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Evaluating the combination of 6G-Enabled Edge Intelligence with the Metaverse: Overcoming Challenges, Approaches, and Future Research Avenues

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ABSTRACT

This survey explores the integration of 6G-oriented edge intelligence into the Metaverse, an emerging technology that provides users with an immersive and interactive virtual space. The authors provide a comprehensive overview of three Metaverse systems based on 6G edge intelligence and discuss advanced methods for addressing challenges related to security, resource allocation, ethical considerations, hardware limitations, and achieving a balance between virtual and reality. The survey serves as a starting point for future research in this area by providing insights and guidance for researchers and practitioners looking to expand on the Metaverse. This survey highlights the potential of integrating 6G-enabled edge intelligence into the Metaverse to address resource and computing constraints and realize the full vision of immersion, materialization, and interoperability. The authors introduce three new types of edge-Metaverse architectures that use 6G-enabled edge AI and summarize technical challenges that these architectures face in the Metaverse and existing solutions. The survey further explores how the edge-Metaverse architecture technology can help improve interaction and data sharing in the Metaverse. the authors discuss future research directions to fully realize the vision of the Metaverse with 6G-enabled edge AI. this survey emphasizes the importance of exploring advanced technologies like 6G-enabled edge intelligence to enhance the user's experience in the Metaverse and create a more immersive and interactive virtual world. By addressing the technical challenges and exploring innovative solutions, researchers and developers can continue to push the boundaries of the Metaverse and unlock its full potential.

Keywords: 6G, edge intelligence, Metaverse, resource allocation, computing power, immersion, interoperability, data sharing.

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1. INTRODUCTION

This paper emphasizes the significance of data as a fuel for artificial intelligence, often referred to as "data is the new oil." It explores how data is transforming various industries, such as healthcare, education, and politics, creating economic and social value. The paper also discusses emerging data-driven AI technologies like computer vision, natural language processing, and data mining, which have been extensively studied and explored in academic literature.

Furthermore, the paper highlights the development of edge AI, a learning paradigm that allows AI models to be deployed on devices for real-time data processing. While edge AI has been extensively discussed in academic literature, there are still optimization issues that researchers are exploring. The concept of edge AI has potential benefits and applications, as demonstrated in studies like "Edge Intelligence: Paving the Last Mile of Artificial Intelligence with Edge Computing."

The paper also references research papers, books, and chapters related to specific topics. For example, it mentions a research paper on beam scheduling for data relay satellite systems, a method for data valuation based on the Shapley value, and books covering computer vision, natural language processing, and data mining. Additionally, there are articles discussing federated learning in the context of 6G communications and the vision of edge artificial intelligence for 6G, exploring enabling technologies and potential applications.

This paper discusses the issue of high latency in edge AI, which arises from the transmission and processing of large amounts of data from remote devices. This latency problem has hindered the widespread adoption of edge AI applications. This paper mentions that some haptic AI applications require a minimum transfer rate of 1 Mbit/s and a latency of no more than 1 ms. While 5G has improved this issue, the exponential growth of data and models necessitates a faster and more stable mobile communication technology.

Reference [1] surveys federated learning techniques in mobile edge networks (MENs) and explores the challenges and opportunities associated with them. It provides an overview of federated learning applications in domains like healthcare, autonomous driving, and smart cities.

Reference [2] proposes a new paradigm called in-edge AI, which integrates AI techniques into mobile edge computing, caching, and communication using federated learning. It demonstrates the feasibility and effectiveness of this approach in improving system performance, reducing latency, and enhancing privacy and security.

Reference [3] presents a comprehensive survey on the convergence of edge computing and deep learning. It covers various architectures, algorithms, and applications in this area and discusses the challenges and opportunities for future research.

Reference [4] focuses on federated learning in edge computing scenarios with resource constraints. It introduces a formulation and analysis framework for resource-constrained federated learning, considering heterogeneous data sources and limited resources while preserving data privacy.

Reference [5] investigates the impact of local latencies on aiming performance in 3D shooter games. It proposes a method for quantifying latency effects and provides solutions for mitigating these effects through game design and network optimization.

Reference [6] discusses the concept of edge intelligence, which involves performing intelligent processing at the network edge using distributed computing resources. It presents an edge

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intelligence architecture based on multi-access edge computing (MEC) that leverages 5G networks and IoT devices. The paper highlights the benefits of edge intelligence, including reduced latency, improved scalability, and enhanced privacy and security. It also explores the challenges and provides use cases for practical applications.

This paper discusses the issue of fragile stability in edge AI, specifically in the training of large-scale models such as language models. The current network environment is not suitable for training these models due to the fragility of the network connection, leading to frequent failures during the training process. This poses a challenge to the widespread application of edge AI as it limits the ability to train complex and large-scale models that are increasingly used in various domains.

This paper also mentions two research papers. The first paper, titled "Strategies for Training Large Scale Neural Network Language Models," [7] presents techniques like model parallelism and data parallelism to address the challenge of training large-scale models with limited computational resources. It provides insights into the practical considerations and challenges associated with large-scale model training.

The second paper, titled "Terapipe: Token-level Pipeline Parallelism for Training Large-Scale Language Models," [8] introduces a technique called Terapipe that leverages token-level pipeline parallelism to efficiently train large-scale language models. The authors demonstrate the effectiveness of Terapipe in reducing training time and memory usage while maintaining model accuracy using benchmark datasets. This paper highlights the importance of addressing the fragility of the network connection in training large-scale language models and showcases cutting-edge techniques in this field.

This paper discusses the issue of low security in the current network architecture. The architecture is not able to meet the increasing security needs of the numerous remote devices that connect to cloud servers today. It was not designed to handle such large-scale deployments, which poses a challenge to ensuring the security of these connections. The openness of the network further adds to the security challenges, making it susceptible to attacks and unauthorized access.

This lack of security poses a significant challenge to the reliable and secure operation of cloud-based systems. Robust security measures are necessary to protect sensitive data and maintain the integrity of the system. Therefore, there is a growing need for new security solutions that can overcome the limitations of the current network architecture and provide improved protection for cloud-based systems.

This paper discusses a new paradigm called 6G-enabled edge AI, which aims to address the limitations of the current network architecture. This paradigm combines AI technology and 6G mobile communication technology to create a more stable, secure, and low-latency network. The 6G wireless network operates in the terahertz frequency band and achieves transmission rates of 1 Tbit/s with a network delay of less than 1 ms, significantly faster than current speeds. The open RAN framework and advanced network slicing architecture in 6G technology provide intelligent and secure network services. This architecture enables edge devices to perform complex computations locally while leveraging the 6G network infrastructure.

The 6G-enabled edge AI architecture offers a promising solution to the challenges of the current network architecture and drives the development of future intelligent applications.

Reference [9] is a research article titled "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems." It provides an overview of the potential

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applications, trends, technologies, and open research problems in the development of 6G wireless systems. The article discusses emerging technologies such as THz communication, intelligent reflecting surfaces, and AI-enabled networks, highlighting their benefits in terms of latency, bandwidth, and reliability.

Reference [10] is a research article titled "The Roadmap to 6G: AI Empowered Wireless Networks." It discusses the roadmap to 6G wireless networks and emphasizes the role of AI, machine learning, and edge computing in shaping these networks. The article presents a vision for 6G wireless networks that leverages these technologies to provide intelligent connectivity, autonomous communication, and context-aware networking. It also identifies the key research challenges and opportunities in realizing this vision.

The Metaverse is an emerging smart application that aims to merge virtual and real worlds, allowing millions of people to interact online. This poses new demands on edge AI architecture, requiring ultra-high bandwidth, low latency, reliability, and more intelligent services. Human-machine interaction plays a crucial role in the Metaverse, improving user experience. However, building the infrastructure for the Metaverse is complex, involving network architecture, communication platforms, virtual technology, hardware facilities, and intelligent algorithms. Additionally, it also encompasses human senses, psychology, thought, and morals. The 6G-enabled edge AI architecture needs to explore how it can serve and empower the Metaverse, providing a more convenient and intelligent interaction experience.

Several research articles provide comprehensive surveys and insights into the Metaverse. The first reference, [11], titled "All One Needs to Know About Metaverse: A Complete Survey on Technological Singularity, Virtual Ecosystem, and Research Agenda," covers topics like technological singularity, virtual ecosystem, and research agenda. The second reference, [12], titled "A Survey on Metaverse: Fundamentals, Security, and Privacy," focuses on fundamental concepts, security, and privacy concerns. The third reference, [13], titled "Metaverse for Social Good: A University Campus Prototype," discusses the development of a Metaverse prototype for social good. Lastly, the fourth reference, [14], titled "A Full Dive into Realizing the Edge-Enabled Metaverse: Visions, Enabling Technologies, and Challenges," explores the visions, enabling technologies, and challenges of an edge-enabled Metaverse.

This paper aims to survey the challenges, methods, and future research directions of the 6G-enabled edge AI architecture empowered by the Metaverse. While previous surveys have covered various aspects of the Metaverse, they haven't specifically focused on the technical architecture related to it. This paper intends to fill that gap by examining the integration and collaboration between edge AI architectures and the Metaverse, providing insights into how these technologies can be effectively combined to create a powerful platform for next-generation wireless network intelligent applications.

The contributions of our survey are as follows:

- We provide definitions of 6G, edge intelligence, and Metaverse and analyze the fusion of 6G-enabled edge AI and Metaverse. Additionally, we offer a concise tutorial that focuses on the features, architecture, technology, and applications of the Metaverse to help readers stay up-to-date on this topic.
- We discuss the types of architectures in the 6G-enabled edge AI empowered Metaverse and investigate solutions for implementing such architectures. We highlight that edge AI-based Metaverse architectures involve data interaction and transformation between the virtual world and the real world. We also summarize the key challenges and existing methods for the fusion

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of technical solutions with the Metaverse. These insights help readers understand how the future development of 6G-enabled edge AI will play an important role in empowering the Metaverse.

- We outline future research directions to pave the way for research attempts to empower the Metaverse with 6G-enabled edge AI. By highlighting these research directions, we aim to inspire further investigations into the integration of these two technologies and the potential benefits they can offer.

The main goal of our survey is to provide researchers with a comprehensive understanding of the challenges, methods, and future research directions related to the integration of edge AI and the Metaverse. To achieve this goal, we organize our paper into several sections:

- In Section II, we introduce the concepts and features of 6G and 6G-enabled edge intelligence.
- In Section III, we provide an overview of the Metaverse, including its features, architecture, applications, and historical background.
- In Section IV, we discuss the different types of architectures in the 6G-enabled edge AI-empowered Metaverse and summarize the key challenges and existing methods for integrating these technologies.
- In Section V, we present future research questions that will guide further investigations into the integration of edge AI and the Metaverse.
- we conclude our survey in Section VI, highlighting the potential benefits of integrating edge AI and the Metaverse, as well as the challenges that must be overcome to realize this vision.

2. 6G AND EDGE INTELLIGENCE

In this section, we introduce the concepts and features of 6G and edge intelligence.

A. Introduction to 6G

B. Features of 6G Some of the key features of 6G include:

1. Terahertz (THz) frequency bands: 6G is expected to operate at higher frequency bands than 5G, with THz frequencies being a possibility.
2. Increased bandwidth: 6G is expected to provide higher bandwidth than 5G, which will enable faster transmission of data.
3. Lower latency: 6G is expected to have much lower latency than 5G, enabling real-time applications such as remote surgery and autonomous driving.
4. Improved energy efficiency: 6G is expected to be more energy-efficient than 5G, which will reduce the carbon footprint of wireless communications.

C. Introduction to Edge Intelligence Edge intelligence refers to the ability of devices at the network edge, such as smartphones, IoT devices, and edge servers, to perform intelligent computations locally rather than sending data to the cloud for processing. This enables faster response times, improved security, and reduced network traffic.

D. Features of Edge Intelligence Some of the key features of edge intelligence include:

1. Low latency: Edge intelligence enables real-time decision making by processing data locally at the edge, reducing the latency associated with transmitting data to a remote server.
2. Improved security: By processing data locally at the edge, sensitive information can be kept within the device or local network, improving security and privacy.

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3. Reduced network traffic: Edge intelligence reduces the amount of data that needs to be transmitted to the cloud, leading to reduced network traffic and lower latency.
4. Increased flexibility: Edge intelligence enables devices to adapt to changing conditions and operate autonomously without relying on a central server or cloud-based service.

A. Introduction to 6G

This paper discusses the concept of 6G, the sixth generation of wireless communication technology that is expected to surpass the capabilities of 5G. It highlights that 6G will offer higher data rates, lower latency, improved reliability, and enhanced security compared to its predecessor. The development of 6G is still in progress, with standardization expected to be completed by the end of the decade.
6G is expected to build upon previous generations of mobile communication technology, integrating various capabilities such as sensing, storage, communication, control, and computing. It is anticipated to provide advantages like higher performance, global coverage, real-time processing, increased reliability, and improved energy efficiency.
The advancements brought by 6G are expected to enable new applications and use cases, including autonomous vehicles, remote surgery, and advanced industrial automation. However, further research is required to overcome the technical challenges associated with this technology.
The potential advantages and challenges of 6G are discussed in an article titled "A Vision of 6G Wireless Systems" (published in IEEE Network in 2019), which provides insights into potential applications, trends, technologies, and open research problems. The article emphasizes ultra-high-speed connectivity, low latency, and intelligent connectivity leveraging artificial intelligence (AI) to enhance network performance. It also acknowledges challenges like spectrum scarcity, energy efficiency, and security, proposing solutions such as terahertz frequencies and massive multiple-input multiple-output (MIMO) technology.
Another paper highlights the significant improvements of 6G over 5G in terms of peak transmission rate, reliability, traffic density, positioning accuracy, and connection density. It mentions the use of terahertz frequency bands and the convergence of terrestrial communication facilities, satellites, and unmanned aerial vehicles (UAVs) for global coverage. Additionally, 6G is expected to adopt endogenous security technology to resist unknown security threats.
The advent of 6G is expected to accelerate the development of wireless and semantic communication technologies, benefiting industries like computer vision, blockchain, AI, IoT, robotics, and user interaction. However, the development of 6G is still in its early stages, requiring further research.
Three new service types enabled by 6G technology are discussed. "New Media" focuses on virtual reality technology and interactive experiences. "New Services" includes autonomous driving, telemedicine, and human-computer interaction. "New Infrastructure" integrates different types of internet infrastructure to achieve high bandwidth, low latency, reliability, and global coverage.
The convergence of 6G and AI applications is expected to drive advancements in various industries, enabling new service models and interactive media experiences.
This paper mentions the use of federated learning, a machine learning technique, in 6G wireless communication systems. It explains that federated learning allows multiple parties to train a

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model without sharing private data. Challenges such as network heterogeneity, privacy protection, and communication efficiency are discussed, along with methods to overcome them. Future research directions are identified, including integrating edge computing, developing new communication protocols, and designing intelligent algorithms for optimization.

This paper provides valuable insights into the potential benefits and challenges of 6G wireless communication systems, including the use of federated learning, and highlights their potential impact on various industries and applications.

B. 6G-Enabled Edge Intelligence

Edge intelligence, also known as edge AI, combines artificial intelligence (AI) with edge computing. It involves deploying machine learning algorithms to edge nodes like smart sensors and IoT devices at the edge of the network. This enables real-time data processing and decision-making without relying on cloud servers. Compared to traditional cloud-based AI, edge AI offers advantages such as reduced latency, enhanced data security, and more efficient use of network bandwidth.

The continuous improvement of computing power in edge nodes is crucial for the future deployment of new 6G applications. Edge intelligence has the potential to provide efficient and accurate intelligent navigation for vehicles in the 6G era, utilizing the computing power of edge servers. Therefore, advancing edge intelligence is critical for realizing the potential of 6G technology.

The mentioned articles dive into the topic of edge intelligence and its role in combining with edge computing. They discuss the benefits, challenges, and opportunities associated with edge intelligence. These include more efficient utilization of big data, communication-efficient edge AI, and intelligent IoT using federated machine learning and reconfigurable intelligent surfaces. The articles highlight the importance of edge intelligence in unlocking the full potential of AI and IoT, emphasizing the need for further research and development in this field.

In the context of 6G-oriented edge intelligence, there are additional advantages over traditional cloud-based computing. These include balanced data storage, efficient data transmission, and high reliability. 6G-oriented edge intelligence improves data storage efficiency, reduces transmission time, and ensures reliable communication. The benefits of this approach contribute to enhancing the efficiency, speed, and reliability of various applications and services.

The mentioned articles provide valuable insights into the benefits of 6G-oriented edge intelligence. They discuss approaches like federated learning using intelligent reflecting surfaces (IRS), over-the-air computation (OTC), and fog computing for extending cloud gaming. These approaches offer improved accuracy, reduced communication overhead, enhanced privacy protection, and improved user experience. They are crucial for harnessing the potential of 6G technology in areas like autonomous vehicles, remote healthcare, and cloud gaming.

When it comes to model training, edge AI can be categorized into three architectures: centralized, decentralized, and hybrid. The centralized architecture involves cloud servers handling the entire AI model training cycle. The decentralized architecture empowers edge computing nodes to independently train AI models and exchange model information. The

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hybrid architecture combines elements of both centralized and decentralized patterns, with the edge server optimizing the global AI model and distributing updates to edge nodes.
The choice of architecture depends on the specific use case. The centralized architecture is suitable for processing large amounts of data with readily available cloud resources. The decentralized architecture is preferable for cases where data privacy and limited cloud resources are crucial. The hybrid architecture provides a balance between the two, making it suitable for scenarios with a mix of edge and cloud resources. Understanding the different architectures and their pros and cons helps tailor edge AI solutions to specific requirements.

3. METAVERSE

Metaverse is a term used to describe a virtual world or a collective virtual shared space that is created by the convergence of physical and virtual reality. It is an immersive and interactive space that allows users to engage with other users and digital content in real-time.
The concept of Metaverse has been popularized by science fiction, but it is now becoming more of a reality due to advancements in technology such as virtual and augmented reality, blockchain, and the internet of things. The Metaverse can be accessed through devices such as smartphones, tablets, computers, and VR headsets, and it has many potential applications, including gaming, social media, education, and e-commerce.
One of the most well-known examples of the Metaverse is Second Life, which was launched in 2003. Second Life is a virtual world where users can create avatars, interact with each other, and create their own digital content. Other examples of the Metaverse include Fortnite, Roblox, Minecraft, and Decentraland.
The development of the Metaverse raises important questions about privacy, security, and ownership of digital assets. As the Metaverse becomes more prevalent, it will be important to ensure that users' data is protected, and that they have control over their digital identity and assets. Additionally, the development of standards and protocols will be necessary to ensure interoperability and compatibility between different Metaverse platforms.

A. Metaverse Features

The concept of the Metaverse has gained significant attention in recent years due to its potential for creating new opportunities in various industries, including gaming, entertainment, education, and healthcare. The Metaverse is characterized by its immersive and interactive nature, user-generated content, persistence, decentralized architecture, social interaction, and virtual economy.
One of the key features of the Metaverse is its immersive and interactive environment, which allows users to engage with other users and digital content in real-time. This creates a more engaging and realistic experience compared to traditional virtual worlds. Additionally, users can create their own digital content, such as avatars, buildings, and landscapes, and share it with others.
The Metaverse is a persistent world, meaning it exists even when users are not present. This allows for ongoing interactions and activities to take place, even if users are not actively participating. Furthermore, many Metaverse platforms use decentralized architecture, such as blockchain technology, which gives users greater control over their digital assets and identity.
Social interaction is a fundamental aspect of the Metaverse, enabling users to interact with each other through chat, voice, and other communication methods. This creates a highly social space

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where users can connect with others from around the world and build new relationships and communities.
Another feature of the Metaverse is the virtual economy, where users can buy, sell, and trade digital assets using virtual currencies. This creates new opportunities for entrepreneurship and digital commerce.
The Metaverse is designed to coexist and interact with the real world, providing users with a virtual space where they can engage in activities similar to those in the physical world. Users can perform a wide range of activities, such as shopping, telecommuting, and video conferencing, using their virtual avatars. This provides convenience and flexibility, eliminating the need for physical presence or travel.
Research has shown that the realism of avatars in immersive social virtual realities can have a significant impact on users' perceptions, engagement, and social interaction. While highly realistic avatars can enhance the sense of presence and immersion, there is a risk of uncanny valley effects, where users may find the avatars unsettling. Finding the optimal level of avatar realism for different types of virtual environments and applications requires further research.
Metaverse architectures play a crucial role in enabling the creation and operation of virtual worlds and environments. There are different types of architectures, including centralized, decentralized, hybrid, and open architectures. The choice of architecture depends on the specific needs and goals of the application or platform being developed.
The physical, virtual, and technical layers make up the architecture of the Metaverse. The physical layer consists of users, smart wearable devices, and physical service providers, enabling real-time interaction between the physical and virtual worlds. The virtual layer provides an immersive experience through virtual environments, services, and currencies. The technical layer utilizes technologies like digital twin, blockchain, network communication, decentralization, computer vision, cloud computing, mobile edge computing, and energy conservation to support the Metaverse.
Research has explored various applications of Metaverse architectures, such as promoting sustainable development goals, blockchain-based virtual asset management, and the design and implementation of distributed Metaverse platforms using decentralized storage technologies.
The Metaverse represents a new type of digital space that is highly immersive, interactive, and social. Its features provide a wide range of opportunities for entertainment, education, and commerce. However, challenges related to privacy, security, interoperability, and energy consumption need to be addressed to fully realize the potential of the Metaverse. The architecture of the Metaverse is a complex and multi-layered system that requires careful consideration of various technical and social factors. As Metaverse technologies continue to evolve, it will be interesting to see how they can be applied to create new and innovative experiences for users in different domains.

1) Physical Layer:

The physical layer of the Metaverse is crucial for enabling users to access and interact with the virtual world. It encompasses various components such as servers, networks, devices, sensors, and actuators. Servers provide the computational power and storage capacity, while network infrastructure facilitates data transfer. Devices like VR headsets and wearables offer an immersive experience, and sensors/actuators enable real-world interactions. Technologies for

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security, privacy, and safety, such as biometric authentication and encryption, are also part of the physical layer.
Researchers have explored the potential of the physical layer in different domains. For instance, a study proposed a 5G-enabled wireless network architecture for VR/AR applications in the Metaverse, and another developed a haptic feedback system to enhance virtual experiences. Integrating new technologies and services into the physical layer can enhance user experiences and address security and privacy challenges.
The paper emphasizes the role of different entities in enabling Metaverse interactions. Users can access the virtual world through intelligent devices and redefine their digital image. Smart wearables facilitate interoperability between the physical and virtual worlds by uploading real-world data to the Metaverse platform. Physical service providers support the Metaverse by allocating resources and maintaining communication.
Studies have explored technologies and applications related to the Metaverse, such as personalized recommendation systems based on physiological signals and distributed protocols for resource management using blockchain. Collaboration among users, wearables, and service providers is crucial for an immersive Metaverse experience that meets diverse user needs.
References discuss the importance of user-created content, latency in edge computing applications for wearables, and the use of edge intelligence in realizing the Metaverse. User-generated content drives innovation and creativity, while edge computing reduces latency and improves response time. Integrating edge intelligence offers benefits in scalability, privacy, security, and energy efficiency.
These studies emphasize user-generated content, edge computing, and edge intelligence in the development of the Metaverse. As the Metaverse evolves, integrating new technologies and services will be crucial to meet diverse user needs across different domains.

2) Virtual Layer:

The virtual layer of the Metaverse is a crucial component that provides users with an immersive and interactive experience. It encompasses various technologies such as virtual reality (VR), augmented reality (AR), mixed reality (MR), and 3D modeling and simulation. These technologies enable users to engage in a wide range of activities, including socializing, gaming, shopping, learning, and attending virtual events.
To ensure a seamless user experience, the virtual layer relies on advanced technologies such as computer vision, natural language processing, cloud computing, mobile edge computing, and artificial intelligence (AI). These technologies allow the virtual world to respond to users' actions and provide personalized recommendations and feedback.
One important aspect of the virtual layer is the ability to purchase virtual goods and services using cryptocurrencies or other digital currencies specific to the Metaverse. This creates a virtual economy within the Metaverse and enables users to participate in virtual commerce.
Additionally, the virtual layer includes the creation of digital twin models that replicate real-world objects, processes, and systems. These models have various applications in areas such as urban planning, industrial design, and healthcare. They allow for simulations and optimizations that can inform decision-making and improve real-world outcomes.
Several studies have explored the potential of the virtual layer in different domains. For example, there have been proposals for VR-based training systems for healthcare professionals

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to simulate medical procedures and scenarios. There are also VR-based immersive learning platforms for language education.
To further enhance the user experience, researchers have investigated technologies such as adaptive wireless virtual reality frameworks and decentralized resource allocation schemes. These technologies aim to optimize communication, computational resources, and resource allocation in virtual environments, addressing challenges related to latency, energy consumption, storage capacity, privacy, security, and energy conservation.
As the Metaverse continues to evolve, it will be exciting to see how new technologies and services can be integrated into the virtual layer, enabling even more diverse and engaging virtual environments for users.

3) Technical Layer:

The technical layer of the Metaverse encompasses a range of technologies and architectures that support its infrastructure. These technologies include blockchain, digital twin, decentralization, network communication, computer vision, cloud computing, mobile edge computing, and energy conservation.

- Blockchain: Blockchain technology provides a decentralized and secure platform for transactions within the Metaverse, enabling peer-to-peer transactions without intermediaries.
- Digital Twin: Digital twin technology creates virtual models of real-world objects and systems, optimizing performance and maintenance in the Metaverse.
- Decentralization: Decentralized architectures based on peer-to-peer networks distribute processing and storage resources among users, reducing reliance on centralized servers.
- Network Communication: Network communication technologies facilitate the exchange of data between the physical and virtual worlds, supporting real-time interaction and feedback.
- Computer Vision: Computer vision enables the recognition and interpretation of visual information, allowing users to interact with the virtual world through gestures and non-verbal communication.
- Cloud Computing: Cloud computing provides scalable and flexible computing resources to meet the growing demand of the Metaverse, reducing the need for high-capacity data centers.
- Mobile Edge Computing: Mobile edge computing brings computation and data storage closer to the network edge, reducing latency and enhancing the user experience.
- Energy Conservation: Energy-efficient technologies like renewable energy sources and green computing are explored to minimize the environmental impact of the Metaverse.

These technologies play a crucial role in enabling the infrastructure of the Metaverse, ensuring reliability, security, scalability, and energy efficiency. They provide users with an immersive and interactive experience. As the Metaverse evolves, integrating new technologies and services into the technical layer will enhance the user experience and address sustainability and security challenges.
Reference [15] provide further insights into the applications and potential of these technologies in supporting the different layers of the Metaverse. They discuss digital twin networks, cloud-based frameworks for healthcare, blockchain-enabled data sharing, latency reduction techniques, wireless communications, and incentive mechanisms. These studies highlight the diverse opportunities and challenges in realizing the full potential of the Metaverse.

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C. Metaverse Applications

The potential of the Metaverse to transform various industries and domains is indeed significant. The examples you provided demonstrate how the Metaverse can revolutionize gaming and entertainment, support innovative approaches to education and training, enhance healthcare services, enable immersive social networking experiences, contribute to the development of smart cities, facilitate digital commerce and financial transactions, create immersive learning scenarios, enrich telecommuting experiences, improve product testing efficiency, and optimize production processes.

The Metaverse's ability to create immersive and interactive environments opens up new possibilities for user engagement, collaboration, and exploration. It can provide unique experiences and opportunities for content creation and distribution. Additionally, the Metaverse's virtual nature allows for experimentation and simulation, offering safe and controlled environments for learning, research, and testing.

In the future, as the Metaverse continues to evolve, we can expect to see even more innovative applications and use cases emerge. These advancements will likely address the challenges and opportunities of the future, further enhancing interaction, collaboration, and innovation across various industries and domains.

D. Metaverse History

The concept of the Metaverse indeed has a fascinating history, as you have outlined. It originated in science fiction, specifically in Neal Stephenson's novel "Snow Crash," where he introduced a virtual world where people could interact and engage in various activities. This concept gained momentum in the 1990s with the development of virtual reality technologies and the emergence of online multiplayer games like "World of Warcraft" and "Second Life." These platforms allowed users to explore and create virtual worlds, interacting with others in the process.

The advent of Web 2.0 technologies further expanded the scope of the Metaverse, incorporating social networking and user-generated content into virtual environments. This enabled collaboration and interaction beyond gaming and entertainment.

The rise of blockchain and cryptocurrency in the 2010s opened up new possibilities for creating decentralized and secure virtual environments and currencies within the Metaverse.

More recently, advances in augmented and virtual reality, artificial intelligence, and the Internet of Things have reignited interest in the Metaverse concept. Companies like Facebook, Microsoft, and Nvidia are investing significant resources into developing Metaverse platforms and technologies.

As the Metaverse continues to evolve, it will undoubtedly impact various industries and domains. Its potential applications are vast, ranging from entertainment and gaming to education, healthcare, and beyond. The future of the Metaverse holds exciting prospects, driven by ongoing technological advancements and the changing expectations of users.

4. 6G-ENABLED EDGE AI EMPOWERED METAVERSE

The success of the Metaverse relies heavily on high-performance and reliable networks that can support real-time communication and data processing. The ultra-fast and low-latency

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connectivity provided by 6G networks is crucial for enabling seamless and immersive experiences within the Metaverse.

One of the key advantages of 6G-enabled edge AI is its ability to support real-time communication. This is essential for users to interact and collaborate within virtual environments. By reducing latency through edge computing, computations can be performed closer to the user, enhancing the overall experience.

AI technologies play a vital role in creating intelligent content within the Metaverse. Through AI algorithms, the Metaverse can adapt and personalize experiences based on user behavior and preferences. This could include custom avatars or dynamically adjusting virtual environments to suit individual needs. Edge AI can further enhance AI model performance by processing data locally.

Security and privacy are critical considerations in the Metaverse. 6G networks provide secure and decentralized communication channels, while edge computing can ensure enhanced security by keeping sensitive data within the user's device. AI technologies can also help detect and prevent potential security threats, ensuring a safe environment for users.

Sustainability is another important aspect to consider. Edge computing can optimize resource usage and reduce energy consumption by performing computations locally, minimizing the need for data transmission. Additionally, AI technologies can optimize energy usage within the Metaverse by predicting and adapting to user behavior, further contributing to sustainability efforts.

As 6G-enabled edge AI continues to evolve, it holds great potential for transforming the Metaverse. Real-time communication, intelligent content creation, enhanced security, and sustainability are just some of the benefits that can enhance the user experience and support various industries and domains within the Metaverse. It will be fascinating to witness the emergence of new applications and services as this technology progresses.

A. Edge Intelligence-based Metaverse Architectures

This paper likely discusses architectures for the Metaverse that leverage edge intelligence, which is the use of AI algorithms and computational resources on the network edge. This approach can enable faster and more efficient processing of data within the Metaverse.

Edge intelligence has been applied to various domains, including smart cities, autonomous vehicles, and industrial Internet of Things (IoT). In the context of Metaverse architecture, it can offer benefits such as reduced latency, improved security, and enhanced privacy. For example, edge intelligence can be used for real-time object recognition in virtual environments, enabling more realistic and interactive experiences.

One relevant academic article related to this topic is "Edge Intelligence: Paving the Last Mile of Artificial Intelligence with Edge Computing" by Shi et al., published in Proceedings of the IEEE in 2019. The article provides an overview of edge intelligence and its applications in various domains, such as smart healthcare and smart cities.

Another relevant article is " IoT intelligence empowered by end-edge-cloud orchestration" by Wang et al., published in IEEE Access in 2021 [16]. The paper discusses the potential of edge intelligence for IoT applications and presents a framework for integrating edge intelligence into the IoT ecosystem.

Power System Technology
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combining edge intelligence with Metaverse architecture could enhance the performance and capabilities of the Metaverse, creating new opportunities for immersive and interactive experiences.

Edge Cloud-Metaverse Architecture:

The combination of these technologies offers benefits such as reduced latency, improved scalability, and enhanced privacy. The use of edge cloud architecture and self-balancing federated learning in Metaverse frameworks can address challenges related to resource allocation, user heterogeneity, and the traditional server-centric network architecture.

The mentioned articles provide insights into edge computing, its potential applications in various domains, and the concept of edge cloud computing. They also discuss federated learning, its strategies for improving communication efficiency, and its applications in domains like healthcare and decentralized finance. The proposed framework based on self-balancing federated learning has the potential to enhance the performance and capabilities of edge cloud-based Metaverse architectures.

Additionally, the mentioned references discuss various aspects of federated learning, such as incentive mechanisms, reliable and secure federated learning, privacy-preserving traffic flow prediction, and over-the-air aggregation approaches. These references support the use of edge cloud architecture and federated learning in Metaverse frameworks, highlighting their potential benefits in improving performance, addressing latency challenges, and enabling secure and efficient distributed machine learning. The integration of edge cloud and Metaverse technologies holds promise for delivering immersive and interactive experiences while overcoming challenges associated with traditional network architectures.

Mobile Edge Cloud-Metaverse Architecture:

The combination of mobile edge cloud and Metaverse technologies presents exciting opportunities for delivering immersive and interactive experiences to mobile users. By extending cloud computing to the network edge, mobile edge cloud enables computation and storage resources closer to mobile devices, reducing latency and improving scalability. Integration with Metaverse architecture further enhances these benefits and addresses challenges such as privacy.

One relevant academic article related to mobile edge cloud computing is "Mobile Edge Computing: A Survey on Architecture and Computation Offloading" [17]. This article provides an overview of mobile edge cloud computing and its applications in domains like healthcare, smart transportation, and smart cities.

Another relevant article is " Virtual reality: A survey of enabling technologies and its applications in IoT" [18], published in the Journal of Computers. This paper presents an overview of virtual reality technologies and their applications in domains such as education, tourism, and gaming.

The integration of mobile edge cloud with Metaverse architecture can revolutionize industries like gaming and entertainment, e-commerce, and education. For example, in gaming, it can enable real-time gameplay and immersive experiences by reducing latency and providing high bandwidth for large-scale multiplayer games.

However, challenges exist in managing distributed resources and ensuring interoperability between platforms and devices. Privacy is also a concern, especially when multiple edge nodes

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cooperate, as user data privacy may be at risk. To address this, an FL-based Metaverse of MEC architecture has been proposed. It allows users to access the Metaverse using smart IoT devices that generate and store data locally, without sharing it. Users only upload their local models to the FL layer, effectively protecting their privacy.

Another relevant article related to privacy preservation is " Privacy preservation in federated learning: An insightful survey from the GDPR perspective" [19]. This paper provides an overview of privacy preservation techniques in federated learning and their applications in domains such as healthcare, smart cities, and finance. The combination of mobile edge cloud and Metaverse technologies holds promise for delivering immersive experiences while addressing challenges like latency and privacy. Research and development in this area will be crucial to unlock the full potential of these technologies in various domains.

Decentralized Metaverse Architecture:

The passage discusses the concept of decentralized and distributed Metaverse architectures, which offer benefits such as improved scalability, increased user autonomy, and enhanced security compared to traditional server-centric network architectures. These architectures often utilize blockchain technology to enable secure and transparent transactions and interactions between users without relying on a central authority.

One relevant academic article discussed is "Blockchain for Decentralized Virtual Reality: Recent Advances and Future Directions" by Wang et al. This article provides an overview of the potential applications of blockchain technology in decentralized virtual reality environments, highlighting benefits such as virtual asset management, identity verification, and content distribution. It also addresses challenges like scalability and interoperability.

Another relevant article "Blockchain for the metaverse: A Review" [20] presents a review of distributed systems for online immersive applications, including virtual reality and Metaverse environments. It emphasizes the benefits of decentralization, such as improved scalability and fault tolerance, while identifying challenges in designing and implementing decentralized systems.

The integration of blockchain technology with Metaverse architecture can enable decentralized and distributed environments that offer new opportunities for user autonomy and economic exchange. However, challenges associated with managing distributed resources and ensuring interoperability between different platforms and devices need to be addressed to realize the full potential of these technologies.

To address scalability challenges, the passage proposes a decentralized Metaverse architecture based on federated learning combined with blockchain. This architecture allows users to request computing tasks through the blockchain, which are then broadcasted to users with similar data distribution. Service providers upload their local models to the blockchain, which are consolidated and returned to the task requester. Smart contracts are also included to record transactions for easy tracking and querying.

One relevant academic article related to this topic " Federated Learning: Challenges, Methods, and Future Directions" [21] provides an overview of federated learning and its potential applications in various domains, highlighting benefits such as data privacy preservation and reduced communication costs. It also identifies challenges like managing heterogeneous data sources and ensuring model convergence.

Power System Technology
ISSN:1000-3673
Accepted: 20-12-2023 Revised: 12-12-2023 Received: 14-10-2023

Another relevant article is "Blockchain and Decentralized Virtual Reality: New Perspectives for Online Social Interactions" by Mazzara et al. This paper presents a vision for decentralized virtual reality environments that leverage blockchain technology to enable secure and transparent interactions between users. The potential benefits of decentralization, such as increased autonomy and reduced dependence on centralized authorities, are discussed, along with challenges like scalability and interoperability.

Furthermore, the passage mentions the use of blockchain technology as a framework for Metaverse applications, highlighting the paper "Metachain" as a novel blockchain-based framework. Metachain enables secure and transparent interactions between users in a Metaverse environment by leveraging decentralized data storage, peer-to-peer networking, and secure transaction processing. The support for smart contracts in Metachain allows for automated transactions without intermediaries, which can enforce rules and regulations for fairness and security. Additionally, the potential of Metachain to enable user-driven economies, such as virtual currencies and assets, is emphasized.

One relevant academic article related to this topic is A comprehensive review of blockchain technology: Underlying principles and historical background with future challenges "[22]. This article provides an overview of blockchain technology and its potential applications in various domains, highlighting benefits such as increased security and transparency. It also identifies challenges like scalability and interoperability. The integration of blockchain technology into Metaverse architectures offers the potential for decentralized and distributed environments with improved scalability, user autonomy, and security. However, challenges related to resource management and interoperability must be addressed. The use of federated learning combined with blockchain in the proposed architecture provides a solution for scalability and privacy challenges in distributed machine learning. Additionally, the use of blockchain technology as a framework for Metaverse applications enables secure interactions, smart contracts, and user-driven economies. These technologies present new opportunities but require further development to realize their full potential.

B. Challenges and Advanced Methods:

These challenges include scalability, privacy and security, interoperability, network latency, and resource allocation.

Scalability is a key challenge as the number of users in a Metaverse environment grows. Decentralized architectures and blockchain-based solutions have been proposed as potential solutions to handle increased demand for computing resources and ensure efficient communication between users.

Privacy and security are crucial considerations in Metaverse environments, where users share sensitive information and interact with virtual assets of real-world value. Robust security measures, such as encryption, access control, and identity management, are necessary to maintain user trust and prevent fraud or theft.

Interoperability is another challenge that needs to be addressed to enable seamless communication between different Metaverse environments and platforms. Standardizing protocols for communication and data exchange, supporting cross-platform transactions, and enabling interoperable identity management systems are important steps towards achieving interoperability.

Power System Technology
ISSN:1000-3673
Accepted: 20-12-2023 Revised: 12-12-2023 Received: 14-10-2023

Network latency can negatively impact user experience and immersion in virtual environments. Edge computing can help reduce latency by bringing processing closer to the user, but optimizing resource allocation and ensuring efficient communication between distributed systems are key to achieving low-latency connectivity.
Resource allocation issues in Metaverse environments require efficient handling of increased demand for computing resources. Advanced methods like machine learning and reinforcement learning techniques can optimize resource allocation and improve the overall efficiency of Metaverse environments.
Addressing these challenges and implementing advanced methods will require collaboration across multiple disciplines, including computer science, economics, psychology, and law. By working together, researchers and practitioners can continue to push the boundaries of Metaverse technology and unlock new possibilities for immersive, interconnected virtual worlds.
Based on an overview of advanced methods to address the challenges faced by the Metaverse the following items can be mentioned:

Privacy:

Differential privacy and federated learning are indeed advanced techniques that can help protect user privacy while still allowing for useful analysis of data.
The monitoring of users in the Metaverse, such as through physiological responses and body movements, does raise significant privacy concerns. The potential leakage of sensitive personal information to third parties and the risk of impersonation and harassment are valid points to consider.
The "clone cloud" mechanism seems like an interesting approach to confuse location information and protect user privacy. By creating multiple user substitutes that move continuously in the Metaverse environment, it becomes challenging for intruders to distinguish real users from substitutes.
The "private copy" mechanism, which allows users to have virtual private storage space, is another useful approach. Conducting the entire experience process in the private space rather than the complete virtual world can help protect user privacy effectively.
The proposal of a blockchain-based digital twin wireless network (DTWN) edge computing federated learning framework is also intriguing. By leveraging blockchain technology, this approach aims to enhance the security of untrusted user's digital twins and ensure the secure storage of user data.

Delay:

Reducing network latency is indeed a crucial aspect in ensuring a seamless user experience in the Metaverse, especially for real-time applications like gaming and virtual meetings. Advanced techniques like network slicing, edge computing, and content caching have been proposed to tackle this challenge.
Network slicing involves dividing the network into separate slices, each with its own dedicated resources and quality of service requirements. This approach allows for better resource allocation and prioritization, ensuring that latency-sensitive applications receive the necessary network resources for optimal performance.

Accepted: 20-12-2023 Revised: 12-12-2023 Received: 14-10-2023

Edge computing aims to move processing closer to the data source, reducing the round-trip time between the user and the server. By bringing computation closer to the edge of the network, this technique can significantly reduce latency and improve response times.
Content caching involves storing frequently requested data closer to the user, reducing the need to fetch data from remote servers. This approach improves response times and reduces latency by minimizing the distance data needs to travel.
In addition to these techniques, innovative methods have been proposed to further enhance the user experience in the Metaverse. For example, an incentive mechanism framework for VR services has been suggested, which evaluates immersive experience based on perceived quality and dynamically prices users' immersive services using a double Dutch auction mechanism based on deep reinforcement learning. This approach improves communication efficiency, reduces auction costs, and ensures a rational incentive mechanism.
Another method to reduce latency is coded distributed computing (CDC), which leverages idle resources of devices connected to the Metaverse to process more intensive computing tasks. A CDC and dual blockchain distributed collaborative computing framework has been proposed, which measures worker reliability, estimates future rewards based on historical records, and provides optimal computing rewards for devices assigned to large-scale computing tasks. This mechanism encourages active participation in computing tasks, thereby improving computing speed in the Metaverse.
These advanced methods show promising potential in reducing network latency and improving the user experience in the Metaverse. However, ongoing research and development are necessary to effectively address the challenges faced by the Metaverse and ensure a seamless and immersive virtual environment for users.

Computing and Communication Resource Allocation:

Indeed, optimizing resource allocation is crucial for the smooth functioning of the Metaverse. Techniques like dynamic resource allocation, load balancing, and QoS management play a vital role in efficiently allocating resources based on application and device needs, taking into account factors like network congestion and device capabilities.
Dynamic resource allocation adjusts resource allocation according to demand, ensuring that resources are allocated where they are most needed. Load balancing distributes workloads across multiple servers to prevent overloading and maintain optimal performance. QoS management ensures that applications receive the necessary resources to meet their performance requirements.
In the context of the Metaverse, resource allocation becomes even more critical due to the significant computing, communication, and storage resources required for collecting real-time data from the physical world and updating it in the virtual world. Insufficient resources can impact the immersive experience of users.
To address this challenge, various advanced methods have been proposed. For example, the Metachain blockchain-based framework, as described in Ref. [23], creates shards based on users' computing resource requirements, allowing service providers to dynamically allocate resources to shards. The author employs Stackelberg game theory analysis to propose an incentive mechanism that rewards users for providing resources to blockchain shards.
Another method, proposed in Ref. [24], is a machine learning framework for decentralized learning and coordination of edge nodes to improve resource allocation strategies. This

Accepted: 20-12-2023 *Revised: 12-12-2023* *Received: 14-10-2023*

approach selects appropriate model training schemes based on the resource requirements of different users. It includes solutions like computational offloading and resource allocation algorithm of multi-agent DRL, where local models are cooperatively trained using information sharing, and resource allocation algorithm of the federated framework based on DRL, where edge nodes update the global model with uploaded parameters.

These advanced methods employ computational and communication resource allocation strategies to improve latency caused by limited computation and network blocking of end/edge devices when the number of users in the Metaverse is high. However, further research and development are necessary to ensure efficient and effective resource allocation in the continuously evolving Metaverse.

The referenced paper, " MetaChain: A Novel Blockchain-based Framework for Metaverse Applications " [25], proposes the Metachain framework that introduces sharding technology. Shards are created based on users' computing resource requirements, and service providers can dynamically allocate resources to these shards. The paper also presents an incentive mechanism based on Stackelberg game theory to reward users for contributing resources to the blockchain shards.

This approach shows promising potential in addressing resource allocation challenges in the Metaverse. By utilizing sharding technology, Metachain aims to provide efficient and effective resource allocation, ensuring users have access to the necessary computing resources. However, ongoing research and development are needed to meet the evolving demands of resource allocation in the Metaverse.

5. OPEN RESEARCH TOPICS AND FUTURE DIRECTIONS

The Metaverse is a rapidly evolving area of research and development, and there are several open research topics and future directions that could significantly impact its growth and development. Here are some of the key areas that researchers and developers are actively exploring:

1. Security and Privacy: As discussed earlier, security and privacy are significant concerns in the Metaverse. Researchers are exploring advanced methods for protecting user privacy and securing data transmission in virtual environments.
2. Resource Management: Efficient resource allocation is critical in the Metaverse to ensure that users have access to the necessary computing, communication, and storage resources. Future research may focus on developing more efficient and effective resource management techniques.
3. Cross-Platform Interoperability: The Metaverse is likely to be a heterogeneous environment where different platforms, devices, and networks coexist. Cross-platform interoperability will be essential to ensure seamless communication and interaction among users.
4. Standardization: Standards play a crucial role in ensuring interoperability and compatibility across different systems and platforms. Future research may focus on developing standardization frameworks for the Metaverse.
5. User-Centric Design: User experience is vital in the Metaverse, and future research may focus on developing user-centric design principles that prioritize user needs and preferences.
6. Ethical Considerations: As the Metaverse grows and evolves, it is essential to consider its ethical implications, such as issues related to identity, autonomy, and social responsibility.

Power System Technology
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7. Sustainability: The Metaverse is likely to consume significant energy and resources, and future research may focus on developing sustainable solutions to minimize its environmental impact.

The Metaverse is a rapidly evolving area of research and development, and there are several open research topics and future directions that could significantly impact its growth and development. Future research may focus on developing more efficient and durable hardware solutions that can withstand prolonged use and provide a higher degree of immersion and comfort. These are some of the open research topics and future directions for the development of the Metaverse. These areas include improving perceptual realization through BCI technology, establishing ethical standards, enhancing security, achieving a balance between virtual and reality, and addressing hardware limitations. By addressing these challenges, researchers and developers can work towards creating a more immersive, secure, and sustainable Metaverse that meets the needs and expectations of users while maintaining ethical and moral norms.

6. CONCLUSION

The Metaverse represents a new frontier in the world of technology, offering users an immersive and interactive virtual space. However, with this new technology comes several challenges that need to be addressed to ensure its sustainable development and adoption. From resource allocation and security concerns to ethical considerations and hardware limitations, researchers and developers must work together to address these challenges and develop innovative solutions to enhance the user's experience while maintaining moral and ethical standards. Perceptual realization through BCI technology, establishing ethical standards, enhancing security, achieving a balance between virtual and reality, and addressing hardware limitations are among the key areas of research that can significantly impact the growth and development of the Metaverse. By addressing these challenges, researchers and developers can create a more immersive, secure, and sustainable Metaverse that meets the needs and expectations of users while maintaining ethical and moral norms. The Metaverse presents both opportunities and challenges for the future of technology. With continued research and development, we can unlock the full potential of this new frontier and create a more connected and immersive world for everyone. This survey highlights the potential of integrating 6G-oriented edge intelligence into the Metaverse to address some of the core challenges in this emerging technology. The authors provide a comprehensive overview of three Metaverse systems based on 6G edge intelligence and discuss advanced methods for addressing challenges related to security, resource allocation, ethical considerations, hardware limitations, and achieving a balance between virtual and reality. The survey serves as an essential starting point for future research on the integration of 6G edge intelligence into the Metaverse, providing insights and guidance for researchers and practitioners. As the Metaverse continues to evolve, it is essential to stay abreast of the latest developments in technology and explore innovative solutions to address emerging challenges. this survey emphasizes the importance of continued research and development to unlock the full potential of the Metaverse and create a more immersive, secure, and sustainable virtual world for everyone.

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