Research on Metaverse Application Technologies Based on 6G Networks (Postprint)

Authors: 郎大鹏, 傅文军, 孙建国

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Abstract

[**Objective**] The Metaverse delivers authentic immersive experiences through its powerful simulation capabilities. In recent years, rapid advances in artificial intelligence, blockchain technology, and digital twins have gradually revealed the Metaverse's development prospects across industry and academia. This article aims to explore applied technology research for the Metaverse based on 6G networks.

[**Methods**] We provide a detailed overview of the Metaverse technology's evolutionary trajectory and analyze several key technologies in its development process.

[**Results**] By introducing the metric characteristics and advantages of 6G network technology, we discuss the significance of 6G technology for enhancing the stability of multi-source heterogeneous data, improving transmission speeds, and expanding coverage in Metaverse applications.

[**Conclusion**] The article provides an outlook on Metaverse development under 6G network environments, emphasizing that in the new round of technological innovation, China should strengthen research and development of key Metaverse technologies, building upon its advantages in 5G network deployment.

Full Text

Preamble

Research on Metaverse Application Technology Based on 6G Networks

Lang Dapeng[1], Fu Wenjun[2], Sun Jianguo[3]
(1. Harbin Engineering University, Harbin, Heilongjiang 150001;
2. Zhejiang Mobile Information System Integration Co., Ltd., Hangzhou, Zhejiang 310006)

Abstract:
[**Purpose**] The Metaverse offers users authentic immersive experiences through its powerful simulation capabilities. In recent years, rapid advancements in artificial intelligence, blockchain technology, and digital twinning have revealed the Metaverse's promising prospects in both industry and academia. This paper aims to explore Metaverse application technologies based on 6G networks. [**Method**] We detail the evolution of Metaverse technology and analyze several key technologies in its development trajectory. [**Results**] By introducing the technical specifications, characteristics, and advantages of 6G networks, we demonstrate the significance of 6G technology for enhancing the stability of multi-source heterogeneous data, improving transmission speeds, and expanding coverage in Metaverse applications. [**Conclusion**] The paper concludes with a forward-looking perspective on Metaverse development under 6G network environments, emphasizing that China should strengthen R&D on key Metaverse technologies by leveraging its advantageous 5G network infrastructure amid the new wave of technological innovation.

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1. Introduction to the Metaverse

The American novel *Snow Crash* depicted a compelling 3D virtual space called the Metaverse. Since 2021, the flourishing of artificial intelligence and various virtualization technologies has inspired researchers to simulate and construct physical spaces based on the Metaverse concept. The Metaverse features pervasive connectivity, shared perception, and highly immersive interaction environments that closely approximate the real world [1]. Scholars have highly praised the development and future of Metaverse technology, identifying its core as the integration of advanced digital technologies to model and simulate the physical world, construct virtual identities, devices, and assets, and provide more authentic interactive production environments [2].

The "immersive" quality of the Metaverse extends two-dimensional images and sound into three-dimensional space, creating a complete sensory experience. All forward-looking research requires historical contextualization to address present realities. Under the influence of the global COVID-19 pandemic, users have been compelled to adopt online interactions extensively, and the Metaverse provides "all-real" technical support for this demand. Industry has actively integrated technologies and products to build new technologies around the Metaverse. Microsoft acquired Blizzard Entertainment, Sony acquired Bungie, and NVIDIA and Meta jointly launched the new-generation supercomputing architecture "AI Research SuperCluster." Under such active industrial participation, the Metaverse holds infinite development potential.

In October 2021, Facebook officially rebranded as Meta, ushering in a new era for the Metaverse in commerce. Against this backdrop of rapidly developing key technologies, technological maturity and application integration have reached a stage suitable for large-scale production and commercialization. Just as the internet transformed human life, the Metaverse's penetration into production and daily life will profoundly impact human lifestyles and interaction patterns.

1.1 Development Background

In 2021, the Metaverse company "game Lego" Roblox went public, becoming the world's largest multiplayer online creative virtual gaming company. In the same year, Facebook changed its name to Meta, establishing Metaverse development as the company's future focus. Meta currently owns a series of VR products such as Meta Quest and has launched research on collaborative work and multi-user immersive social experiences [4]. The emergence of the Metaverse has not only driven technological and application development but also presented new challenges for researchers and legislators in data security and privacy protection. In studying Metaverse technology, all participants—including enterprises, users, and device providers—must supply various types of critical information such as identity, location, consumption data, and bank account credentials, making privacy data more vulnerable to unauthorized access than ever before.

The U.S. government has proposed the concept of "metaverse" to strengthen protection of critical information, while the South Korean government has vigorously promoted Metaverse R&D. The Metaverse Exchange Traded Fund (ETF) has attracted numerous innovative enterprises, including those in autonomous driving, artificial intelligence, and spatial economics. By the end of 2021, the total scale of Metaverse ETFs exceeded $600 million [5]. China has also conducted extensive research and pilot deployments for the Metaverse. In July 2022, Shanghai released the "Shanghai Metaverse New Track Action Plan (2022-2025)" [6], which emphasizes building a virtual digital space through VR and XR as key innovation routes, focusing on "virtual-real interaction" and "strengthening reality with virtuality" based on the real economy.

1.2 Current Development Status

The Metaverse's development has reached a stage where technological maturity and application integration can support large-scale production and commercialization. As internet technology transformed human life, the Metaverse's integration into production and social activities will profoundly impact human lifestyles and interaction methods. However, this rapid development also introduces significant challenges in data security and privacy protection, requiring robust legislative frameworks to address potential risks.

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2. Introduction to 6G Network Technology

2.1 Characteristics and Advantages of 6G Network Technology

2.1.1 Advantages of 6G Networks The Metaverse's development relies on high-speed, advanced network technologies, and existing 5G networks have gradually revealed limitations in supporting Metaverse application scenarios. China has proposed research on next-generation network technologies from multiple perspectives. Building upon 5G, 6G technology fully utilizes the communication capabilities of the terahertz band and can support non-cellular networks in multi-class network communication channel fusion scenarios, offering irreplaceable advantages for IoT connectivity in the era of ubiquitous connectivity.

First, 6G-based network connectivity is an all-connected network integrating terrestrial wireless and satellite communications. The network incorporates satellite communications to achieve global coverage, not only improving internet connectivity but also promoting hardware connections among network devices and advancing IoT development. Second, 6G networks are fundamentally internet-based, enabling the interconnection of all devices and assets [7]. Their characteristic is extending user operations, data, and perception to object-to-object connections on the internet foundation, establishing more extensive connectivity capabilities. Third, 6G technology offers more obvious advantages for supporting the Internet of Things [8]. IoT encompasses numerous sensing, transmission, and computing devices that can perceive environmental information (RFID, infrared sensors), provide global positioning functions, and perform autonomous scanning and sensing. By installing intelligent perception chips for high-speed computing, a new integrated network architecture is established.

2.1.2 Key Metrics of 6G Technology Emerging intelligent services such as unmanned driving, drone emergency communications, immersive extended reality, and industrial internet rely on multi-dimensional environmental information perception and supercomputing power. These applications impose extremely high requirements on transmission rate, end-to-end latency, reliability, and power consumption. The IMT-2030 (6G) Promotion Group released the "6G Overall Vision and Potential Key Technologies White Paper" in 2021 [11], proposing that 6G technology should develop toward immersion, intelligence, and full coverage, achieving deep integration between the physical and virtual worlds with breakthroughs in immersive scenario construction, holographic communication, intelligent interaction, and sensory interconnection.

6G networks offer inherent advantages for transmitting 3D data, high-definition images, and multi-source multi-track audio data. For Metaverse applications requiring indoor VR and virtual simulation positioning, 6G networks provide long-distance, high-precision positioning within 10 centimeters. Even in indoor motion positioning and cluster coordination scenarios, accuracy can reach 1 meter. Compared with existing 5G networks, 6G increases speed by ten times while reducing communication latency to one-tenth of 5G, achieving 0.1 milliseconds. For high-security and reliability application scenarios such as industrial control and digital twin-based Metaverse simulation, 6G networks also demonstrate excellent performance with communication interruption rates of less than one in a million.

2.1.3 Typical Devices and Scenarios in 6G Networks While 5G network technology significantly improved connectivity and transmission speeds for personal smart devices and found extensive industrial applications, 6G technology can effectively compensate for 5G's increasingly limited spectrum support for emerging applications and technologies. Typical devices in 6G networks include autonomous vehicles, Wi-Fi-embedded chip devices, cellular network equipment, and public devices for location and weather information. In industrial control, holographic communication and digital twinning technologies comprehensively characterize and transmit workshop production environments, while remote driving and autonomous robots complete production tasks. In the near future, 6G technology will be widely applied in IoST fields such as unmanned aerial vehicles and small low-earth-orbit satellites, realizing the vision of comprehensive coverage through ubiquitous connectivity.

2.2 Typical Metaverse Applications in 6G Environments

6G communication technology meets the technical indicator requirements for Metaverse construction. Technology companies, industrial enterprises, and research institutes have actively deployed Metaverse technologies in typical application scenarios, including consumer electronics, online social networking, immersive gaming, and upgrading traditional manufacturing. A key characteristic of the evolving "Metaverse" concept is its increasing comprehensiveness, with continuous technological innovations feeding back to expand the Metaverse blueprint [12].

2.2.1 Audio-Visual Entertainment Extended Reality (XR) technology encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). Supported by 6G networks, XR can present virtual scenes and objects more realistically and in real-time, gradually transforming human-device and human-human interaction methods. Through 3D modeling, high-definition rendering, and data-image fusion from motion capture devices, images, sound, and even other senses can be displayed in three-dimensional form.

2.2.2 Immersive Social Interaction Traditional online social interaction relies on screens for end-to-end communication through text and video. However, with the Metaverse era, holographic imaging technology can build virtual simulation platforms for social interaction. These platforms replace current mobile terminal devices, enabling immersive experiences for meetings, discussions, and online gaming, thereby forming new social paradigms. Current devices supporting such social and gaming experiences include products from American and Japanese companies like Meta and Oculus.

2.2.3 Industrial Manufacturing Metaverse technology integrates artificial intelligence and multi-source device data to construct virtual environments close to the real world. Digital twinning technology simulates industrial product production, design, and manufacturing processes, significantly enhancing the intelligence and scientific sophistication of the manufacturing industry. 6G technology not only accelerates data flow in production but also integrates basic applications with low latency and high throughput, providing crucial support for industrial R&D, production, and service markets.

2.3 Key Technologies for Metaverse in 6G Networks

2.3.1 Metaverse Application Architecture Under 6G Networks The Metaverse architecture based on 6G network environments addresses communication link speed, accuracy, and fault tolerance issues, enabling rapid development and integration of key technologies. These include digital twinning, blockchain, VR/AR/MR, brain-computer interfaces, motion perception, AI, and robotics. As shown in

, the Metaverse based on 6G network environments comprises a hardware foundation platform, network connection layer, service and management layer, and open interface layer. The hardware foundation platform builds upon 5G network hardware to provide computing and storage resources. The network connection layer extends 5G architecture to provide various state perceptions and network connections. The service and management layer corresponds to data control and user/security management functions in network services. The open interface layer provides various interfaces for network modules and Metaverse applications, including computing power, connectivity, and other applications [12].

2.3.2 Key Technologies for Metaverse in 6G Networks

2.3.2.1 6G Technology and Virtualization Technology Virtualization technologies employed in the Metaverse primarily include Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), collectively known as Extended Reality (XR) [4]. These technologies integrate real scenes through computers to create realistic interactive application environments. Their core function is to create transitions between virtual and real environments by fusing environmental, visual, auditory, and sensory information, forming authentic "immersion." Therefore, immersion is one of the most significant characteristics

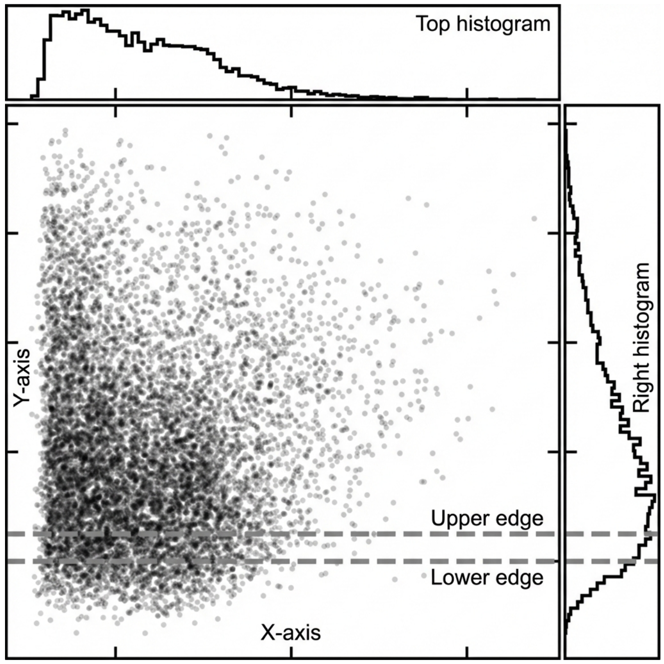

Figure 1: Figure 1

of Metaverse technology, as immersive virtual environments can convey information more effectively and intuitively.

VR technology constructs virtual simulation environments through 3D modeling and interactive simulation. While this technology has been applied in gaming and online live streaming, and companies like Microsoft and Meta have launched VR devices and applications, current limitations prevent meeting the precision, real-time, and long-duration interaction demands of Metaverse scenarios. AR technology requires not only simulating and displaying real-world information but also overlaying more specific, targeted virtual information according to application scenarios and user needs. Common applications include product demonstrations, AR modeling, and scene construction, though further research is needed for multi-dimensional data overlay in Metaverse applications. The superposition and interaction of these technologies represent key future Metaverse developments. Currently, major hardware platforms remain mobile phones and tablets, lacking dedicated hardware platforms, while multiple technologies lack mature algorithms and experience for data and device fusion, falling far short of large-scale application requirements.

2.3.2.2 Brain-Computer Interface (BCI) The original purpose of BCI was to directly connect human brain information with computers, enabling brain-controlled operation of computing devices. The Metaverse requires more efficient interaction between participants, environments, and devices. Existing interaction methods primarily rely on video images and motion perception, which are inefficient and impose high physical and spatial requirements on operators. BCI-based Metaverse applications offer stronger immersion and more efficient, direct interaction methods. BCI not only improves human-device interaction efficiency but also enables people with mobility or learning limitations to experience virtual scenes authentically. Research has shown that connecting patients with medical devices through BCI can accelerate limb recovery, a concept already validated and proven effective in other medical applications.

2.3.2.3 Artificial Intelligence Technology Recent deep learning advancements have enabled AI to achieve remarkable results in natural language understanding, image processing, and video comprehension, often approaching or exceeding human-level performance. AI possesses increasingly autonomous learning capabilities, continuously acquiring new knowledge from existing data and cases. Even without explicit learning objectives, AI can obtain near-realistic analysis results through logical reasoning and fuzzy logic processing. Algorithms continue to optimize, and with higher hardware-software integration and the development of edge computing and IoT, energy consumption has been well controlled.

In Metaverse application scenarios, AI faces greater challenges in two aspects. First, the Metaverse virtualizes the real physical world. Compared with traditional virtual applications, Metaverse scenarios involve more data access devices, more complex types, more diverse data formats, larger data volumes, and broader coverage. Therefore, big data-based AI algorithms must combine deep learning characteristics to construct data analysis at the big data level. Second, a more severe challenge is the semantic-level fusion of massive heterogeneous data. While big data-based AI algorithms can achieve deep understanding of specific domain content, Metaverse applications must integrate data across multiple scenarios to establish a semantically consistent virtualization platform. Additionally, due to data diversity and incompleteness, algorithms must automatically generate necessary information according to Metaverse application requirements, including virtual devices, scenes, and characters—critical steps for enhancing immersive experiences.

2.3.2.4 Motion Capture and Interaction Technology Motion capture technology records the movement speed and trajectory of human body key points, digitizing moving object information for subsequent computation and visualization. This technology first appeared on a large scale in the 2008 film *Avatar*, where virtual characters perfectly displayed actors' body movements. The Metaverse-themed film *Ready Player One* more clearly demonstrated motion capture technology and immersive spatial implementation, providing users with realistic and comfortable experiences. While motion capture technology is relatively mature, its implementation cost remains high. Metaverse technology requires further research not only in software-level fusion and understanding but also in hardware platform cost and computational performance breakthroughs.

The immersive experience provided by the Metaverse requires stimulating user senses through sound, images, video, and environmental factors. Currently commercialized technologies include VR and holographic projection for image display, while 3D printing can produce irregular and unique physical objects such as components, organs, and equipment. Interaction technology has become essential for creating Metaverse experiences based on various supporting technologies. The difficulty of Metaverse applications lies in multi-scenario fusion and efficient communication through BCI. BCI effectively improves user-device interaction, while 6G technology enables low-latency, high-reliability data transmission. Motion perception and interaction technologies serve as crucial connections for Metaverse virtual platforms, enhancing the possibility of immersive experiences and enabling the Metaverse to gradually evolve into a virtual world for all humanity's work and life.

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3. Opportunities and Challenges for the Metaverse

3.1 Unidirectional Data Transmission Characteristics of Brain-Computer Interfaces

Metaverse technology provides new solutions for virtual environment construction and typical application scenarios from both theoretical and practical perspectives. However, substantial work remains to complete its key technologies in practice. Current Metaverse prototype systems primarily interact through audio-visual technologies including VR and holographic imaging [3]. Future BCI development will enable more direct information transfer. However, current BCI information interaction methods still feature unidirectional data flow—for example, controlling cursors or images through thought without feeding information back to the brain. This unidirectional transmission hinders efficient interaction between users, environments, and other devices in the Metaverse.

3.2 Efficient Self-Consistent Hardware and Software Platform Technologies

The virtual world constructed through advanced hardware and software technologies must be self-consistent to flexibly expand with new modules, devices, functions, and roles. Self-consistency ensures all components conform to unified standards, guaranteeing sufficient flexibility and scalability during Metaverse operation. Additionally, due to the Metaverse's persistent nature requiring continuous operation without arbitrary interruption of computation and perception, the system demands powerful computing engines. Currently, we cannot even accurately estimate the hardware scale required to support the necessary computing power. However, it is clear that existing hardware platforms and computing capabilities require joint efforts from industry and research communities to achieve technological breakthroughs for fully supporting Metaverse functions and delivering immersive user experiences.

3.3 Legislation and Ethical Challenges for Virtual Environments

All developmental limitations typically stem from a lack of holistic perspective. Technically, the Metaverse is built upon internet infrastructure, and as the internet is not a lawless space, Metaverse behaviors also require continuous legislative refinement as the technology matures. Protection and regulation of privacy information such as personal identity and location data are essential. As Metaverse technology improves, work and tasks completed by individuals through virtual identities may impact real-world persons, raising questions about legal frameworks for handling illegal acts in virtual worlds. Resolving such issues will significantly promote Metaverse technology development and application.

Properly managing the relationship between governance order and industrial vitality is necessary for promoting high-quality economic and social development. The Metaverse concept represents a major test for existing technologies and hardware-software conditions. Its super-realistic immersive experience has been welcomed by industry and academia. The core of Metaverse applications lies in AI algorithms based on massive data derived from various applications and scenarios, including text, images, video, voice, and high-dimensional data covering land, sea, air, and space. Supported by 6G network technology, the Metaverse can transmit and synchronize data with higher spectrum, faster rates, and lower latency. 6G technology has become the bridge connecting the real physical world and the virtual world, and its close integration with Metaverse technology will greatly expand application scenarios, enhance industry and user acceptance, and stimulate new waves of technological innovation.

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Author Biographies:
Lang Dapeng (1983-), male, from Harbin, Heilongjiang, is a faculty member at Harbin Engineering University. His research focuses on network and information security.
Fu Wenjun (1988-), male, from Beihai, Guangxi, is a senior solutions expert and engineer at Zhejiang Mobile Information System Integration Co., Ltd. His research focuses on 6G theory and digital industry practice.
Sun Jianguo (1981-), male, from Harbin, Heilongjiang, is a professor and assistant dean at the Hangzhou Research Institute of Xidian University. His research focuses on network and information security.

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Figures

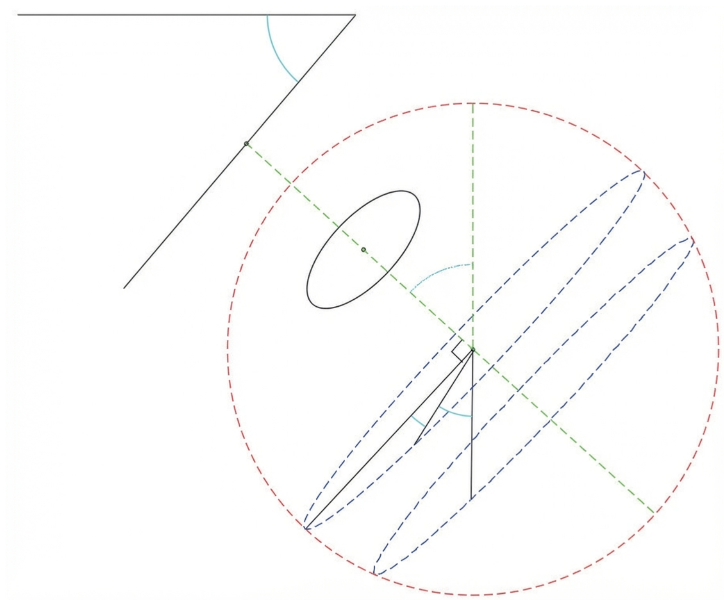

Figure 2: Figure 2