, J. Metaverse and personal healthcare. *Procedia Computer Science* **2022**, *210*, 189–197.
111. Albouq, S.S.; Abi Sen, A.A.; Almashf, N.; Yamin, M.; Alshanqiti, A.; Bahbouh, N.M. A survey of interoperability challenges and solutions for dealing with them in IoT environment. *IEEE Access* **2022**, *10*, 36416–36428.
112. Huzaifa, M.; Desai, R.; Grayson, S.; Jiang, X.; Jing, Y.; Lee, J.; Lu, F.; Pang, Y.; Ravichandran, J.; Sinclair, F.; others. Illixr: An open testbed to enable extended reality systems research. *IEEE Micro* **2022**, *42*, 97–106.

113. Javerliat, C.; Villenave, S.; Raimbaud, P.; Lavoué, G. Plume: Record, replay, analyze and share user behavior in 6dof xr experiences. *IEEE Transactions on Visualization and Computer Graphics* **2024**.
114. Martí-Testón, A.; Muñoz, A.; Gracia, L.; Solanes, J.E. Using WebXR metaverse platforms to create touristic services and cultural promotion. *Applied Sciences* **2023**, *13*, 8544.
115. Partarakis, N.; Zabulis, X. A review of immersive technologies, knowledge representation, and AI for human-centered digital experiences. *Electronics* **2024**, *13*, 269.
116. Hassan, S.Z.; Salehi, P.; Røed, R.K.; Halvorsen, P.; Baugerud, G.A.; Johnson, M.S.; Lison, P.; Riegler, M.; Lamb, M.E.; Griwodz, C.; others. Towards an AI-driven talking avatar in virtual reality for investigative interviews of children. Proceedings of the 2nd Workshop on Games Systems, 2022, pp. 9–15.
117. Li, Y.; Hashim, A.S.; Lin, Y.; Nohuddin, P.N.; Venkatachalam, K.; Ahmadian, A. AI-based Visual Speech Recognition Towards Realistic Avatars and Lip-Reading Applications in the Metaverse. *Applied Soft Computing* **2024**, p. 111906.
118. Hu, Y.H.; Yu, H.Y.; Tzeng, J.W.; Zhong, K.C. Using an avatar-based digital collaboration platform to foster ethical education for university students. *Computers & Education* **2023**, *196*, 104728.
119. Jones, C.L.E.; Hancock, T.; Kazandjian, B.; Voorhees, C.M. Engaging the Avatar: The effects of authenticity signals during chat-based service recoveries. *Journal of Business Research* **2022**, *144*, 703–716.
120. Morrow, E.; Zidaru, T.; Ross, F.; Mason, C.; Patel, K.D.; Ream, M.; Stockley, R. Artificial intelligence technologies and compassion in healthcare: A systematic scoping review. *Frontiers in Psychology* **2023**, *13*, 971044.
121. Sumon, R.I.; Uddin, S.M.I.; Akter, S.; Mozumder, M.A.I.; Khan, M.O.; Kim, H.C. Natural Language Processing Influence on Digital Socialization and Linguistic Interactions in the Integration of the Metaverse in Regular Social Life. *Electronics* **2024**, *13*, 1331.
122. Li, B.; Li, X.; Cui, Y.; Bian, X.; Teng, S.; Ma, S.; Fan, L.; Tian, Y.; Wang, F.Y.; others. Integrating large language models and metaverse in autonomous racing: An education-oriented perspective. *IEEE Transactions on Intelligent Vehicles* **2024**.
123. Far, S.B.; Rad, A.I.; Bamakan, S.M.H.; Asaar, M.R. Toward Metaverse of everything: Opportunities, challenges, and future directions of the next generation of visual/virtual communications. *Journal of Network and Computer Applications* **2023**, *217*, 103675.
124. Sun, Y.; Wang, H.; Chan, P.M.; Tabibi, M.; Zhang, Y.; Lu, H.; Chen, Y.; Lee, C.H.; Asadipour, A. Fictional Worlds, Real Connections: Developing Community Storytelling Social Chatbots through LLMs. *arXiv preprint arXiv:2309.11478* **2023**.
125. Cheng, R.; Wu, N.; Varvello, M.; Chen, S.; Han, B. Are we ready for metaverse? A measurement study of social virtual reality platforms. Proceedings of the 22nd ACM internet measurement conference, 2022, pp. 504–518.
126. Zhong, L.; Chen, X.; Xu, C.; Ma, Y.; Wang, M.; Zhao, Y.; Muntean, G.M. A multi-user cost-efficient crowd-assisted VR content delivery solution in 5G-and-beyond heterogeneous networks. *IEEE Transactions on Mobile Computing* **2022**, *22*, 4405–4421.
127. Krauss, D. Mean-time-to-cloud: Enabling a metaverse-ready network, 2023.
128. Liu, S.; Xu, X.; Claypool, M. A survey and taxonomy of latency compensation techniques for network computer games. *ACM Computing Surveys (CSUR)* **2022**, *54*, 1–34.
129. Yu, H.; Shokrnezhad, M.; Taleb, T.; Li, R.; Song, J. Toward 6g-based metaverse: Supporting highly-dynamic deterministic multi-user extended reality services. *IEEE Network* **2023**, *37*, 30–38.
130. Chu, N.H.; Hoang, D.T.; Nguyen, D.N.; Phan, K.T.; Dutkiewicz, E.; Niyato, D.; Shu, T. Metaslicing: A novel resource allocation framework for metaverse. *IEEE Transactions on Mobile Computing* **2023**, *23*, 4145–4162.
131. Zalan, T.; Barbesino, P. Making the metaverse real. *Digital Business* **2023**, *3*, 100059.
132. Sihare, S.; Khang, A. Effects of quantum technology on the metaverse. In *Handbook of Research on AI-Based Technologies and Applications in the Era of the Metaverse*; IGI Global, 2023; pp. 174–203.
133. Zawish, M.; Dharejo, F.A.; Khowaja, S.A.; Raza, S.; Davy, S.; Dev, K.; Bellavista, P. AI and 6G into the metaverse: Fundamentals, challenges and future research trends. *IEEE Open Journal of the Communications Society* **2024**, *5*, 730–778.
134. Mozaffariahrar, E.; Theoleyre, F.; Menth, M. A survey of Wi-Fi 6: Technologies, advances, and challenges. *Future Internet* **2022**, *14*, 293.

135. Chen, C.; Chen, X.; Das, D.; Akhmetov, D.; Cordeiro, C. Overview and performance evaluation of Wi-Fi 7. *IEEE Communications Standards Magazine* **2022**, *6*, 12–18.
136. Reshef, E.; Cordeiro, C. Future directions for Wi-Fi 8 and beyond. *IEEE Communications Magazine* **2022**, *60*, 50–55.
137. Liu, X.; Chen, T.; Dong, Y.; Mao, Z.; Gan, M.; Yang, X.; Lu, J. Wi-Fi 8: Embracing the Millimeter-Wave Era. *arXiv preprint arXiv:2309.16813* **2023**.
138. Domeke, A.; Cimoli, B.; Monroy, I.T. Integration of network slicing and machine learning into edge networks for low-latency services in 5G and beyond systems. *Applied Sciences* **2022**, *12*, 6617.
139. Dommeti, V.S.; Dharani, M.; Shasidhar, K.; Reddy, Y.D.R.; Moorthy, T.V. Quality Enhancement with Frame-wise DLCNN using High Efficiency Video Coding in 5G Networks. *Scalable Computing: Practice and Experience* **2024**, *25*, 1264–1275.
140. Shin, H.; Lee, J. Hardware Multi-Threaded System for High-Performance JPEG Decoding. *Journal of Signal Processing Systems* **2024**, *96*, 67–79.
141. Zhou, Y.; Chen, W.; Li, L.; Li, M.; Zhang, T. Initiative, Immersive Human-Computer Interactions: Software Defined Memristive Neural Networks for Non-Linear Heterogeneous Scheme in the Internet of Brains. *IEEE Internet of Things Journal* **2023**.
142. Ghirmai, S.; Mebrahtom, D.; Aloqaily, M.; Guizani, M.; Debbah, M. Self-sovereign identity for trust and interoperability in the metaverse. 2022 IEEE Smartworld, Ubiquitous Intelligence & Computing, Scalable Computing & Communications, Digital Twin, Privacy Computing, Metaverse, Autonomous & Trusted Vehicles (SmartWorld/UIC/ScalCom/DigitalTwin/PriComp/Meta). IEEE, 2022, pp. 2468–2475.
143. Aung, N.; Dhelim, S.; Chen, L.; Ning, H.; Atzori, L.; Kechadi, T. Edge-enabled metaverse: the convergence of metaverse and mobile edge computing. *Tsinghua Science and Technology* **2023**, *29*, 795–805.
144. Abilkaiyrkyzy, A.; Elhagry, A.; Laamarti, F.; Elsaddik, A. Metaverse key requirements and platforms survey. *IEEE Access* **2023**.
145. Rawat, D.B.; Hagos, D.H.; others. Metaverse Survey & Tutorial: Exploring Key Requirements, Technologies, Standards, Applications, Challenges, and Perspectives. *arXiv preprint arXiv:2405.04718* **2024**.
146. Chen, B.; Song, C.; Lin, B.; Xu, X.; Tang, R.; Lin, Y.; Yao, Y.; Timoney, J.; Bi, T. A cross-platform metaverse data management system. 2022 IEEE International conference on metrology for extended reality, artificial intelligence and neural engineering (MetroXRAINE). IEEE, 2022, pp. 145–150.
147. Li, T.; Yang, C.; Yang, Q.; Lan, S.; Zhou, S.; Luo, X.; Huang, H.; Zheng, Z. Metaopera: A cross-metaverse interoperability protocol. *IEEE Wireless Communications* **2023**, *30*, 136–143.
148. Jaimini, U.; Zhang, T.; Brikis, G.O.; Sheth, A. imetaversekg: Industrial metaverse knowledge graph to promote interoperability in design and engineering applications. *IEEE Internet Computing* **2022**, *26*, 59–67.
149. Zhang, Y.; Kutscher, D.; Cui, Y. Networked Metaverse Systems: Foundations, Gaps, Research Directions. *IEEE Open Journal of the Communications Society* **2024**.
150. Ooi, B.C.; Chen, G.; Shou, M.Z.; Tan, K.L.; Tung, A.; Xiao, X.; Yip, J.W.L.; Zhang, B.; Zhang, M. The metaverse data deluge: What can we do about it? 2023 IEEE 39th International Conference on Data Engineering (ICDE). IEEE, 2023, pp. 3675–3687.
151. Altundas, S.; Karaarslan, E. Cross-platform and personalized avatars in the metaverse: Ready player me case. In *Digital twin driven intelligent systems and emerging metaverse*; Springer, 2023; pp. 317–330.
152. Hasan, M.; Starly, B. Decentralized cloud manufacturing-as-a-service (CMaaS) platform architecture with configurable digital assets. *Journal of manufacturing systems* **2020**, *56*, 157–174.
153. Golam, M.; Tuli, E.A.; Alief, R.N.; Kim, D.S.; Lee, J.M. Meta-Learning: A Digital Learning Management Framework using Blockchain for Metaverses. *IEEE Access* **2024**.
154. Lin, Y.; Liu, S. The integration strategy of information system based on artificial intelligence big data technology in metaverse environment. *Cluster Computing* **2024**, pp. 1–9.
155. Deshmukh, R.; Nand, N.; Pawar, A.; Wagh, D.; Kudale, A. Video conferencing using WebRTC. 2023 International Conference on Sustainable Computing and Data Communication Systems (ICSCDS). IEEE, 2023, pp. 857–864.
156. Praschl, C.; Krauss, O. Extending 3D geometric file formats for geospatial applications. *Applied Geomatics* **2024**, *16*, 161–180.
157. Singh, K.D.; Singh, P.D. QoS-enhanced load balancing strategies for metaverse-infused VR/AR in engineering education 5.0. *Computer Applications in Engineering Education* **2024**, *32*, e22722.

 doi:10.20944/preprints202409.0889.v1

158. Cheng, S. Basic Infrastructure of the Metaverse. In *Metaverse: Concept, Content and Context*; Springer, 2023; pp. 25–46.
159. Zhou, L.; Lambert, J.; Zheng, Y.; Li, Z.; Yen, A.; Liu, S.; Ye, V.; Zhou, M.; Mahar, D.; Gibbons, J.; others. Distributed scalable edge computing infrastructure for open metaverse. 2023 IEEE Cloud Summit. IEEE, 2023, pp. 1–6.
160. Othman, A.; Chemnad, K.; Hassanien, A.E.; Tlili, A.; Zhang, C.Y.; Al-Thani, D.; Altınay, F.; Chalghoumi, H.; S. Al-Khalifa, H.; Obeid, M.; others. Accessible Metaverse: A Theoretical Framework for Accessibility and Inclusion in the Metaverse. *Multimodal Technologies and Interaction* **2024**, *8*, 21.
161. Yang, S. Storytelling and user experience in the cultural metaverse. *Heliyon* **2023**, *9*.
162. Ramaseri Chandra, A.N.; El Jamiy, F.; Reza, H. A systematic survey on cybersickness in virtual environments. *Computers* **2022**, *11*, 51.
163. Guo, C.; Blair, G.J.; Sehgal, M.; Sangiuliano Jimka, F.N.; Bellafard, A.; Silva, A.J.; Golshani, P.; Basso, M.A.; Blair, H.T.; Aharoni, D. Miniscope-LFOV: a large-field-of-view, single-cell-resolution, miniature microscope for wired and wire-free imaging of neural dynamics in freely behaving animals. *Science advances* **2023**, *9*, eadg3918.
164. Radanliev, P.; De Roure, D.; Novitzky, P.; Sluganovic, I. Accessibility and inclusiveness of new information and communication technologies for disabled users and content creators in the Metaverse. *Disability and Rehabilitation: Assistive Technology* **2023**, pp. 1–15.
165. Di Pietro, R.; Cresci, S. Metaverse: Security and privacy issues. 2021 third IEEE international conference on trust, privacy and security in intelligent systems and applications (TPS-ISA). IEEE, 2021, pp. 281–288.
166. Chen, Z.; Wu, J.; Gan, W.; Qi, Z. Metaverse security and privacy: An overview. 2022 IEEE International Conference on Big Data (Big Data). IEEE, 2022, pp. 2950–2959.
167. Huang, Y.; Li, Y.J.; Cai, Z. Security and privacy in metaverse: A comprehensive survey. *Big Data Mining and Analytics* **2023**, *6*, 234–247.
168. Bakare, S.S.; Adeniyi, A.O.; Akpuokwe, C.U.; Eneh, N.E. Data privacy laws and compliance: a comparative review of the EU GDPR and USA regulations. *Computer Science & IT Research Journal* **2024**, *5*, 528–543.