A Survey of Blockchain and Intelligent Networking for the Metaverse

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***Abstract*—The virtual world created by the development of the Internet, computers, artificial intelligence (AI), and hardware technologies have brought various degrees of digital transformation to people's lives. With multiple demands for virtual reality increasing, the metaverse, a new type of social ecology that can connect the physical and virtual worlds, is booming. However, with the rapid growth of data volume and value, the continuous evolution of the metaverse faces the demands and challenges of privacy, security, high synchronization, and low latency. Fortunately, the ever-evolving blockchain and intelligent networking technologies can be used to satisfy the trusted construction, continuous data interaction, and computing demands of the metaverse. Therefore, it is necessary to conduct an in-depth review of the role and gains of blockchain, intelligent networking, and the combination of both in providing the immersive experiences of the metaverse. In this survey, we first discuss the development trend, characteristics, and architecture of the metaverse. Then, the existing work on blockchain, networking, and the combination of the two technologies are reviewed, including overviews, applications, and challenges. Next, applications of the metaverse are summarized, emphasizing the importance of the metaverse and the fields of development. Finally, we discuss some open issues, challenges, and future research directions.**

***Index Terms*—blockchain, computing first network intelligent (CFN) networking, Metaverse.**

I. Introduction

IN RECENT years, due to the rapid development of communication networks, artificial intelligence (AI), computing technology, blockchain, and other technologies, humanity enters an extraordinary era of technological explosion. The way we interact with the physical world around us is rapidly changing, which gives rise to the reemergence of the concept of the metaverse. The term "metaverse" consists of the prefix "meta" and the root "verse" (derived from the universe), which first appeared in a science fiction novel called "Snow Crash" written by Neal Stephenson in 1992 [1]. Presently, the metaverse can be regarded as is a hypothesized iteration of the Internet, which combines physical and digital virtual environments through extended reality (XR) to realize perception and sharing [2]. Therefore, the metaverse provides an infinite virtual digital world, which breaks the dimensional wall of the physical world. In the digital world of any field, we have an avatar that can directly and deeply participate in the interaction.

To achieve such a complex ecosystem, what underlying technology is needed to support and maintain its operation? The core supporting technologies of the metaverse can be summarized as "BIGANT" [3]. Here, "B" refers to Blockchain; "I" refers to Interactivity; "G" refers to Game; "A" refers to AI; "N" refers to network and computing technology (Network); and "T" refers to Internet of Things (IoT). Among the above technologies, interactivity, AI, and games are relatively mature after long-term development. For example, many virtual reality (VR) devices and metaverse games have emerged one after another [2]. In order to provide users with an immersive experience, the interaction and processing of massive amounts of data generated by the vast array of facilities and devices contained in metaverse require ultrareliable, high-rate communications and powerful continuous computing, which drives the intelligent networking technology to ensure high synchronization and low latency service. In addition, with the rapid growth of data volume and the improvement of data value, when building the metaverse, security issues, such as privacy protection, trusted management, and data exchange cannot be ignored. In this regard, blockchain can provide security for the metaverse due to its characteristics of decentralization, immutability, and transparency. Therefore, the application of the intelligent networking and blockchain technology to the metaverse is the focus of this survey.

To achieve the virtual-real fusion and trusted management of the metaverse, it is conceivable that the combination of blockchain and intelligent networking can provide a promising solution for the evolution of metaverse, which motivates us to conduct this survey. An earlier long survey written by Dionisio et al. [4] summarized the development of the metaverse from four aspects, that is, reality, universality, interoperability, and scalability. The latest technologies, such as blockchain and 6G are not involved. Recently, Lee et al. [5] conducted a comprehensive survey of the metaverse from 14 aspects, as well as discuss six user-centric factors and research agenda. Ning et al. [6] mainly investigated the technical

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TABLE I
COMPARATIVE STUDY OF THIS ARTICLE WITH EXISTING SURVEYS ON THE METAVERSE

Ref.	Contributions	Differences from related content in this paper
[4]	Summarizes the development of the metaverse from reality, universality, interoperability, and scalability.	Investigate the latest technologies such as blockchain, 6G, and computing first network for the metaverse.
[5]	Investigate 14 aspects of the metaverse, and discuss research agenda.	Focus on the enhancement of the metaverse by the integration of blockchain and intelligent networking technologies.
[6]	Summarize the work of different countries and enterprises on the metaverse, and introduce the characteristics and application fields of the metaverse.	Investigate the enabling technologies and research of the metaverse in security privacy, interconnection, and applications in different fields.
[7]	Summarize wireless communication architectures for the metaverse, and discuss the potential and application scenarios.	Consider security and network performance, summarize the role of blockchain and networking technologies in the metaverse.
[8]	Investigate the privacy issues in the metaverse.	Investigate privacy, user experience with high synchronization and low latency issues in the metaverse.
[9]	Investigate blockchain technology for the metaverse.	Consider other potential technologies that could be combined with blockchain.
[10]	Investigate blockchain and AI technologies for the metaverse.	Emphasizes secure intelligent networking for the metaverse and discusses related applications.

architecture of the metaverse from five aspects: 1) infrastructure; 2) management technology; 3) general technology; 4) VR object connection; and 5) VR integration. The survey mainly focuses on the work of different countries and enterprises regarding the metaverse. Khan et al. [7] investigated wireless communication architectures for the metaverse in detail, and discuss the potential and application scenarios of the metaverse for improving wireless systems. In a short survey, Falchuk et al. [8] mainly focused on privacy issues in the metaverse to help VR participants protect privacy while socializing. Recently, Gadekallu et al. [9] and Yang et al. [10] investigated the blockchain technology for metaverse. Table I compares this article and existing surveys on the metaverse.

Different from previous surveys, this work focuses on the *secure intelligent networking* for the metaverse, especially to see how to combine blockchain and intelligent networking to create a better ecosystem. First, we provide background knowledge about the metaverse, including the development trend, characteristics, and structure of the metaverse, which can provide readers with a systematic understanding and basic concepts of this direction. Then, we introduce in detail the application and integration of blockchain and intelligent networking (including communication and computing networks) into the metaverse, as well as opportunities and challenges. In order to bridge the gap between academic research and actual products in the industry, we also discuss some representative metaverse applications. Subsequently, some open issues, challenges, and potential solutions are proposed.

The remainder of this article is organized as follows. First, background knowledge of the metaverse is introduced in Section II. Subsequently, from Sections III–V, how blockchain and intelligent networking work on the metaverse are discussed, including: 1) blockchain for the metaverse (Section III); 2) networking technologies for the metaverse (Section IV); and 3) blockchain meets intelligence networking in the metaverse (Section V). In Section VI, we introduce some application examples of the metaverse. Finally, Section VII discusses the challenges of building a metaverse and how to solve these problems to meet the requirement of data security, reliability, and user experience, followed by concluding remarks in Section VIII. Fig. 1 outlines the organization of the survey.

II. BACKGROUND KNOWLEDGE OF THE METAVERSE

In this section, we briefly introduce the background knowledge of the metaverse from the development trend, characteristics, and architecture.

A. Development Trend of the Metaverse

The metaverse is not a completely new concept, and a virtual world similar to the metaverse is proposed very early. A well-known pioneering work is TSR in 1974, which developed a role-playing game "Dungeon & Dragon."[1] In this game, the player plays an adventurer in a virtual world. In this stage, the virtual world is still described in words.

Later, with the advent and application of personal laptops, the description of the virtual world changed from text to code. For example, AberMUD written by Alan Cox in 1987 was the first popular MUD program Library. Players can create virtual worlds through code language, and realize the interaction between players in the virtual world. In 1990, with the development of computer graphics technology, the virtual world had a graphical description.

Then, in 1992, Stephenson first proposed the term "metaverse" in the science fiction novel "Snow Crash" [1]. After that, the popularization of computers and the rapid development of the Internet gave rise to new developments in the virtual world. With the goal of creating a metaverse-like world described by Stephenson, the Linden Lab developed a game called second life in 2003 [11]. In the virtual world constructed by this game, players can complete many social activities through their virtual avatars. From the screen of the game to the user's behavior, it is very close to the physical world. In addition, the virtual currency used in Second Life is called Linden Dollar, which can not only be used for goods transactions in the virtual world, but also can be exchanged for U.S. dollars with some companies in the real world [12]. In particular, the development of the blockchain technology and virtual currency as well as its combination with virtual world games has accelerated the development of virtual transactions.

The rapid development of the XR technology has laid a new foundation for the metaverse. In 2016, Pokemon games

[1] https://dnd.wizards.com/

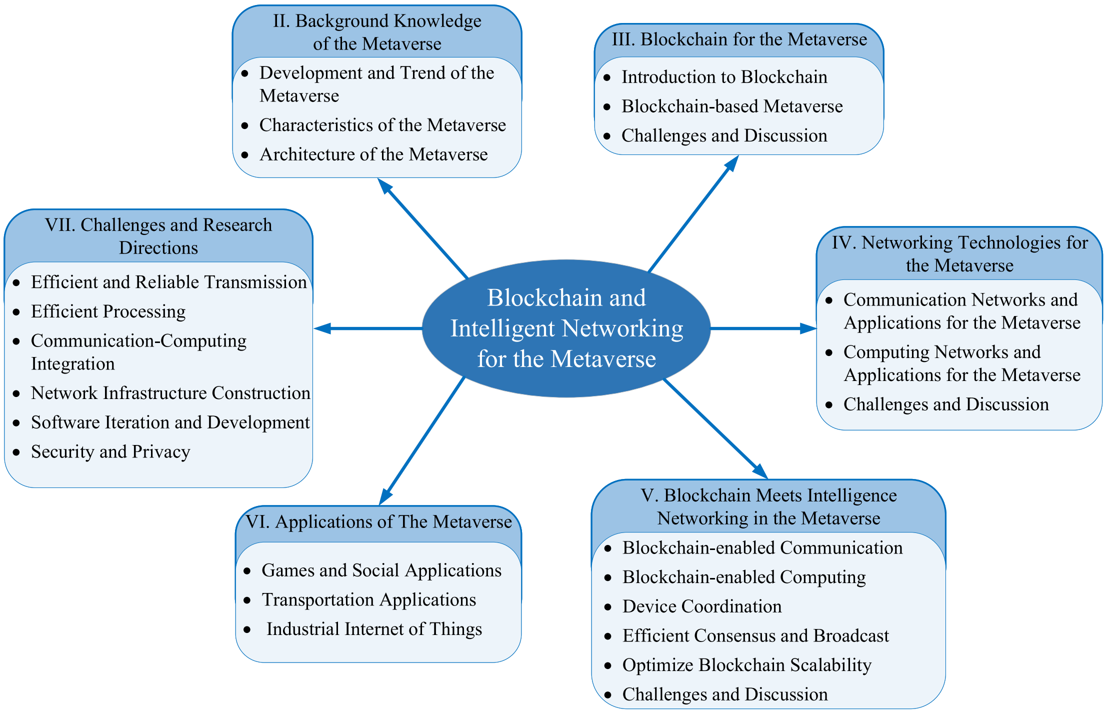

Fig. 1. Road map of the survey.

based on the augmented reality (AR) technology became popular all over the world. In this game, players can discover Pokemon in the real world through smartphones, and capture and fight them [13]. Another technology, namely, VR, enables users to obtain a more realistic experience in a virtual environment by wearing VR devices (e.g., glasses and helmet). For example, with Oculus Quest 2, which has excellent wireless performance and high screen resolution, users can experience VR games and movies.

The COVID-19 epidemic in 2020 has restricted people's actions in the physical world, which greatly increases the demand for behavioral interaction in the virtual world. Online education, online meeting, and online shopping become people's new choices, which makes the concept of the metaverse once again attract widespread attention [14]. In 2021, Roblox, an online game creation platform, began to invest heavily in the metaverse business. In addition, Facebook, Microsoft, ByteDance, and other companies have also begun to conduct research on metaverse applications. 2021 is also known as the year of the metaverse explosion.

B. Characteristics of the Metaverse

Presently, there is no standard definition of the metaverse. Therefore, regarding the characteristics of the metaverse, in [15], Matthew Ball describes the characteristics of the metaverse as the following five aspects, that is persistence, synchronicity, availability, economy, and interoperability. Roblox, the first stock of the metaverse, proposes eight key characteristics of the metaverse, namely, identity, friends, immersive, low friction, variety, anywhere, economy, and civility. Although there are different disputes about these characteristics, most of them are accepted.

In addition, with the continuous development of the metaverse, the metaverse has broader characteristics. For example, corporateity means being bound by the laws of physics and limited resources. Open and free creation shows that a large number of participants in the metaverse can create. We can conclude that most of the important characteristics recognized are availability, immersive experience, low latency (synchronization), interaction, economic system, and civilization.

C. Architecture of the Metaverse

Although the concept of the metaverse has been proposed for decades, there is still no unified architecture. Duan et al. [2] summarized a three-layer architecture of the metaverse from a macro perspective, from bottom to top, namely, infrastructure, interaction, and ecosystem. Jon Radoff [16] proposed a seven-layer architecture based on the value chain of the expected market, which includes infrastructure, human interface, decentralization, spatial computing, creator economy, discovery, and experience from bottom to top.

In this survey, we combine [2], [5] to agree that the architecture of the metaverse spans the physical world and the virtual world. Therefore, as shown in Fig. 2, from the bottom to up, the digital twin is used to connect the physical world and further realize the metaverse. On the right side of the figure, we also list the corresponding six key components, including technologies, hardware platforms, systems, software, applications, and ecosystems. For each component, the key elements are listed. For example, AI, network, computing power, and blockchain, are used as the underlying hard technical support. On this basis, various hardware platforms (such as XR devices, sensors, computers, mobile phones, and helmets), software, and systems (such as Windows, IOS, and

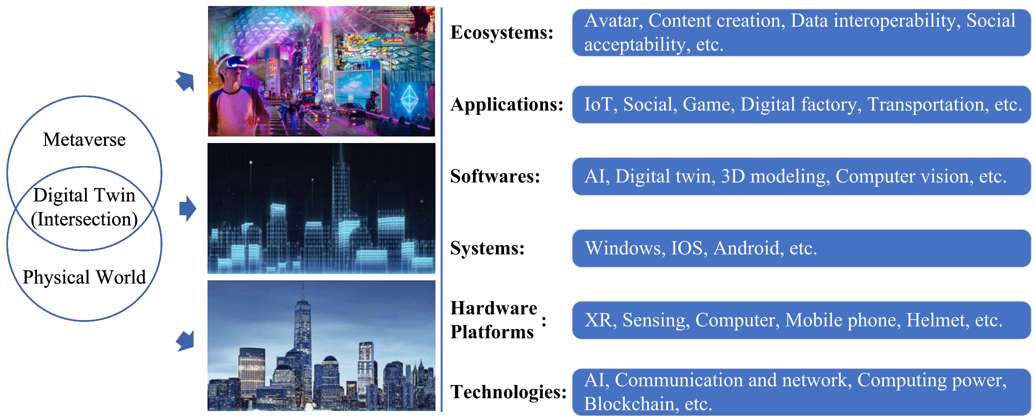

Fig. 2. Architecture of the metaverse [2], [5].

Android) are used to implement interaction and computing. Through the support of different technologies, systems, and platforms, the metaverse can be applied in various fields, such as IoT, social, game, digital factory, and transportation. The top layer is the ecosystem that allows the entire metaverse to run, including avatar, content creation, data interoperability, etc. Due to the focus of this survey, some components and elements will not be emphasized. We focus on blockchain and intelligent networking for the metaverse, as well as some applications. The specific details will be discussed in subsequent sections.

III. Blockchain for the Metaverse

The successful application of the blockchain technology has changed the paradigm of economic activity in virtual space. As a key technology for secure and reliable data sharing, blockchain can perfectly match the various requirements of the metaverse for data services and asset exchange. In this section, we introduce the blockchain and its applications and challenges in the metaverse.

A. Introduction to Blockchain

As a shared, consensus, and jointly maintained ledger, blockchain can effectively promote the entire process of transaction recording and asset tracking in a distributed network. The concept of the blockchain was originally proposed by Satoshi Nakamoto [17] to ensure the peer-to-peer (P2P) electronic cash payment technology without the need for a centralized financial institution [18].

1) Why Blockchain Is Important?: As an ideal information transmission and storage solution, blockchain can provide timely, transparent, nontamperable, and multiparty shared information services for various businesses [19], [20], [21]. Blockchain is mainly divided into three categories: 1) public blockchain; 2) consortium blockchain; and 3) private blockchain [22]. The degree of openness of different blockchains is quite different. The public blockchain allows any legal user to access and use the blockchain. In a consortium blockchain, only the nodes that have obtained registration permission can access the blockchain network. Private blockchain is limited to the internal use of the group. The internal entities of the blockchain are transparent to each other, but external entities cannot access any transaction content of the blockchain. In conclusion, the blockchain provides differentiated services for users with different needs. In addition, several key elements of blockchain are also the key factor for its wide applications.

Distributed Ledger: The internal network members of the blockchain can access the transaction content recorded in the blockchain. Once the transaction stored in the blockchain is verified, there is no cancellation, that is, the transaction is irreversible. Since the recorded transaction information does not contain any privacy content, any member of the network can effectively track all transaction orders, timestamps, transfer content, accounts, etc., which ensures the transparency of data. Li et al. [23] proposed a scheme for issuing trusted and authorized certificates which is based on a distributed ledger. The domain ownership validation and attested results are recording into blockchain for validation, which ensures the security and tamper resistance.

Immutability of Transactions: Once a transaction is recorded in the blockchain, any participant cannot change or tamper with the completed blockchain content. Asheralieva and Niyato [24] proposed a learning-based resource management scheme in public blockchain networks. The immutability of blockchain is utilized to prevent the potential attacks and provide the traceable information.

Smart Contract: In addition to transaction content, there are a series of agreed rules stored in the blockchain that run automatically, called a smart contract. The existence of smart contracts makes the blockchain jump out of the scope of virtual currency, enabling transactions, and transaction queries of anything of value in the blockchain. The smart contract-based negotiation frame proposed by Wang et al. [25] is designed to ensure that the transactions are automatically and reliably performed between the service participants. The reliability and security are guaranteed.

2) Advantage of Blockchain: Trust: Members in the blockchain network can record, transmit, and store data safely, accurately, and in a timely manner. And according to different application requirements, different types of blockchains can be established to support the availability of data to users in different ranges.

Security: All members in the blockchain network need to reach a consensus on the legality of transactions on the chain. In addition, once the transaction is confirmed to be legal, it will become immutable. Therefore, the content recorded on the blockchain will be permanently recorded. No user can modify or delete the transaction.

Efficiency: The members in the blockchain network share the ledger, thus avoiding repeated reconciliations during the interaction of the members in the network. In addition, the existence of smart contracts can automatically execute the rules stored in the blockchain to ensure efficient and orderly transactions.

B. Blockchain-Based Metaverse

First of all, as a typical representative of blockchain applications, virtual currencies such as Bitcoin can provide unified digital asset services for metaverse. The reliability and consistency of various transactions in the system can be effectively guaranteed. Second, in the face of the metaverse's demand for large-scale data recording, sharing, and storage, traditional centralized methods are faced with problems, such as single point of failure and consumption of large amounts of communication and computing resources. As an interdisciplinary technology, blockchain can perfectly match the metaverse's needs for data services. On the one hand, P2P communication and storage solutions can effectively prevent low security and low efficiency in the process of mass transactions in the metaverse. On the other hand, the underlying blockchain architecture based on cryptography, such as asymmetric encryption and digital signatures can provide metaverse users with a secure and reliable way to interact. Finally, as a basic distributed ledger, the blockchain can effectively help the participating entities in the metaverse to establish a personalized service system. Therefore, the blockchain can provide differentiated services for diversified metaverse applications.

1) Data Sharing: Any users in the metaverse can serve as the data providers or data requesters. The P2P data-sharing scheme of the blockchain can well meet the various needs of data services in the metaverse. Blockchain-based information sharing could provide users with data services ranging from the virtual world to the physical world, and all the shared information could be uniquely accepted by the data requesters due to the characteristics of nontamperability and security [26]. Besides, the metaverse has certain customization requirements and functions for the design of the blockchain system in different application scenarios. Therefore, on the one hand, the consistency of changes in the physical world and the virtual world can be ensured under the framework of blockchain due to the real-time consensus and audit of all participating nodes, and the information sharing between the two worlds could remain consistent and accurate. On the other hand, the information sharing between blockchains could remain consistent and accurate to break the barriers of different applications, and thereby preventing the risk of tampering during cross-chain information sharing.

Doku et al. [27] proposed a distributed data-sharing network based on blockchain to ensure that data undergoes a thorough review process before being accepted into the network. The system uses natural language processing (NLP) and a distributed data-sharing platform to ensure the consistency of the real world and the virtual world. Zhang et al. [28] proposed a blockchain-based multiaccess edge computing (MEC) for future vehicular networks. Liu et al. [29] proposed a secure data-sharing scheme based on blockchain to provide an adaptive privacy protection mechanism based on system resources and user privacy requirements. Cui et al. [30] proposed a distributed scheme for sharing vehicle driving data in the Internet of Vehicles (IoVs) scenario. The system uses a blockchain-based solution to implement a vehicle-to-vehicle (V2V) traceable information-sharing solution, which can effectively prevent malicious data sharing under anonymous addresses.

Hence, blockchain-based data sharing could enable metaverse to achieve the secure information exchange between virtual and physical world and various applications. Thereby, the audit and quality of data can be guaranteed as well. In addition, the effective consensus mechanism design could avoid many unnecessary disputes against the unreality of data and economical issues due to the nontamperability of blockchain. Furthermore, the avatar in will generate considerable data once entering the metaverse. Thus, any private information leaked will greatly affect the users' participating confidence. Blockchain-based information could avoid the situation that the centralized data storage is compromised. All in all, the decentralized essence of blockchain enable the data sharing in a more secure, efficient, and reliable manner.

2) Data Storage: Facing the situation where all system operations in the metaverse are digital, how to use the blockchain to realize the efficient storage, retrieval and use of data in the metaverse is a key issue. The blockchain technology is based on a P2P network to achieve data consistency through distributed storage, which can provide effective data storage services for the metaverse.

Facing the problems of high data update overhead and fragile data storage strategies in traditional centralized methods, Yin et al. [31] proposed a blockchain-based data storage system to support incremental data updates. The smart contract and the interesting release of data effectively reduce the amount of reuploaded data, thus reducing system overhead. Chen et al. [32] focused on solving the high-efficiency data access requirements in massive data storage, and therefore propose a method to divide data into continuous data and state data. An index-based storage engine is used to efficiently store and manipulate data. In order to protect the security of stored data, Li et al. [33] proposed a blockchain-based distributed data storage scheme, which can effectively solve the serious trust problem caused by the strong dependence on centralized servers. Dwivedi et al. [34] proposed a data storage solution based on the interplanetary file system (IPFS) [35], which can effectively solve the problem of limited storage capacity in the blockchain by adopting a content addressing solution.

Therefore, blockchain-based data storage in metaverse could guarantee the secure interaction between the users and the applications in the virtual world. For example, the private healthcare, real estate, etc. could be securely stored in a private blockchain. Only the authorized entity could access the relative sensitive information. Besides, secure data storage in blockchain could ensure the consistency and continuity between the virtual and physical world due to the characteristics of consensus which could be uniquely designed for different applications. To be more specific, the virtual life in metaverse is the mapping of the real life in the physical world, and the data stored in the blockchain can ensure the authenticity and verifiability of the data, thus ensuring the consistency of data changes. Furthermore, secure data storage could enable participants to engage in the financial market because the blockchain-based virtual currency could be the bridge between the virtual items in metaverse and real objects in the physical world.

3) Virtual Economy System: The metaverse needs to provide users with a rich interactive experience. An effective and reliable virtual economic system is the key bridge to ensure consistency between the virtual world and the real world. The flow of funds in the system is closely related to virtual resources (land, goods, etc.). Virtual images, wearable devices, and virtual items will have interesting potential capital in the virtual world. The ownership of items will determine the user's avatar in the virtual world and help users become real residents in the metaverse. The digital virtual assets in the traditional game industry will be estimated to reach 40 billion U.S. dollars each year. Therefore, the virtual economic system in the metaverse has a huge window of opportunity.

Blockchain has gained widespread popularity in recent years due to its distributed nature. As an early successful application of the blockchain technology, Bitcoin was released by a user whose code name is Satoshi Nakamoto. Since then, the blockchain-based P2P payment system has attracted widespread attention from academia and industry. By exploring the impact of the future economic system based on the blockchain, [36] analyzed how the blockchain will affect the global economic order. Swan [37] proposed a simple and efficient virtual economic system model based on blockchain to promote the impact on the future economic system. Xu et al. [38] considered the existence and nonexistence of a centralized management platform in the distributed banking system, so that the corresponding payment system can be designed according to different application requirements. However, in a centralized management platform with better management and control, users privacy may still be exposed to risks. Sasson et al. [39] proposed a distributed anonymous payment system based on zero-knowledge proof. In the point-to-point payment process, the source and destination of the transaction, and the amount of the transaction are all hidden in proof. At the same time, the verification and inspection of the proof are concise and efficient.

Just as Bitcoin and other virtual payment systems ensure transactions between humans, blockchain can also realize machine-to-machine (M2M) and IoT payments [37]. More and more machine interaction research and algorithm programming are continuously promoting the economic system of machine interaction. Miehle et al. [40] proposed an industrial market based on blockchain. The machines in the system have corresponding identities and accounts, and smart contract-based solutions are utilized to realize the interaction and cooperation between machines. Seitz et al. [41] introduced a distributed market that relies on blockchain in industrial edge applications to create a transparent environment for system participants and support the traceability of edge device installations. Tönnissen and Teuteberg [42] proposed a blockchain-based order processing scheme. The smart contract-based solution improves the auditability and automation of machine interaction in the system. However, there is no overall solution that can concentrate the business solutions in the industrial system into a single blockchain-based market.

A summary of typical applications and benefits of blockchain for the metaverse is depicted in Table II.

C. Challenges and Discussion

Blockchain can provide a promising solution for the data sharing, storage, and transaction of the metaverse. However, there are still some urgent challenges to be solved, which are mainly divided into two aspects: 1) reliability and 2) effectiveness.

Privacy of Users: Although the blockchain-based scheme uses an addressing scheme based on public and private keys for anonymization, attackers with strong computing power can still track the user's system participation history through a large amount of network analysis. In addition, due to the different degrees of openness of the blockchain, the access mechanism of the blockchain determines the privacy and security performance of the users on the chain. Therefore, how to design a highly secure and reliable blockchain architecture still requires in-depth research.

Centralization Problem: The consensus mechanism based on computing power leads to unequal nodes. The miners in the system accumulate hardware in order to obtain high economic returns, which leads to the risk of mining pools with large computing power that may exceed 51% of the global computing power. The randomness of blockchain accounting rights will be greatly threatened, and the security of data will also face great hidden dangers.

System Robustness: Although the blockchain-based scheme supports its underlying architecture with cryptographic knowledge, there are still weak links in the privacy and security of the entire network. Once the network is attacked, can the system reliably resist the attack? And, whether it can recover quickly and steadily after being attacked is still a research challenge in the blockchain system.

Audit Complexity: The various operations of users in the metaverse need to go through a lot of inspection and verification before they are recorded on the blockchain. However, in order to protect user privacy and data security, the transparency of data needs to be reduced, which greatly increases the complexity of transaction auditing.

Efficiency of Blockchain: The demand for low latency in the metaverse places extremely high requirements on the design of the blockchain consensus mechanism. In addition, facing the massive data exchange in the metaverse, the contradiction between blockchain-based data storage and efficient verification mechanism is inevitable. How to ensure

TABLE II
SUMMARY OF TYPICAL APPLICATIONS AND BENEFITS OF BLOCKCHAIN FOR THE METAVERSE

Application	Ref.	Benefit
Data Sharing	[27]	Ensure the data review process.
	[28]	Support controllable data access.
	[29]	Adaptive privacy protection mechanism.
	[30]	Support traceable information sharing.
Data Storage	[31]	Support incremental data updates.
	[32]	High-efficiency data access.
	[33]	Reduce the dependence on centralized server.
	[34]	Solve the problem of limited storage capacity in blockchain.
Virtual Economy System	[38]	Consider different application requirements for centralized center.
	[39]	Support anonymous payment.
	[40]	Consider the M2M and IoT payment.
	[41]	Support transparent environment for system participation.
	[42]	Improve the auditability and automation of machine interaction.

the efficient storage and acquisition of large amounts of data is a key issue that needs to be optimized for the system.

As a distributed ledger, blockchain requires data transparency to ensure the verifiability of transaction content and the authenticity of transactions. On the other hand, it is also necessary to ensure that transparent data cannot expose sensitive information of transactions, that is, to ensure the privacy of transactions. Therefore, how to reconcile the contradiction between data transparency and obscurity is also a point that needs to be paid close attention to in the future metaverse for massive transactions. Guan et al. [43] proposed an account-model blockchain to conceal the private information while the transaction detail could be validated. A dual-balance model is utilized to hide the key transaction information like account balance and transaction amounts. Ma et al. [44] proposed to utilize the noninteractive zero-knowledge (NIZK) combined with the public-key encryption scheme to achieve the secure account. Thereinto, the NIZK-based model could help to solve the contradiction problem between the transparency and privacy because the proof would not reveal any private information. A mixing scheme proposed by Xiao et al. [45] solved the problem that a trusted third party is needed to supervise the transaction. They consider the negotiation process between participants to guarantee the transaction details. Li et al. [46] proposed two schemes which is based on outsourcing differential privacy. The preprocessing method and building blocks are utilized to achieve outsourcing differential privacy. When multiple evaluators query the transaction information, a trusted execution environment is used to process multiple queries. Aitzhan and Svetinovic [47] combined the blockchain technology with multisignatures and encrypted messaging streams to achieve secure energy trading, which enables the anonymous negotiation.

However, transactions in the metaverse are far more than just digital currencies. When facing more complex and diverse transaction information, the issues of information transparency and privacy will be further exacerbated [48]. Therefore, in the future, it is still necessary to explore solutions based on diversification and large-scale transactions to ensure the security of users' private information and the reliability of transaction verification.

In conclusion, while the characteristics of security, decentralization, immutability, privacy preservation, etc. of blockchain, there is still room for research in improving the performance and customization for the application in metaverse.

IV. NETWORKING TECHNOLOGIES FOR THE METAVERSE

The metaverse needs to realize the connection between the virtual world and the physical world, allowing users to experience seamlessly. Therefore, the metaverse requires high synchronization and low latency, which will rely on strong network connections and computing power support. In this section, we will describe network technologies for the metaverse, including communication network and computing network.

A. Communication Networks and Applications for the Metaverse

In order for users to get a good experience, whether it is accessing large databases, computing offloading, user interaction and sharing, or connecting between devices, the metaverse needs to rely on a high synchronization, low-latency communication network [5], [6]. Therefore, in this section, we will describe the communication technologies that can be applied for the metaverse.

1) WiFi: WiFi 6, known as 802.11ax, is the follow-up protocol of 802.11ac. WiFi 6 adopts 2.4G and 5G dual-frequency signal output, which, respectively, integrates the short coverage distance of 5G signal, strong anti-interference, and long-transmission distance of 2.4G signal. In addition, WiFi 6 provides downlink and uplink OFDMA, and uplink MU-multiple-input multiple-output (MIMO). In this mode, the maximum transmission rate and communication latency can reach 9.6 Gb/s and 10 ms, which effectively improves the technical indicators of network latency and communication efficiency [49], [50], [51]. In April 2020, WiFi 6 was expanded on the basis of the original frequency band to form WiFi 6E, thereby providing higher communication efficiency, greater throughput, and lower latency [52].

With new applications with ultrahigh throughput and ultralow latency requirements, such as VR and social networking, the IEEE 802.11 standard has been further developed to adapt to these new service characteristics. WiFi 7 corresponds to the revised standard IEEE 802.11be, or EHT (Extremely High Throughput) [53], [54]. WiFi 7 introduces 320-MHz bandwidth, 4096-QAM, MultiRU, multilink operation, enhanced MU-MIMO, multiAP cooperation, and other technologies on the basis of WiFi 6, making WiFi 7 provide a higher data transmission rate and lower latency than WiFi 6. WiFi 7 is expected to support up to 30 Gb/s throughput, which is about three times that of WiFi 6. In addition, WiFi 7 needs to support VR/AR, cloud gaming, and cloud computing, which requires a latency of less than 5 ms.

With higher transmission rates, lower latency, and greater density of networked devices, WiFi 6 and 7 are very suitable for indoor wireless networks. The WiFi 6 wireless router adopts a low-power design with a power consumption range of 9–12 W, which is suitable for headsets [49]. According to this idea, Meta launched Oculus Air Link in 2021, allowing the most popular Oculus Quest series to connect to computers via WiFi instead of wired connections. In addition, compared with Quest 1 which supports WiFi 5 in 2019, Quest 2 launched in 2020 is equipped with more advanced WiFi 6, which enables Quest 2 to provide a display update frequency up to 120 Hz through Oculus Air Link. The bandwidth, update frequency, and delay requirements of headsets are significantly higher than those of computers and smartphones. Supporting WiFi 6/6E/7 access can improve their wireless experience. In the upcoming new headsets of Meta, Apple, and Sony, the new models of Meta and Apple support WiFi 6E, and Sony's PS 5 VR device supports WiFi 6. According to the analysis in [55], using multiple interfaces can make WiFi fully support AR applications. Compared with WiFi 6, the advantages of WiFi 7 will help the development of immersive AR/VR, Industrial IoT, interactive telemedicine, wireless gaming, and other applications.

2) 5G/6G: The metaverse requires high synchronization and low latency so that users can get a better experience, which is an important manifestation of the communication network. Although for Metaverse users who never leave home, the Internet and WiFi can work well together. However, other scenarios may require the assistance of a cellular network. Lampe et al. [56] evaluated highly interactive applications, such as online and cloud gaming, and showed that 130 ms is a higher threshold. Currently, VR/AR, cloud gaming and cloud computing require a latency of less than 5 ms. Therefore, the existing 4G network cannot afford metaverse applications. With the deployment of 5G networks, many user-centric applications have been migrated to the cloud, such as cloud games, real-time video streaming, or cloud VR [5].

The design goals of 5G are high data rate, low transmission delay, improved transmission quality, energy saving, cost reduction, system capacity increase, and large-scale device connection. The ITU-R M.2083-IMT Vision-Framework and overall objectives of the future development of IMT for 2020 and beyond, released in 2015, proposed key technical features and indicator recommendations for 5G (IMT-2020), including peak data rates (10 Gb/s), user experience data rate, spectrum efficiency, mobility (500k/h), latency (1–10 ms), connection density, network energy efficiency, and regional business capacity. 5G introduces technologies, including network function virtualization (NFV) and software-defined network (SDN) at the network infrastructure level, which can flexibly and quickly satisfy the requirements of high network security and customization. In addition, the application of MEC can facilitate the processing of high-reliability and low-latency services. 5G can be deeply integrated with scenarios, such as smart cities, ultrahigh-definition video, VR/AR, and IoVs [57], [58], [59], [60].

However, the 5G network will not be able to provide a fully automated and intelligent network, and will not be able to satisfy the full immersive experience of the metaverse [61]. As an extension of the 5G, 6G realizes the deep integration of intelligent applications and networks through ubiquitous, intelligent, and in-depth connections to meet the needs of humans and machines for interconnection and intercommunication. From the perspective of network performance indicators, 6G will be greatly improved in terms of transmission rate, end-to-end latency, reliability, connection density, spectrum efficiency, and network energy efficiency, so as to meet the diverse network needs of various vertical industries. Compared with 5G, 6G is expected to increase their respective capabilities by 10–100 times for most technical fields [62], [63], [64]. For example, end-to-end latency is less than 1 ms, reliability exceeds 99.99999%, and peak data rate reaches 1 Tbps. In order to meet more abundant applications and extreme performance requirements in the future, 6G will be driven by the following key technologies, such as AI to achieve endogenous intelligent networks, terahertz communication (THz), wireless optical communication, ultralarge-scale MIMO, intelligent reflective surfaces (IRSs), blockchain, and 3-D networking, and dynamic network slicing. Therefore, 6G can realize applications, such as truly immersive XR experience, haptic communication, smart healthcare, and wireless brain–computer interactions, which is expected to truly meet the metaverse's requirements for communication networks [62], [64].

With the commercialization of 5G, users can enjoy playing games on low-configuration devices [65]. In view of the problems of latency, energy consumption, and high server pressure in existing cloud games, Zhang et al. [66] used 5G networks and edge computing to propose a time-delay superposition method to determine the location of the data center to ensure load balancing and improve node performance. Based on the 5G environment, Park et al. [67] designed a game streaming platform and implemented it using Android Studio. For VR/AR applications in 5G networks, in order to achieve low latency, computing outsourcing, and mobility, Schmoll et al. [68] proposed to use mobile edge cloud for computing offloading to realize VR games. Qiao et al. [69] designed a general service-oriented framework

TABLE III
COMPARISON OF DIFFERENT COMMUNICATION TECHNOLOGIES

	End-To-End Latency	Peak Data Rate	Mobility support	AI	Service Support
WiFi 6	10ms	9.6Gbps	-	No	VR/AR
WiFi 7	<5ms	30Gbps	-	No	Immersive AR/VR, interactive telemedicine, IIoT, wireless gaming
5G	1-10ms	10Gbps	Up to 500km/h	Partial	VR/AR, cloud games, real-time video streaming
6G	0.1-1ms	1Tbps	Up to 1000km/h	Fully	Immersive XR, haptic communication, smart health-care, wireless brain-computer interactions
NB-IoT	6-10s	250kbps	30km/h	No	IoT connection

for the opportunities and challenges of mobile augmented reality (MAR) in 5G networks to provide a scalable, flexible, and easy-to-deploy MWAR solution. Unlike 5G, Maier et al. [70] used the 6G invisible-to-visible (I2V) technology concept to explore the potential of realizing XR. In particular, I2V can connect users with people in the metaverse virtual world and share them with other users.

In addition, the demand for information processing in the metaverse is growing explosively to realize anytime, anywhere, diversification, and virtual-real interaction. Therefore, 6G integration of sensing, communication, and computing is needed to meet the needs of in-depth perception, massive computing, and low latency. As a key application of the 6G technology, the metaverse can perceive the physical world all the time with the improvement of its perception ability in the future, and realize the mapping and integration of the physical world and the virtual world under the empowerment of intelligent computing. The development of integration of sensing, communication, and computing can continuously lower the technical threshold of the metaverse and greatly improve the accessibility of the metaverse.

3) NB-IoT: Narrowband Internet of Things (NB-IoT) is a low-power wide-area network (LPWAN) radio technology standard developed by 3GPP for cellular devices and services. This specification was frozen in 3GPP Release 13 (LTE Advanced Pro) in June 2016. NB-IoT uses a subset of the LTE standard, but limits the bandwidth to a single narrowband of 200kHz. It uses OFDM modulation for downlink communication and SC-FDMA for uplink communication. Specifically, NB-IoT has the characteristics of improving indoor coverage, supporting a large number of low-throughput devices, low latency sensitivity, low device power consumption, optimized network architecture, and ultrahigh cost performance [71], [72], [73], [74]. Compared with Lora, Bluetooth, and ZigBee, NB-IoT is more suitable for application in the metaverse. For example, in the case of the same base station, NB-IoT can provide 50–100 times the number of accesses than existing wireless technologies. In the same frequency band, NB-IoT has a gain of 20 dB over the existing network, which is equivalent to an increase of 100 times the capacity of the coverage area. NB-IoT does not need to rebuild the network, and the radio frequency and antenna are basically universal [72], [73], [75].

The NB-IoT technology can be widely used for information collection and wireless monitoring of systems, such as smart cities and smart homes [75]. In addition, NB-IoT can play a vital role in the network infrastructure of the metaverse, providing users with a smooth and realistic interactive experience through environmental sensing. Khan et al. [76] provided a case study of a smart city as the epitome of IoT. Equipped with different types of electronic sensors and equipment, it aims to provide various value-added services to the administrative departments and citizens. Jung and Jang [77] developed a shared-use mobility monitoring terminal technology to form a mobile terminal device in the form of an IoT sensor platform, providing new services for the metaverse reality for smart city environmental monitoring. Considering that various entities in the physical world, such as users and roads, can be sensed by smart devices (such as IoT devices and sensors) and digitally replicated in the metaverse. Han et al. [78] used a set of IoT devices to represent mobile phone data of virtual service providers, and use hybrid evolutionary dynamics to solve the problem of the metaverse synchronization.

To summarize the above communication technologies, a comparison of different communication technologies is depicted in Table III.

B. Computing Networks and Applications for the Metaverse

Multiple tasks in the metaverse, such as XR, AI, motion capture, data processing, and content creation, making it have huge continuous computing requirements. In this section, we will describe the computing technologies that can be applied for the metaverse.

1) Cloud Computing: Cloud computing is a computing paradigm that provides end-users with on-demand services through computing resource pools (including storage services, computing resources, etc.). The key services provided by cloud computing include infrastructure as a service (IAAS), platform as a service (PAAS), and software as a service (SAAS) [79]. Through the use of the cloud computing technology, massive amounts of data can be processed in a short period of time, thereby realizing powerful network services. Cloud computing deploys applications to the cloud, so users do not need to pay attention to the calculation and storage details required by the service. They only need to put forward service requirements on the user side and accept the service data returned by the cloud. The specific computing services are completed by the service provider in the cloud.

Presently, the metaverse is in the exploration stage, and cloud gaming is a form close to the concept of the metaverse. In the running mode of cloud games, all games run on the server side, and the rendered game screen is compressed and transmitted to the user via the network. Therefore, unlike terminal games and mobile games, in cloud games, there are no configuration requirements for the user's device. Users only need to connect to the Internet without downloading resources to local devices to enjoy cloud game services [80], [81]. However, due to the lack of hardware support for user terminal equipment, in order to ensure user experience, faster calculation speed, larger storage space, and smoother network conditions are required [82]. In addition, for cloud VR, a latency of more than 20 ms will degrade the user experience. When the cloud server supports cloud VR, the physical distance from the cloud data center will inevitably lead to an increase in latency [83].

2) Edge Computing: Although cloud computing provides many services, as the metaverse continues to develop and mature, requirements for greater bandwidth and lower latency are put forward for network transmission, and requirements for computing capacity and efficiency continue to increase. Therefore, as the amount of data increases, cloud computing may face communication bottlenecks and cloud computing services that cannot meet some low-latency applications. Compared with cloud computing, edge computing is closer to the user end, thus effectively alleviating the communication burden and reducing latency [84], [85].

Edge computing transfers computing data, applications, and services from cloud servers to the edge of the network to provide users with services closer to them [84], [85], [86]. In edge computing, services run on devices closer to users, so they have the characteristics of fast processing, fast response, and secure data transmission. Second, services are scattered across multiple edge nodes, which can avoid the impact of a single point of failure.

Under this trend, edge computing is expected to become an important support for the metaverse to ensure a smooth experience for all users. For example, edge computing can effectively solve the problems of high latency and high bandwidth consumption in cloud games [66]. Edge computing also provides reliable support for VR, which is the representative technology of the metaverse. For example, Kim et al. [87] proposed a cloud-based VR service deployed on an edge server, which effectively reduces the total network traffic load by using edge computing. Similarly, the improvement of network latency by edge computing has also promoted the popularization of AR/VR applications [67]. In addition, the edge intelligence technology is also used to capture and analyze the real world to realize the immersion of the metaverse [88]. Edge computing can help users supplement local computing power, improve processing efficiency, and effectively reduce network delays and network risks.

3) Computing First Network: As users and devices connected to the metaverse increase, the deployment of edge computing faces various challenges [84], [90]. The computing power of a single edge node is limited, and the application layer cannot accurately grasp the network status in real time. Due to the lack of coordination, computing tasks may not be able to be scheduled to the optimal edge nodes. This will cause long response times and even loss of requests due to the unbalanced load of the network and computing nodes. Computing power is an indispensable core resource for the construction of. Based on the integration of network and computing, it is an inevitable trend to form an "end-edge-cloud" multilevel architecture collaborative deployment.

In order to deal with the problems of edge computing and cloud computing, computing first network (CFN) is proposed, which is a new architecture for network computing integration [91], [92]. CFN enables computing power to be embedded in the network, forming a dynamic, distributed computing, and network integration architecture. Specifically, the high-speed interconnection of "end-edge-cloud" computing power is realized through the communication technology, thereby forming a multilevel, ubiquitous interconnected computing power system to meet the computing power requirements of the cloud, edge side, and end level. That is, the cloud is responsible for large amounts of complex computing, the edge side is responsible for simple computing and execution, and the end side is responsible for ubiquitous computing of perceptual interaction, as shown in Fig. 3. With ubiquitous network access and efficient and lossless data transmission, users can work together at any time and anywhere by scheduling nodes in the computing power network according to task requirements. According to [89], CFN improves system efficiency by intelligently distributing the workload of multiple nodes and sharing the computing resources of multiple nodes to co-process a large number of requests. Therefore, for a CFN integrating heterogeneous resources, computing power evaluation, heterogeneous resource integration, resource identification, and orchestration and scheduling should be considered and studied [91], [92].

In order to provide CFN-based public FL services, Zhao et al. [93] proposed a generic framework of federated learning platform (FLP) for communication service providers considering operation and security. Specifically, the authors discuss generic frameworks and add security domains to ensure secure service delivery. Some typical application scenarios and requirements of CFN are introduced in [89], such as MR, AR, and CAV. These application scenarios require multiple edge computing nodes to be connected to each other to meet user experience. In order to break the boundaries of each MEC node and form an overall computing resource, Liu et al. [94] proposed CFN-dyncast, which is a distributed technology through the corresponding control plane and data plane to distribute customer demand to the best sites based on computing load and network status. In addition, the authors implement the prototype with servers and physical network devices, and verify that the proposed CFN-dyncast can help the client get response in a shorten period. Ren et al. [95] proposed a layered computing architecture in order to provide a better experience for AR users. The architecture is composed of user layer, edge layer, and cloud layer. The AR devices are located at the user layer and is connected to the edge layer through a wireless link. Through the coordination of various layers, the architecture can reduce latency and improve resource efficiency. Similarly, in order to solve the

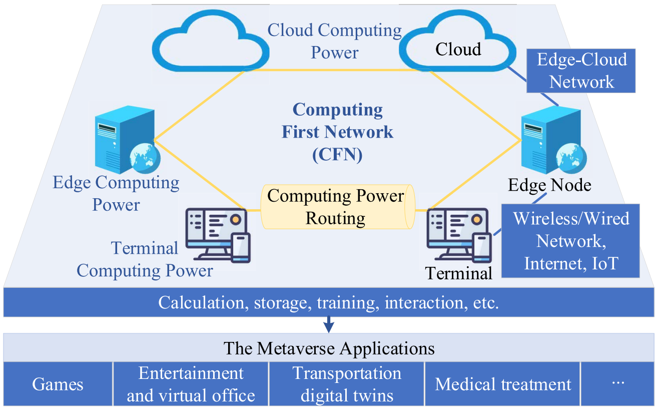

Fig. 3. CFN and applications for the metaverse.

problem of high latency in the uninstallation of AR applications, Younis et al. [96] proposed a three-tier architecture that includes end-users, mobile edge, and cloud, and use the 5G network to make optimized computing offloading decisions in this architecture. In particular, the optimal application placement in the MEC-AR layer is found by using mixed-integer linear programming, thereby reducing energy consumption and network latency. Tian et al. [92] believed that CFN's distributed computing and collaborative optimization of network resources can effectively support Cloud VR video service. That is, through the hierarchical offloading of computing tasks, the cloud computing load is reduced, thereby improving network resource utilization and user experience.

C. Challenges and Discussion

Differences in Communication and Computing: The current technology system, cost, and performance of the network and computing power are in different paths and are relatively independent. The unified intelligent scheduling is full of challenges. Therefore, it is still necessary to break through the problems in the integration of the two technical architectures and realize the real integration of computing and network, so as to provide more efficient, secure and reliable network and computing services for the metaverse.

Multiparty and Distributed Applications: Currently, applications involving multiple parties are gradually increasing, and applications are gradually becoming distributed. However, compared with centralized applications, the performance of distributed systems, such as latency, computing power, and throughput, are not consistent, which poses challenges to the management, operation, and maintenance of the system. Therefore, it is necessary to continuously enhance the automation, self-optimization, and intelligence capabilities of the network to realize intelligent control and decision making.

Orchestration Management: In the future metaverse, tasks, and environments are highly complex, and user needs are flexible, dynamic, and diverse, which pose challenges to the management, deployment, and application of network and computing resources. Therefore, it is necessary to integrate with AI, big data, and other technologies to build an integrated and intelligent orchestration management in network and computing. In addition, the digital twin platform can be used to achieve efficient use of resources and provide users with on-demand services.

Privacy and Security: The network involves multisource and ubiquitous nodes, and the security and reliability of each node cannot be guaranteed. In particular, distributing data to various computing nodes in the network will face risks, such as network attacks and data privacy leakage. Therefore, on the one hand, a feasible solution is to use a distributed training process such as federated learning to achieve privacy protection, so that the data is kept locally [97], [98]. On the other hand, with the help of privacy computing, data labeling, audit traceability, and other technologies, the effect of integrated security protection is achieved.

V. Blockchain Meets Intelligent Networking in the Metaverse

On the one hand, the main features of blockchain, including security, transparency, and nontamperability, provide new opportunities for communication and computing, such as secure sharing, secure storage, and trusted computing [99]. On the other hand, the blockchain has inherent challenges and limitations in terms of consensus efficiency, broadcast efficiency, and scalability [106]. Therefore, the two technologies of blockchain and intelligent networking are combined to work together on the metaverse to achieve a secure and more efficient ecosystem. As shown in Tables IV and V, the blockchain can bring security, privacy, and a trusted distributed computing model to the network; in turn, network performance affects the efficiency of the blockchain.

A. Blockchain-Enabled Communication

The metaverse has extremely high requirements for communication networks, and network resource sharing can be used to cope with the explosive growth of network traffic. However, considering the cost, security, and selfishness, resource sharing becomes difficult. Fortunately, the blockchain technology can effectively promote the collaboration and resource sharing of network entities. Hu et al. [100] combined blockchain and AI to realize dynamic resource sharing in 6G, improving the degree of distribution, security, and automation. In response to the privacy and security issues faced by large-scale spectrum sharing in 5G heterogeneous networks, Zhou et al. [101] developed a blockchain-enabled spectrum sharing architecture to achieve privacy protection, incentive mechanisms, and spectrum allocation. Weiss et al. [102] proposed a blockchain-based two-stage secure spectrum intelligence sensing and shared auction mechanism, which ensures security by uploading auction transaction records to the blockchain. Recently, blockchain-enabled network slicing begins to gain traction. Boateng et al. [103] proposed a blockchain-enabled layered architecture for autonomous resource slicing in 5G RAN. Togou et al. [104] proposed a network slicing architecture that supports distributed blockchain, enabling end-to-end real-time resource leasing and allocation. Wang et al. [105] proposed a new network architecture for 6G trusted wireless communication, namely, B-RAN, to realize the deep integration of

TABLE IV
FUSION POINT AND BENEFITS OF BLOCKCHAIN AND INTELLIGENT NETWORKING FOR THE METAVERSE

Features	Fusion Point	Description
The security, transparency, and non-tampering characteristics of the blockchain	• Security resource sharing • Decentralized computing • Device coordination	• Blockchain can provide trusted and decentralized paradigm for elements in the network, such as network resources and computing power; • Blockchain can be used as a platform to coordinate unreliable devices to to avoid single points of failure and malicious attacks.
Network latency, computing power, and AI algorithms	• Efficient consensus and broadcast • Optimize blockchain scalability	• Network latency will affect efficiency and security of the blockchain; • Computing technology (AI) can be used to manage the blockchain improve robustness and scalability.

blockchain and wireless communication. The key issues, such as cross-network collaboration and sharing, and intelligent group trusted access in B-RAN are discussed in detail.

B. Blockchain-Enabled Computing

The metaverse puts forward extremely high requirements on computing power. Although the current computing power architectures, such as cloud computing and edge computing have been proposed one after another, they still cannot meet the high experience demand of the metaverse. In addition, the ensuing privacy and security issues, computing power matching issues, incentive mechanisms, and other issues need to be resolved. In this case, combining the blockchain technology can provide a promising solution.

For distributed computing capabilities, due to the difficulty of calculating the contribution of each node to the network and the lack of incentive mechanisms, it is difficult to match demand with computing resources. The blockchain technology can solve these problems well. For example, Golem[2] is a decentralized computing power network based on the Ethereum blockchain. Users can buy and sell computing power through the network, which means that users can complete tasks that require computing power on other users' computers or sell their excess computing power to other users. Golem automatically matches users' computing power needs with providers and provides an Ethereum-based payment method to reward users who share their computing resources. The iExec blockchain uses smart contracts to describe the characteristics of computing resources, such as memory capacity, CPU type, and disk space, so as to match resource requests and supplies. Li et al. [107] analyzed the problems of privacy leakage, single point of failure, and high service fees in the traditional centralized crowdsourcing system, and propose a blockchain-based incentive mechanism system architecture. In detail, a series of smart contracts are used for the automatic execution of the system, and the blockchain is used for user reputation management and incentives. Hu et al. [108] proposed to use the emerging blockchain technology to protect user privacy and to achieve a fair incentive mechanism by refining participant registration, perception task execution, and reward distribution.

Data security, privacy issues, and previous lack of trust among users are the keys to hindering the implementation of distributed computing. The application of blockchain can form a secure distributed mechanism. Alcaraz et al. [109] proposed a blockchain-based architecture to implement entity management in the smart grid and secure connections between key resources. Fu et al. [110] used blockchain to implement vehicle collaborative computing architecture to deal with the existence of malicious users. In addition, federated learning is an important method to protect privacy in distributed computing [111]. However, research shows that federated learning will still be attacked, and there is a risk of privacy exposure. Mothukuri et al. [112] comprehensively introduced the challenges faced by federated learning in terms of security and privacy. Blockchain can provide user privacy guarantees and data security for data exchange in the FL process. Lu et al. [113] designed a new model of the digital twin wireless networks (DTWN) that uses digital twins to alleviate unreliable and long-distance communications between end-users and edge servers. In addition, the combination of blockchain and FL enhances the security of parameters and improves the reliability of user models to achieve secure and efficient edge intelligence. Weng et al. [115] used a blockchain-based model to provide FL participants with data confidentiality, computational auditability, and incentives. In order to improve the safety and reliability of model parameters, Lu et al. [116] proposed a hybrid blockchain architecture, which consists of a permissioned blockchain and a locally directed acyclic graph (DAG). On this basis, an asynchronous FL solution is proposed, which ensures the reliability of shared data by integrating the learning model into the blockchain and performing two-stage verification. Furthermore, Kang et al. [117] introduced reputation to measure the reliability and credibility of mobile devices, and design FL participant selection schemes based on reputation. In addition, they use the nontamperable feature of the blockchain to implement secure reputation management in a distributed manner.

C. Device Coordination

In the future, there are many devices that can be connected to the metaverse, such as computers, mobile phones, and IoT devices, all of which can perform computing tasks and make joint decisions [118]. In this case, the interaction of a large number of different devices provides more opportunities for untrusted devices and cyber attacks. For example, some terminal devices and edge systems are inadequately protected and vulnerable to attacks and tampering. When the data in the

[2]https://www.golem.network/#the-network

TABLE V
TYPICAL RESEARCHES OF THE INTEGRATION OF BLOCKCHAIN AND INTELLIGENT NETWORKING

Benefits	Ref.	Purposes	Contributions
Blockchain-enabled Communication	[100]	To improve the degree of distribution, security and automation.	Combine blockchain and AI to realize dynamic resource sharing in 6G.
	[101]	To deal with the privacy and security issues faced by large-scale spectrum sharing in 5G heterogeneous networks.	Develop a blockchain-enabled spectrum sharing architecture to achieve privacy protection, incentive mechanisms, and spectrum allocation.
	[102]	To effectively and securely utilize limited spectrum resources.	Propose a blockchain-based two-stage secure spectrum intelligence sensing and shared auction mechanism.
	[103]	To address security and privacy challenges in network slicing.	Propose a blockchain-enabled layered architecture for autonomous resource slicing in 5G RAN.
	[104]	To achieve end-to-end real-time resource leasing and allocation.	Propose a network slicing architecture that supports distributed blockchain.
	[105]	To address the trust crisis and security challenges in wireless networks.	Propose a network architecture for 6G trusted wireless communication named B-RAN.
Blockchain-enabled Decentralized Computing	[107]	To deal with privacy leaks, single points of failure and high service costs.	Propose blockchain-based incentive mechanism system architecture to realize user reputation management and incentives.
	[108]	To protect user privacy and achieve fair incentives.	Refine participant registration, perception task execution and reward distribution.
	[109]	To realize the security of entities and resources in the smart grid.	Propose blockchain-based management architecture to achieve secure connections.
	[110]	To deal with the existence of malicious users.	Propose blockchain-enabled vehicle collaborative computing architecture.
	[113]	To deal with the privacy and security issues in FL.	Propose the DTWN model to alleviate unreliable communication, and use blockchain to improve the reliability of the model.
	[115]	To deal with the risk of privacy leakage in FL.	Use blockchain to provide FL participants with data confidentiality, computational auditability, and incentives.
	[116]	To improve the safety and reliability of model parameters.	Propose hybrid blockchain architecture and asynchronous FL scheme.
	[117]	To improve the reliability and credibility of FL.	Propose blockchain-based distributed reputation management for FL participant selection.
Device Coordination	[120]	To deal with the security issues of heterogeneous devices in the network.	Use blockchain and smart contracts to realize the security, integrity and auditability of device management and firmware transmission.
	[121]	To realize the security and of IoT device interoperability and communication.	Propose a firmware upgrade plan for embedded devices based on blockchain technology.
	[122]	To realize the software patch update in the IoT environment.	Implement patch transmission incentives by deploying smart contracts on the blockchain.
	[123]	To deal with the authentication and user trust issues in the IoTa system.	Use blockchain and smart contracts to track, identify, and verify user information.
	[124]	To improve the safety and efficiency of network maintenance.	Use the non-tamperable feature of the blockchain to manage and monitor equipment.
Efficient Consensus and Broadcast	[129]	To study the relationship between Bitcoin and network performance.	Bitcoin cannot make full use of network bandwidth and needs to optimize network topology.
	[130]	To realize the fast and reliable broadcasting of the blockchain.	Consider the transmission rate and reliability, and establishes a trusted-enhanced blockchain P2P topology.
	[131]	To speed up the efficiency of blockchain broadcasting.	Propose BlockP2P, which is an optimized design that can speed up broadcast efficiency while maintaining security.
	[132]	To reduce consensus time and improve network scalability.	Improve the topology of the peer-to-peer blockchain structure to the structured topology in the cluster.
Optimize Blockchain Scalability	[142]	To improve authentication efficiency.	Propose distributed and trusted authentication system based on blockchain and edge computing.
	[143]	To improve the robustness of the system.	Develop decentralized paradigm for big D2C by using FL and blockchain jointly.
	[144]	To achieve highly secure and trusted edge computing.	Propose BlockTDM to provide a common paradigm for tamper-proof trusted data management.

device is tampered with, it will adversely affect the decision making of the entire system. Security experts can turn off these harmful programs and compromised devices by locating the centralized control center. However, while satisfying security, for the metaverse, the delay, and availability of services, as well as the difficulty of adapting to complex environments and monitoring are also worth considering. Therefore, blockchain can be applied to the management and coordination of network and network devices, whose distributed feature allows greater scalability and improves robustness by eliminating single points of failure [106], [119].

Aiming at the security issues of heterogeneous devices in the network, Gong et al. [120] proposed a device management architecture based on the blockchain. Specifically, the architecture provides differentiated management and firmware update mechanisms based on device performance and requirements, thereby optimizing network and device resources at the same time. In addition, the use of blockchain and smart contracts for equipment management history and firmware transmission ensures the safety, integrity, and auditability of each device. Similarly, in order to realize the security and correctness of the interoperability and communication of IoT devices, Lee et al. [121] proposed a firmware upgrade plan for embedded devices based on the blockchain technology. By requesting firmware updates from nodes in the blockchain network, the device can securely check the firmware version, verify the correctness of the firmware, and download the latest embedded device firmware without being tampered with. Lee et al. [122] used blockchain to spread software update patches in the IoT environment and deploy smart contracts to automatically realize the incentives for successful patch transmission.

In response to the problem of identity verification and user trust in the IoT system, Mohanta et al. [123] proved that the application of the blockchain technology can track, identify, and verify user information at any time in a decentralized manner. With the help of the blockchain technology and smart contracts, trust in IoT applications can be established between all entities. Koštál et al. [124] used the nontamperable feature of the blockchain to manage and monitor equipment to improve the security and efficiency of network maintenance. By storing device configuration files in the blockchain, secure distributed management and easy recovery after accidents can be realized.

D. Efficient Consensus and Broadcast

Network performance will have an impact on the consensus efficiency of the blockchain and the efficiency of block broadcasting. Researchers have separately studied the influence of network delay on the rate of blockchain convergence, blockchain security, transaction throughput, and other proportions [125], [126], [127]. In theory, when there is infinite bandwidth, infinitely small network delay, and infinitely strong computing power, the efficiency of consensus and transaction per second (TPS) in the blockchain system can be infinitely high. However, in reality, most users have limited resources and capabilities. Therefore, improving the blockchain consensus and broadcasting efficiency through the optimization of network performance is a direction worth studying.

For example, the communication between blockchain nodes has always been a difficult technical problem to solve. Compared with 4G networks, 5G networks have wide coverage, high data and information transmission rates, low communication delays, and support for massive connections [128]. Therefore, the combination with the blockchain can greatly increase the end-to-end communication rate and achieve faster transaction processing speed while maintaining the degree of decentralization of the blockchain. Croman et al. [129] analyzed how Bitcoin restricts P2P networks to support higher throughput and lower latency. The result shows that Bitcoin cannot make full use of network bandwidth and needs to optimize the network topology to reduce the network latency of the blockchain. In order to realize the fast and reliable broadcasting of the blockchain, Hao et al. [130] considered the transmission rate and reliability at the same time, and establish a trust-enhanced blockchain Peer-to-Peer (P2P) topology. This topology can speed up the transmission rate while maintaining transmission reliability, and at the same time adopt an effective node deactivation detection method to reduce network load. Hao et al. [131] proposed BlockP2P, which is a novel and optimized design that can accelerate broadcast efficiency while retaining security. Al-Musharaf et al. [132] improved the topology of the peer-to-peer blockchain structure to a decentralized topology (structured topology in a cluster) to reduce consensus time and improve network scalability.

E. Optimize Blockchain Scalability

For blockchain systems, the three characteristics of decentralization, security, and scalability need to be combined. Among them, scalability refers to the ability of the blockchain system to process transaction information, which largely depends on transaction processing performance, that is, the TPS. With the significant increase in the number of transactions, scalability is the biggest obstacle that today's blockchain systems cannot be adapted to practical application scenarios (such as Bitcoin) [133]. The main reason for this result is that each transaction must be agreed on all nodes and the cost of each node's participation in the blockchain system. For the metaverse, there are a large number of user and service needs. In addition, the network changes dynamically and transactions are updated rapidly. Therefore, the scalability problem needs to be well resolved.

Presently, the mainstream ways to improve the scalability of the blockchain (mainly to improve the TPS) are rough as follows: changing the consensus protocol, replacing the DAG network, adopting the cross-chain technology, and adopting the sharding technology [134]. For the consensus mechanism, in addition to Proof-of-Work (PoW) used by the BTC system, there are Proof-of-Stake (PoS), practical Byzantine fault tolerance (PBFT), and various improved versions. These consensus mechanisms are all to improve the deficiencies of PoW, but they also weigh and compromise in different aspects [135], [136]. Since the blockchain is a chain structure, using DAG can change the structure to a net type. In this structure, each transaction is connected to multiple other transactions, thereby improving the overall verification efficiency [137]. Cross-chain is divided into multichain and side-chain, which uses multiple chains to conduct transactions in parallel. Compared with a single chain, TPS is bound to increase. However, as the transaction volume increases, the demand for cross-chain data intercommunication will increase at any time, which will greatly increase the difficulty of management [138]. The sharding technology is to publish each shard after each transaction block is decomposed to the blockchain network, and each shard is in a parallel state so that each node does not have to download all transaction data, thereby greatly improving the processing speed of the blockchain system [139], [140].

The network technology can be used to optimize the scalability and robustness of the blockchain. For example, a distributed computing network architecture can use multiparty computing power and storage resources to enhance scalability. When the transaction volume increases, the AI technology can be used to increase the block creation rate to increase throughput. As mentioned in the survey on blockchain and edge computing, Yang et al. [141] thought that the integration of blockchain and edge computing into one system can enable reliable access and control of the network, storage, and computation distributed at the edges. Guo et al. [142] also applied edge computing in blockchain edge nodes and propose distributed and trusted authentication system based on blockchain and edge computing, aiming to improve authentication efficiency, the caching strategy based on edge computing performs well in terms of average delay and hit ratio. Qu et al. [143] developed a decentralized paradigm for big data-driven cognitive computing (D2C), using federated learning and blockchain jointly. The blockchain-enabled federated learning helps quick convergence with advanced verifications and member selections, so the robustness of the system is improved. The BlockTDM scheme proposed in [144] provides a general, flexible, and configurable blockchain-based paradigm for trusted data management with tamper resistance, which is suitable for edge computing with high-level security and creditability.

F. Challenges and Discussion

Large-Scale Distributed Computing: The existing blockchain structure determines that the amount of calculations it can make and the nodes that can be allowed to participate are limited, so it is full of challenges to support large-scale distributed computing and application scenarios. The vision of mobilizing computing power of any scale according to demand in an ideal distributed computing system is restricted by the scalability of the blockchain. Therefore, cross-chain structure, network technology, resource optimization, and other aspects are worth studying, so as to further make full use of distributed computing power.

Big Data Analysis: The combination of blockchain and intelligent networking can provide new opportunities for data security analysis and storage. However, on the one hand, different applications have different data requirements, and how to achieve multitask parallel processing is a challenge. In addition, in practice, the data in the network may be unlabeled or mislabeled, which is a challenge for the processing of this type of raw data. Therefore, semi-supervised learning and collaborative learning between devices are possible solutions.

Resource Optimization: In order to provide on-demand services to users in the metaverse, communication resources, computing resources, and storage resources need to be allocated and scheduled reasonably. Especially after joining the blockchain system, how to design an effective coordination mechanism, consensus mechanism, and incentive mechanism to optimize limited resources is an important research question. In addition, in an insecure and complex network environment, it is necessary to balance the relationship between privacy assurance and system performance.

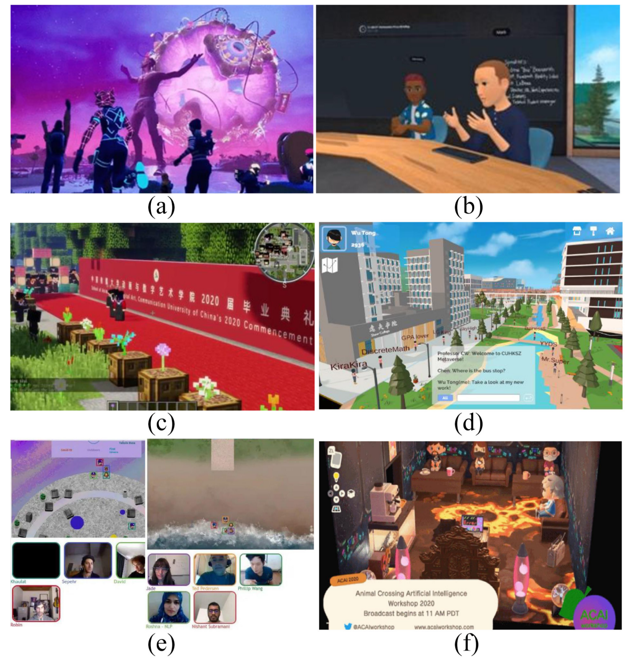

Fig. 4. Some use cases of the metaverse in social: (a) "ASTRONOMICAL" virtual concert in "Fortnite"[3]; (b) Horizon Workrooms platform [145]; (c) Virtual graduation ceremony of Communication University of China[5]; (d) CUHKSZ Metaverse [2]; (e) ICLR 2020 virtual meeting scenario[4]; (f) Animal Crossing AI workshop.[6]

VI. Applications of the Metaverse

The development of technology has enabled the metaverse to be applied in various fields. In order to bridge the gap between academia and industry, in this section, we will focus on the application of the metaverse in games, social platforms, transportation, and industrial IoT. A summary of applications areas of the metaverse is depicted in Table VI.

A. Games and Social Applications

The metaverse has many related application scenarios, such as XR and other applications that can enhance the immersive experience. Relatively speaking, the mature development of metaverse is games and social platforms, as shown in Fig. 4.

Games: As introduced in Section II-A, since the concept of the virtual world was put forward, with the update of technology, the development of metaverse games has gone through different stages so far. For example, the early text-based interactive games, such as Dungeon and Dragon, and Colossal Cave Adventure; virtual open worlds, such as Web World, Worlds Inc., and ActiveWorlds; massive multiplayer online video games, such as Second Life, Minecraft, and Fortnite; and the relatively new decentralized virtual world

TABLE VI
SUMMARY OF APPLICATIONS AREAS OF THE METAVERSE

Application area	Example	Description
Games	Dungeon & Dragon, Colossal Cave Adventure, ActiveWorlds, Second Life, Minecraft, Fortnite, Cryptovoxels, Decentraland, etc.	Bring an immersive experience of the game, improve interactivity, playability and user experience.
Entertainment and virtual office	"ASTRONOMICAL" virtual concert, Horizon Workrooms platform, etc.	Break geographical restrictions and improve entertainment and office functions.
Education and academic	CUHKSZ Metaverse, ICLR Town, Animal Crossing ACAI workshop, etc.	Break geographical restrictions, improve the interactivity and diversity of education and meetings, and facilitate understanding.
Transportation digital twins	Digital twin box, IDT-SDVN, transport for NSW, Gohigh, etc.	Use the virtual transportation world to achieve accurate sensing, real-time data analysis, scientific decision-making, and intelligent and precise execution to achieve full-cycle intelligent management of the physical transportation world.
Connected and autonomous vehicles	Waymo-Castle, Toyota-60-acre facility, Uber-Almono, WayRay, ARCAR, Nissan I2V, etc.	Accurately test the real-time environmental sensing of the autonomous driving system in response to various road events, as well as the rapid coordination ability of associated decision-making control.
Industrial production	BMW's Regensburg production line, Boeing, Unilever, Siemens Energy, Ericsson, PBC Linear, etc.	Reduce labor costs, accelerate production process design, and reduce implementation time.
Medical treatment	Magic Leap, HoloLens 2, etc.	Use holographic projection and somatosensory equipment to facilitate the analysis of the condition, reduce the operation time and the incidence of complications.

that uses the blockchain technology, such as Cryptovoxels and Decentraland. In addition, the metaverse with games as its carrier has developed rapidly, and the boundaries of games have continued to expand, forming a new ecology.

Entertainment and Virtual Office: Due to the catalysis of the COVID-19 epidemic, the "ASTRONOMICAL" virtual concert[3] held by American rapper Travis Scott in "Fortnite" attracted more than 12 million audiences, which brings players to fantasy scenarios, such as deep sea and space. In addition, the online office has gradually become a trend, breaking the geographical restriction of people going to work. Unlike telephone conferences and video conferences, the metaverse can be able to enhance the experience of online office. In August 2021, Facebook launched a public beta version of the Horizon Workrooms platform. Using Oculus Quest 2 devices to log in, people working from home can participate in meetings virtually and enjoy the feeling of being in the same room. At the same time, users who do not wear AR/VR devices can join through video calls. The panel of the conference room can be connected to the user's computer screen in real time for display [145].

Education and Academic: In addition, academia and education industry are also worth looking forward to [6]. In [2], the Chinese University of Hong Kong, Shenzhen (CUHKSZ) Metaverse is introduced. It is a blockchain-driven system used to provide students with an interactive metaverse, that is, behaviors of students in the virtual or physical world can influence each other. As a cross-platform system, users can use smartphones, computers, and browser-based cloud streaming to connect to CUHKSZ Metaverse. In addition, interaction, content creation, and ecosystem are realized through location reporting, sensors, AI, and blockchain technology. Due to the epidemic, many academic conferences are held online. For example, the ICLR 2020 has a Pokemon-style virtual environment "ICLR Town."[4] The image of participants in this environment is almost synchronized with the video conference [146], [147]. The online virtual environment has become the most important way for people to continue to communicate. In order to prevent students from missing the graduation ceremony due to the epidemic, Communication University of China rebuilt the campus in the sandbox game "Minecraft,"[5] and students gathered together to complete the ceremony with virtual avatars [148]. Similarly, the AI academic conference has been moved to the game. For example, ACAI put the workshop 2020 on Nintendo's "Animal Crossing."[6] Each part of the workshop consists of four to five speakers, taking turns to give lectures, with prearranged seats, podium, and laptops.

In the future, the metaverse will cover many aspects, such as work, life and entertainment, education, and medical care, and its applications will be more extensive.

B. Transportation Applications

Currently, the intelligence of the traditional transportation infrastructure has been effectively improved with the help of the sensing system. The network provides ubiquitous high-speed, multinetwork collaborative access services, and computing facilities provide high-speed information processing capabilities. In addition, vehicles are equipped with sensors, communication modules, and computing equipment, and realize V2X communication through 4G, 5G, and even more advanced networks, and finally connect with the metaverse. Therefore, transportation is one of the important application scenarios of the metaverse, as shown in Fig. 5.

Transportation Digital Twins: In the metaverse, the location and status of transportation participants and infrastructure can be accurately measured and accurately predicted, so as to

[3]https://www.npr.org/sections/coronavirus-live-updates/2020/04/24/843631981/travis-scotts-fortnite-event-draws-record-audience

[4]https://twitter.com/shagunsodhani/status/1255271160620765186

[5]http://www.china.org.cn/china/2020-07/06/content_76241462.htm

[6]https://acaiworkshop.com/index.html

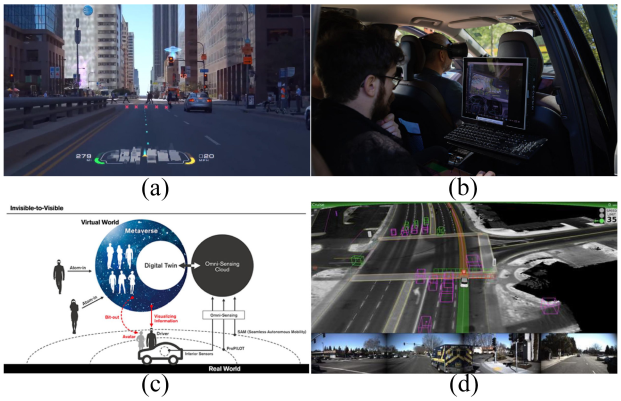

Fig. 5. Some use cases of the metaverse in transportation: (a) WayRay displays traffic and map information through AR[8]; (b) ARCAR realizes virtual information display and driving control [160]; (c) I2V uses 3-D AR to connect the physical world and the virtual world to improve driving safety and comfort[9]; (d) Waymo trains, tests, and verifies its automatic driving control software in Simulation City.[7]

realize the full-cycle intelligent management and control of the transportation system. When managing virtual transportation, we can realize transportation simulation, monitoring, diagnosis, prediction, and control through accurate sensing, real-time data analysis, scientific decision making, and intelligent and precise execution to solve problems in transportation planning, design, construction, management, and service processes, so as to more accurately serving the physical transportation world. Therefore, the transportation digital twins in the metaverse are the perfect candidate applications for realizing the transportation brain in the true sense [149]. Marai et al. [150] introduced the proposed digital twin box (DTB) for road infrastructure digital twin, which is considered to be a step toward the realization of a series of essential basic technologies (e.g., autonomous driving) and services. Specifically, the DTB includes 360° cameras, GPS devices, Internet dongle, and other IoT devices for environmental measurement. When many DTBs are deployed on the road, different types of data can be collected, stored, and analyzed, resulting in a database that is easy to access and understand. Gao et al. [151] summarized the application of DT in four types of transportation infrastructure and the characteristics of time dynamic models. Especially for road traffic, Zhao et al. [152] proposed an intelligent digital twin-based software-defined vehicular networks (IDT-SDVNs) to realize intelligent networking, functional prediction verification, and maintenance and diagnosis of operating networks in the physical world. At the same time, there are challenges in road traffic prediction, data fusion, high-speed multisource data fusion, energy consumption, and security. Kaliske et al. [153] explored the potential of all substructures of road traffic (vehicles, tires, and roads) and the steps to achieve a road digital twin. Based on the IoVs, Gohigh focuses on core features of the metaverse, namely, collaborative interconnection, digital twins, and interactive experience, and provides a cooperative vehicle infrastructure system (CVIS) that integrates "vehicle-road-network-cloud-map-location."

Connected and Autonomous Vehicles: As mentioned above, the metaverse can simulate a world that combines reality and the virtual, and CAVs can be connected with the metaverse for testing [154]. The metaverse cleans, integrates, and selects typical scenarios through the road network monitoring data accumulated during the operation of intelligent transportation, generates new samples based on this mixture, and constructs a dynamic space-time mapping of the real world to form a high-fidelity mixed VR transformation scenario. Compared with the traditional test, this mode can accurately test the real-time environmental sensing of the autonomous driving system in response to various road events, as well as the rapid coordination ability of associated decision-making control. Currently, in addition to real roads and test grounds, several autonomous driving companies, such as Waymo-Castle [155], Toyota-60-acre facility [156], and Uber-Almono [157], have established their virtual cities, allowing their vehicles to be tested in various environments without being affected by uncertainty. Specifically, Waymo trains, tests, and validates its autonomous driving control software in its latest virtual world, i.e., Simulation City, to ensure that its vehicles can better respond to all adjustments on open roads.[7] As of 2020, 15 billion miles have been simulated, while the actual mileage is only 20 million kilometers.

In addition, the development of the XR technology promotes the technological innovation of CAVs, and preliminary research mainly involves navigation, driving behavior, and safety [158], [159]. In terms of navigation, WayRay[8] proposes the metaverse on wheels, which is to achieve a seamless connection between the virtual world and the physical world through the information displayed by Holographic AR Display and display information, such as traffic lights, pedestrian warnings, and route maps to drivers and passengers to improve driving safety, comfort, and entertainment. Similarly, in [160], a mixed reality (XR) experience named ARCAR based on a proof-of-concept headset is introduced, which is implemented in the 2019 Volvo XC90 for the driver to control a moving vehicle. The headset contains cameras, a depth sensor, and a high-end display system, which can realize safe driving under conventional speed limits, and is used to investigate issues, such as driver distraction, perception, and safety [161].

Furthermore, the invisible-to-visible (I2V)[9] that Nissan is developing uses a 3-D AR interface to integrate the real world and the virtual world so that the driver can obtain (see) information that is invisible. Through Nissan Omni-Sensing, seamless autonomous mobility (SAM), ProPILOT, and digital twin technologies, connecting the vehicle to the metaverse can improve driving safety and comfort. Specifically, the information collected by on-board sensors is combined with data from Omni-Sensing Cloud to provide the driver with enhanced information about the surrounding area, including predictive information, blind spot obstacles, and potential hazards to improve driving safety. In addition, by connecting to the metaverse, distant family and friends can appear in the car as a 3-D AR virtual image [5].

[7]https://blog.waymo.com/2021/06/SimulationCity.html
[8]https://wayray.com/#what-we-do
[9]https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/i2v.html

C. Industrial Internet of Things

Given that the metaverse meets the needs of simulators and professional virtual spaces for various purposes in games, social interactions, and transportation, applications in industrial production, medical and other fields have gradually begun [162], [163]. Fig. 6 depicts some typical use cases.

Industrial Production: The application of metaverse in industrial production can significantly reduce labor costs, accelerate production process design, and reduce implementation time [164], [165]. Specifically, the metaverse allows the creation of a "cyber–physical system" of digital models of real events and objects, thereby using the network technology to use related systems in all stages of product design, production, and delivery. For example, BMW's Regensburg production line[10] can plan their production process more accurately through computer simulation. They can simulate the physical world and determine ways to improve work efficiency and safety without having to slow down production through physical testing and actual modifications.

In addition, Microsoft has implemented digital twin on its cloud platform, providing a bridge between the virtual world and the physical world. Boeing and Unilever use it to build engines and build assembly line simulators to reduce production waste, respectively, [166], [167]. Furthermore, digital twins will be used to simulate processes in 5G systems, WiFi 6, cloud computing, and edge computing to create smart sensors and other systems [165]. For example, Siemens Energy and Ericsson are using the NVIDIA Omniverse platform to manage virtual power plants and distribute 5G equipment.

The rapid development of the XR technology and the interface of human–computer interaction allows the use of digital twins and the metaverse to train employees [168]. In the future, the metaverse will be able to get through the entire life cycle of design, manufacturing, and marketing, as well as promote the transformation of industrial production.

Medical Treatment: On 25 October 2020, surgeons at the Children's Hospital of the University of California, Davis, successfully separated a pair of twins with consecutive skulls after 24 h.[11] During the preparation process, a team of 30 experts used the Magic Leap[12] technology for VR previews [169], [170]. Specifically, the data from MRI and CT scans created a 3-D virtual model of the twins' heads and used Brainlab's mixed reality viewer to view them on the Magic Leap 1 headset. Experts can walk around and simultaneously observe the AR model located in the center of the room, so as to deeply study the complex blood vessel network of the twins' skulls to determine which veins can be separated to help them explore the surgical plan.

Similarly, the head-mounted hardware device HoloLens 2[13] developed by Microsoft can achieve similar functions to the 360° XR of Surgical Theatre. That is, the holographic projection combined with the patient's own data during the operation

(a) (b)

Fig. 6. Some use cases of the metaverse in IIoT. (a) Metaverse for industrial production.[10] (b) Metaverse for medical treatment.[12]

can reduce the operation time and the incidence of complications [171]. In addition, when explaining the procedure to the patient, the doctor can use interactive 3-D images to explain everything, so as to better eliminate the patient's worries.

In addition to these XR-based medical images, the rapid development of technologies, such as brain-computer interfaces, AI, IoT, somatosensory devices, and quantum computing will make the metaverse more widely used in the medical field.

VII. Challenges and Research Directions

Through the iteration and progress of technology, the boundary between the physical environment and the virtual environment will gradually blur and finally achieve a perfect combination, allowing us to have an immersive experience in the metaverse. However, increasingly stringent experience requirements and increased users' awareness of privacy pose challenges to supporting technologies of the metaverse. Therefore, in this section we have summarized the aspects that require in-depth research and possible solutions.

A. Efficient and Reliable Transmission

The user experience provided by metaverse is highly related to several typical network indicators, such as bandwidth, latency, and reliability. For example, the social nature of metaverse means that it has strict requirements on latency and reliability, because users expect a smooth and synchronized experience. In addition, the mobility of users, the diversity of sensing devices, and a large amount of data increase the challenges to the network. Therefore, the communication network is worthy of further development. Moreover, the combination of 6G and the metaverse is attracting a lot of attention as a research hotspot. On the one hand, 6G will provide stronger communication capabilities for the development of the metaverse, which will provide a more stable and faster link for the mapping between the virtual world and the physical world in the metaverse. On the other hand, metaverse will become the key and even mainstream application scenario of 6G in the future. In the 6G era, higher access rates, lower access delays, faster motion speeds, and wider communication coverage will further promote the development of metaverse. The corresponding communication protocol and resource optimization need to be studied in depth to satisfy the content transmission.

B. Efficient Processing

In addition to the high requirements for communication networks, when entering the era of sensing, interconnection,

[10] https://www.wired.com/story/bmw-virtual-factory-ai-hone-assembly-line/
[11] https://health.ucdavis.edu/children/conjoined-twins/
[12] https://www.magicleap.com/en-us
[13] https://www.microsoft.com/en-us/hololens

and intelligence of everything, the differentiated needs of users and massive innovative applications also put forward new requirements for computing networks. That is, the requirements for computing performance are high, and the demand for computing power supply is large and diversified. Besides, the distributed computing network also poses a great challenge for the performance of blockchain under the circumstance that massive computing devices run simultaneously. The security problem is also the key reason that threats the network performance at any time. Therefore, end-edge-cloud collaboration and distributed computing need further research. Finally, the extreme demand for low delay poses a great demand for the consensus mechanism design for blockchain, which will be the key factor of quality of real-time users' experience.

C. Communication-Computing Integration

The current CFN and communication networks have different technical systems and architecture designs and are relatively independent. Therefore, it is difficult to meet the computing requirements of the metaverse. In order to provide better communication and computing services, it is urgent to establish a unified CFN architecture to achieve unified measurement, intelligent scheduling, and management of communication and computing networks. On this basis, a series of cutting-edge technologies, such as computing power routing, in-network computing (INC), and trusted CFN are worthy of in-depth research and breakthroughs [172]. In addition, facing the future of the integrated resources, the relationship between demand and supply of resources will be further developed. Specifically, the metaverse, as a dual combination of the physical world and the virtual world, poses severe challenges to the demand and invocation of resources. For example, the virtual world and the physical world are one-to-one mapping, which requires strong coordination of sensing, communication, and computing resources. The integrated resources will effectively solve the metaverse's demand for multiple resources, thereby effectively satisfying the scheduling of resources by different users or systems. However, how to effectively ensure the traceability of resources and prevent potential malicious attacks under the condition that resources are allocated on demand and on demand are still key issues that the metaverse needs to solve, such as malicious resource theft and unfair resource allocation.

D. Network Infrastructure Construction

The development of front-end applications will be restricted by infrastructure. For the metaverse, to build a better ecosystem and ensure user experience, further network enhancement is necessary. In addition, the development of existing equipment, such as mobile phones and computers continue to integrate better hardware. However, it brings challenges to equipment costs and technical requirements. Therefore, in addition to improving the performance of the device itself, how to get our smart devices out of the shackles is also a direction worth studying. For example, with the help of edge computing, cloud computing, and high-speed communication networks, complex computing tasks can be placed on the server. Finally, facing the all-scenario requirements of all users, how to keep the secure interface between the users and the infrastructure is another concern. For example, the users need to connect the mataverse by the wireless connection technology. However, the various centralized or decentralized attacks happen due to the malicious behaviours like infrastructure compromising, and the virtual asset should also be protected by softwares and hardwares under the decentralized network attacks.

E. Software Iteration and Development

In addition to hardware issues, the metaverse still lacks a large amount of software support. For example, in the current popular sandbox games, such as Roblox and Minecraft, the modeling is not detailed enough. The underlying reason is that fine production is very strict with performance requirements, time periods, and personnel requirements. Therefore, to build a metaverse, high-quality software support can bring huge productivity and a better user experience. In this case, we can use the AI technology to solve the problem, such as using AI to make basic materials in the virtual world, thereby reducing personnel input. In addition, after users and designers carry out creative designs, use AI to realize complex constructions. For example, in [2], untrained users can use editing tools based on the AI technology to assist the creative process. In addition, the software compatibility shall be securely stored in the blockchain to ensure users' on-demand access. Also, the barriers between different blockchains should be reasonably broken to ensure the secure acquisition and storage of information in order to achieve the effective information exchange between softwares by one certificate.

F. Security and Privacy

In addition to network technology, application innovation, and portable equipment, privacy security is a huge risk lurking in the metaverse. First, in order to provide users with a richer, more realistic, and stable experience, the metaverse is bound to collect network, user, and environmental data. In addition, it is difficult to trace the source of malicious behavior in the network, and trust risks and security problems are frequent. Due to more detailed tracking of users, the attack surface in the metaverse will expand, raising the security and privacy challenges to multiple dimensions. Furthermore, the application of XR also provides richer intrusion and attack opportunities. For example, an attacker can create an identical replica in the metaverse based on the user's access history and data. Blockchain, AI, encryption algorithms, and protocols require more in-depth research to implement identity management, trust systems, and security monitoring systems to meet the needs of future Metaverse applications. In particular, it should focus on preventing potential attacks, such as DDoS and IP tracking in the decentralized metaverse, in order to enhance users' confidence in participating and ensure financial and information security.

VIII. CONCLUSION

In addition to the requirements for equipment, the construction of metaverse requires secure, reliable, and high-synchronization data transmission and processing, thus posing challenges to the development of secure intelligent networking for the metaverse. In response to the continuous communication and computing requirements and security challenges faced in the evolution of metaverse, we have surveyed the cutting-edge achievements of blockchain and intelligent networking in the metaverse. In order to realize the fusion and interaction of virtual and physical worlds, the metaverse requires the network to be authentic and credible. Therefore, we have explored how the combination of blockchain and intelligent networking can benefit the metaverse, including distributed computing, network, and equipment management, and blockchain optimization, aiming to bridge the physical and virtual worlds, thus forming a more credible, secure, and efficient ecosystem to provide users with an immersive experience. In addition, we have discussed the current challenges and future research directions, such as communication-computing integration, infrastructure, security, and privacy, and thus can provide a reference for researchers' future work.

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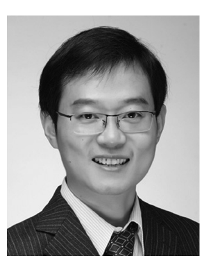

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