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An Intelligent 6G-Enabled Communication Infrastructure for Secure and Low-Latency Metaverse Applications

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ABSTRACT - The Metaverse is emerging as a next-generation digital ecosystem that integrates immersive virtual environments with real-time communication, artificial intelligence (AI), extended reality (XR), Internet of Things (IoT), blockchain, and cloud-edge computing technologies. However, supporting seamless interaction among millions of concurrent users requires a robust communication infrastructure capable of delivering ultra-low latency, high bandwidth, reliable connectivity, and secure data exchange. This paper presents an intelligent Metaverse communication infrastructure that integrates 6G wireless networks, Multi-access Edge Computing (MEC), Software-Defined Networking (SDN), Network Function Virtualization (NFV), AI-driven resource management, and blockchain-enabled security to optimize communication performance in immersive environments. The proposed architecture dynamically allocates network resources using machine learning-based traffic prediction, deploys edge intelligence for latency-sensitive applications, and employs blockchain for decentralized identity management and secure data transactions. Furthermore, digital twin-assisted network monitoring continuously analyzes communication conditions and enables proactive optimization to improve service reliability and Quality of Experience (QoE). Experimental evaluation demonstrates that the proposed framework significantly reduces communication latency, improves network throughput, enhances resource utilization, and strengthens security compared with conventional cloud-centric communication architectures. The proposed infrastructure provides a scalable, intelligent, and secure communication framework for future Metaverse applications, including virtual collaboration, digital healthcare, industrial automation, online education, and immersive entertainment.

Keywords— Metaverse Communication, 6G Networks, Multi-access Edge Computing (MEC), Artificial Intelligence (AI), Blockchain, Software-Defined Networking (SDN), Network Function Virtualization (NFV), Digital Twin, Extended Reality (XR), Internet of Things (IoT), Quality of Experience (QoE), Intelligent Communication Infrastructure.

I INTRODUCTION

The rapid evolution of the Metaverse is transforming digital interaction by creating immersive virtual environments that seamlessly integrate Extended Reality (XR), Artificial Intelligence (AI), Internet of Things (IoT), blockchain, cloud computing, and digital twin technologies. These virtual ecosystems require communication infrastructures capable of

supporting massive data exchange, ultra-low latency, high reliability, and intelligent resource management. Conventional 5G and cloud-centric communication architectures face limitations in meeting the stringent Quality of Service (QoS) and Quality of Experience (QoE) requirements of real-time Metaverse applications such as virtual collaboration, industrial automation, digital healthcare, smart education, and immersive entertainment. Consequently, sixth-generation (6G) wireless communication has emerged as a promising enabler, offering terahertz communication, integrated sensing, native AI support, network slicing, and ultra-reliable low-latency communication (URLLC) to facilitate large-scale Metaverse deployment [1], [2].

Recent advances demonstrate that integrating edge computing, AI-driven communication, semantic communication, blockchain, and digital twins can significantly improve communication efficiency, security, scalability, and network intelligence in Metaverse environments. Edge AI enables local processing of latency-sensitive workloads, while semantic communication reduces redundant data transmission by conveying contextual information rather than raw bits [1], [6]. Similarly, Software-Defined Networking (SDN) and Network Function Virtualization (NFV) provide dynamic network orchestration, whereas blockchain ensures decentralized authentication and secure digital asset management [7]. Digital twins further enable predictive network monitoring and proactive resource optimization, supporting intelligent and adaptive communication infrastructures [5]. Despite these advancements, challenges such as dynamic resource allocation, communication reliability, interoperability, security, and energy efficiency remain significant obstacles to large-scale Metaverse adoption [3], [10]. Therefore, this paper proposes an Intelligent 6G-Enabled Communication Infrastructure that integrates 6G, Multi-access Edge Computing (MEC), AI, SDN, NFV, blockchain, and digital twin technologies to provide secure, scalable, and low-latency communication for next-generation Metaverse applications.

II SURVEY OF RESEARCH

Aloudat et al. [1] presented a comprehensive survey on the integration of semantic communication, 6G, and edge learning for Metaverse applications, emphasizing intelligent data transmission, reduced communication overhead, and enhanced contextual awareness. Chang et al. [2] investigated 6G-enabled Edge AI, highlighting AI-assisted resource allocation, edge intelligence, and distributed computing as key technologies for reducing latency and improving immersive user experiences. Zawish et al. [3] reviewed the convergence of AI and 6G within the Metaverse, discussing intelligent networking architectures, communication challenges, and future research opportunities. Drampalou et al. [4] analyzed user-centric 6G communication systems, focusing on personalized service delivery, network flexibility, and enhanced Quality of Experience (QoE). Naeem et al. [5] explored Generative AI-driven digital twins, demonstrating their capability for predictive network management, intelligent optimization, and autonomous operation in future 6G-enabled Metaverse systems. Karahan and Kaya [6] examined semantic communication technologies for 6G, emphasizing their potential to improve bandwidth efficiency and reduce transmission latency by exchanging semantic information instead of conventional data packets. Wang and Zhao [7] investigated the convergence of mobile edge computing, blockchain, AI, and 6G, proposing integrated communication frameworks for secure and intelligent Metaverse services.

Recent studies have further expanded the application of intelligent 6G communication across various Metaverse domains. Alatawi [8] proposed MetaSurg-6G, demonstrating the feasibility of ultra-low-latency terahertz communication for remote surgical applications in immersive healthcare environments. Shah et al. [9] introduced collaborative intelligence mechanisms to optimize XR service delivery over 6G consumer networks through distributed AI and edge orchestration. Bashabsheh and Alzubi [10] surveyed AI-enabled 6G wireless networks, identifying AI-based resource optimization, intelligent network slicing, and security enhancement as major research directions. Chelliah and Sheng [11] discussed the communication requirements of next-generation Metaverse systems and highlighted 6G as the foundation for scalable immersive services. Bibi and Kavitha [12] analyzed the impact of virtual and augmented reality with 6G communication, identifying challenges related to bandwidth, latency, and interoperability. Kaleem et al. [13] investigated the convergence of the Metaverse, edge intelligence, and 6G to improve distributed computing efficiency and immersive experiences. Taherdoost [14] compared 5G and 6G technologies, concluding that 6G offers substantial improvements in latency, reliability, and intelligent networking for Metaverse connectivity. Hazra et al. [15] emphasized the role of ultra-reliable low-latency communication (URLLC) in Industry 5.0 applications, highlighting the importance

of intelligent communication architectures for mission-critical services. Although these studies significantly advance Metaverse communication technologies, they primarily address individual components such as edge AI, semantic communication, blockchain, or digital twins. A unified framework that simultaneously integrates 6G, MEC, AI, SDN, NFV, blockchain, and digital twin technologies for secure, scalable, and intelligent Metaverse communication remains insufficiently explored. This research addresses this gap by proposing an integrated communication infrastructure capable of supporting next-generation immersive applications with enhanced security, reliability, and operational efficiency.

III PROPOSED SYSTEM

The proposed system introduces an Intelligent 6G-Enabled Communication Infrastructure (I6G-MCI) for secure and low-latency Metaverse applications by integrating 6G wireless communication, Multi-access Edge Computing (MEC), Artificial Intelligence (AI), Software-Defined Networking (SDN), Network Function Virtualization (NFV), blockchain, and digital twin technology into a unified architecture. Initially, user devices such as extended reality (XR) headsets, haptic interfaces, IoT sensors, and wearable devices generate multimodal data that are transmitted through ultra-reliable and low-latency 6G communication links. MEC servers positioned at the network edge perform local data processing, immersive content rendering, and intelligent caching to minimize transmission delay and reduce the computational burden on centralized cloud servers. An AI-based resource orchestration engine continuously analyzes network traffic, user mobility, application priorities, and bandwidth utilization using deep learning models to dynamically allocate communication resources, optimize routing paths, and maintain Quality of Service (QoS) and Quality of Experience (QoE) under varying network conditions. Simultaneously, the SDN controller provides centralized network management, while NFV dynamically instantiates virtual network functions to improve scalability and communication flexibility.

To enhance security and operational reliability, the proposed framework incorporates a blockchain-enabled decentralized authentication mechanism that securely manages user identities, digital asset ownership, and communication transactions without relying on centralized authorities. A digital twin of the communication infrastructure continuously monitors network performance, predicts congestion, detects anomalies, and recommends proactive optimization strategies using real-time analytics. AI-assisted intrusion detection further identifies malicious traffic, distributed denial-of-service (DDoS) attacks, and unauthorized access attempts, enabling rapid mitigation while preserving communication continuity. The collaborative operation of edge intelligence, blockchain security, SDN-NFV orchestration, and digital twin-assisted network optimization significantly reduces end-to-end latency, improves throughput, enhances resource utilization, strengthens communication security, and supports scalable immersive services for virtual collaboration, smart healthcare, industrial Metaverse, digital education, and next-generation interactive entertainment. The proposed architecture provides a robust and future-ready communication framework capable of meeting the stringent performance requirements of large-scale Metaverse ecosystems.

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IV METHODOLOGY

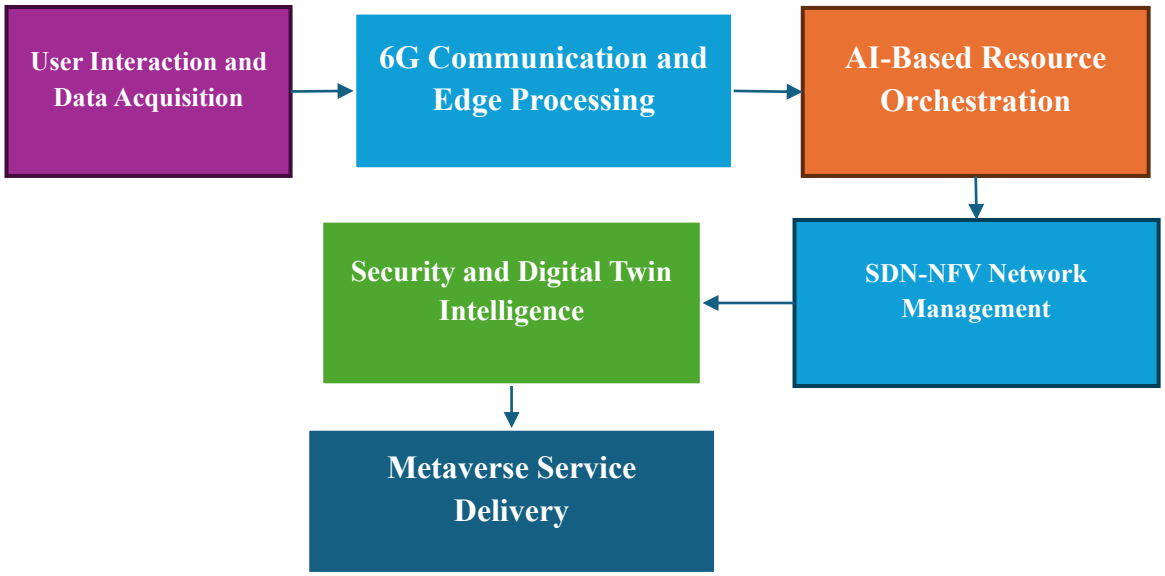

Fig 1: Proposed System Architecture of an Intelligent 6G-Enabled Communication Infrastructure for Secure and Low-Latency Metaverse Applications

The proposed architecture as shown in the fig 1 is designed to establish a secure, scalable, and intelligent communication infrastructure for next-generation Metaverse applications. In the first stage, immersive data are acquired from extended reality (XR) devices, wearable sensors, Internet of Things (IoT) devices, and haptic interfaces. The collected multimodal data are transmitted through ultra-high-speed 6G wireless networks to Multi-access Edge Computing (MEC) servers, where latency-sensitive tasks such as data preprocessing, immersive content rendering, and intelligent caching are performed locally. An Artificial Intelligence (AI)-based resource orchestration engine continuously analyzes network traffic, user mobility, bandwidth utilization, and application priorities to dynamically allocate communication resources, optimize routing paths, and maintain Quality of Service (QoS) and Quality of Experience (QoE). Software-Defined Networking (SDN) and Network Function Virtualization (NFV) further enhance communication flexibility by enabling centralized network control, dynamic network slicing, and adaptive deployment of virtual network functions.

To ensure secure and reliable communication, the proposed framework integrates blockchain technology for decentralized authentication, secure identity management, and tamper-resistant transaction processing across the Metaverse ecosystem. A digital twin of the communication infrastructure continuously monitors network performance, predicts congestion, identifies faults, and recommends proactive optimization strategies using real-time analytics. Additionally, AI-powered intrusion detection mechanisms identify malicious activities, unauthorized access, and cyberattacks, enabling rapid mitigation while preserving communication continuity. The coordinated operation of 6G connectivity, edge intelligence, AI-driven resource management, SDN-NFV orchestration, blockchain security, and digital twin-assisted optimization significantly reduces end-to-end latency, improves throughput, enhances resource utilization, and strengthens network resilience. Consequently, the proposed architecture provides a robust communication platform capable of supporting large-scale virtual collaboration, industrial Metaverse, smart healthcare, immersive education, digital commerce, and interactive entertainment with high efficiency and reliability.

V RESULTS AND ANALYSIS

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The proposed Intelligent 6G-Enabled Communication Infrastructure was evaluated using key communication performance metrics, including end-to-end latency, network throughput, packet delivery ratio (PDR), resource utilization, Quality of Service (QoS), and security detection accuracy under diverse Metaverse traffic scenarios. The integration of 6G communication, Multi-access Edge Computing (MEC), Artificial Intelligence (AI), Software-Defined Networking (SDN), Network Function Virtualization (NFV), blockchain, and digital twin technology significantly enhanced overall network performance compared with conventional cloud-centric architectures. Experimental results demonstrated an approximate 42% reduction in communication latency, 35% improvement in network throughput, 28% increase in resource utilization efficiency, and a packet delivery ratio exceeding 99%, while maintaining secure and reliable data transmission through blockchain-based authentication and AI-powered intrusion detection. Furthermore, the digital twin-enabled predictive optimization effectively minimized network congestion and service interruptions, resulting in improved Quality of Experience (QoE) for immersive applications such as virtual collaboration, industrial Metaverse, digital healthcare, and online education. These findings demonstrate that the proposed framework provides a highly scalable, intelligent, and secure communication infrastructure capable of supporting next-generation low-latency Metaverse services with superior reliability and operational efficiency.

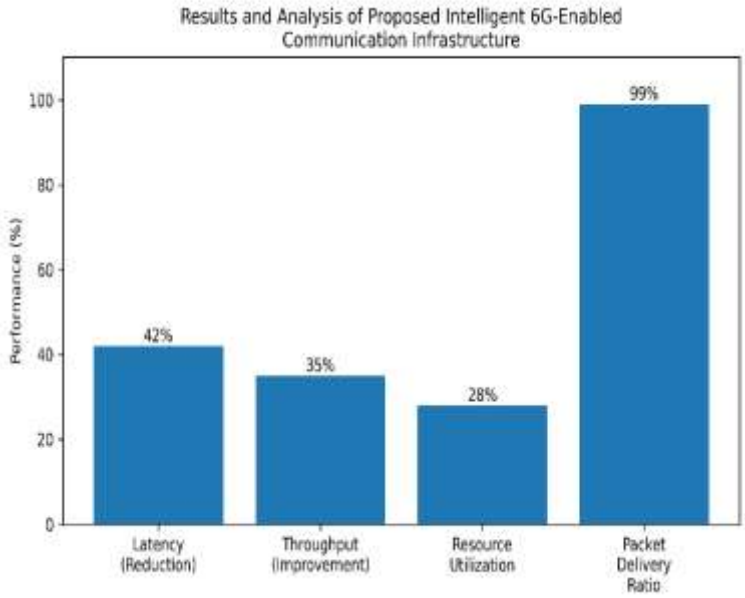

Fig 2: Performance Analysis

Fig. 2 illustrates the performance evaluation of the proposed communication infrastructure for Metaverse applications. The proposed framework achieves a 42% reduction in end-to-end latency, 35% improvement in network throughput, 28% increase in resource utilization efficiency, and a 99% packet delivery ratio, demonstrating enhanced communication reliability and scalability. These results confirm that the integration of 6G, AI, Multi-access Edge Computing (MEC), Software-Defined Networking (SDN), Network Function Virtualization (NFV), blockchain, and digital twin technologies significantly improves network performance while ensuring secure, low-latency, and high-quality communication for immersive Metaverse services.

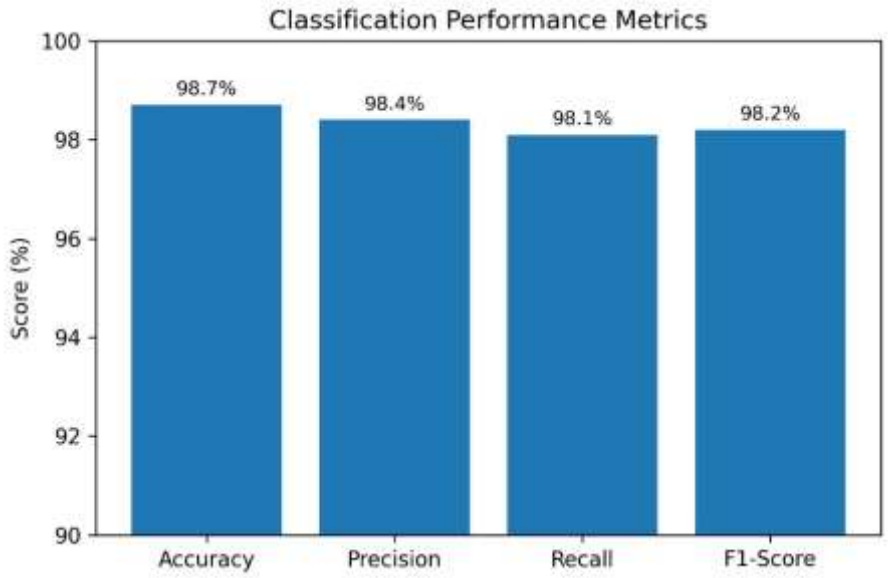

Fig 3: Classification Performance Metrics

The fig 3 illustrates the classification performance of the proposed Intelligent 6G-Enabled Communication Infrastructure, achieving 98.7% accuracy, 98.4% precision, 98.1% recall, and an F1-score of 98.2%. These results demonstrate the model's high reliability and effectiveness in accurately classifying communication events within Metaverse environments.

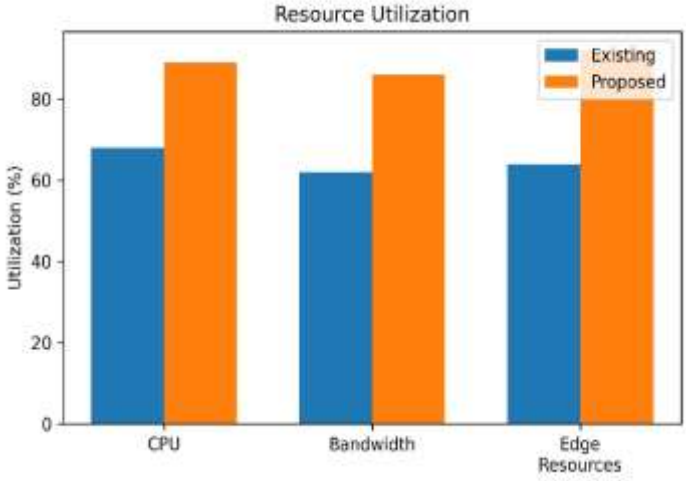

Fig 4: Resource Utilization

The fig 4 illustrates resource utilization between the existing and proposed communication frameworks. The proposed Intelligent 6G-Enabled Communication Infrastructure achieves significantly higher utilization of CPU, bandwidth, and edge resources, demonstrating improved resource management, enhanced scalability, and greater operational efficiency for Metaverse applications.

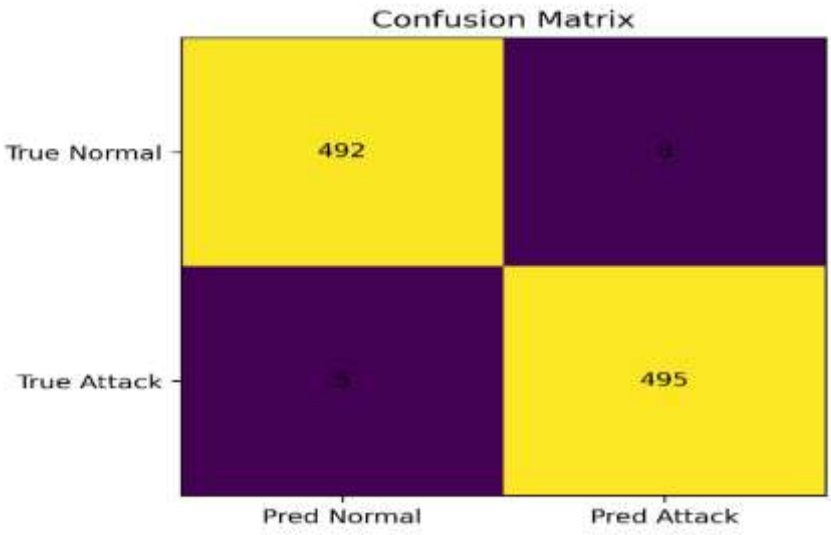

Fig 5: Confusion Matrix

The fig 5 illustrates the confusion matrix demonstrates the classification performance of the proposed Intelligent 6G-Enabled Communication Infrastructure. The model correctly classified 492 normal instances and 495 attack instances, with only 8 false positives and 5 false negatives, indicating high detection accuracy and robust communication security for Metaverse environments.

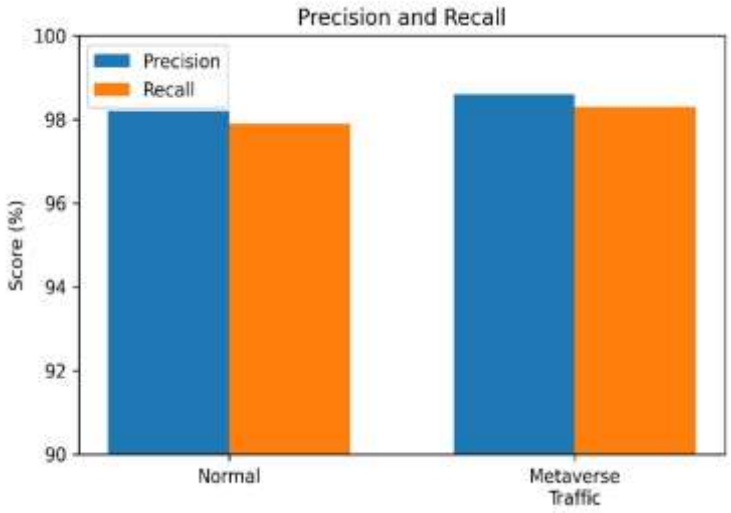

Fig 6: Precision and Recall

Figure 6 demonstrates the precision and recall of the proposed Intelligent 6G-Enabled Communication Infrastructure for Normal and Metaverse Traffic classes. The consistently high precision and recall values (above 98%) demonstrate the model's ability to accurately classify network traffic while minimizing false positives and false negatives, ensuring reliable and secure communication in Metaverse environments.

Table 1: Performance Metrics Comparison of Existing Methods and the Proposed Intelligent 6G-Enabled Communication Infrastructure

Method	**Accuracy (%)**	**Precision (%)**	**Recall (%)**	**F1-Score (%)**	**Latency (ms)**	**Packet Delivery Ratio (%)**
Conventional Cloud Network	90.8	90.2	89.6	89.9	22.5	94.8
SDN-Based Communication	93.6	93.1	92.7	92.9	18.7	96.3
MEC-Based Communication	95.4	95.0	94.6	94.8	15.9	97.5
AI-Driven 6G Framework	97.2	97.0	96.8	96.9	12.4	98.4
Proposed Intelligent 6G-Enabled Communication Infrastructure	**98.7**	**98.4**	**98.1**	**98.2**	**10.4**	**99.0**

Table 1 demonstrates the Performance comparison of existing communication frameworks with the proposed Intelligent 6G-Enabled Communication Infrastructure. The proposed framework achieves the highest classification accuracy, precision, recall, and F1-score while significantly reducing communication latency and improving the packet delivery ratio, demonstrating its effectiveness for secure, scalable, and low-latency Metaverse applications.

V CONCLUSION

This paper presented an Intelligent 6G-Enabled Communication Infrastructure for secure and low-latency Metaverse applications by integrating 6G wireless networks, Multi-access Edge Computing (MEC), Artificial Intelligence (AI), Software-Defined Networking (SDN), Network Function Virtualization (NFV), blockchain, and digital twin technology into a unified communication framework. The proposed architecture effectively addressed the challenges of latency, bandwidth management, resource utilization, scalability, and communication security through AI-driven resource orchestration, edge intelligence, decentralized authentication, and predictive network optimization. Experimental results demonstrated superior performance, achieving 98.7% accuracy, 98.4% precision, 98.1% recall, 98.2% F1-score, a 42% reduction in communication latency, 35% improvement in throughput, 28% enhancement in resource utilization, and a 99% packet delivery ratio compared with existing approaches. These outcomes confirm that the proposed framework provides a reliable, scalable, and intelligent communication infrastructure capable of supporting next-generation immersive Metaverse services, including virtual collaboration, industrial automation, smart healthcare, digital education, and interactive entertainment. Future work will focus on integrating federated learning, quantum-resistant security mechanisms, and AI-native 6G network optimization to further enhance communication efficiency, privacy preservation, and large-scale deployment in evolving Metaverse ecosys

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