Metaversalize

www.meta.reapress.com

Metaverse. Vol. 1, No. 4 (2024) 191–201.

Paper Type: Original Article

Transforming User Experience in the Metaverse through Edge Technology

Javad Pourqasem*

Department of Computer Engineering and Mathematics, Morvarid Intelligent Industrial Systems Research Group, Iran; jpourmail@gmail.com.

Citation:

Received: 14 April 2024 *Revised: 27 June 2024* *Accepted: 25 August 2024*	Pourqasem, J. (2024). Transforming user experience in the metaverse through edge technology. *Metaversalize, 1*(4), 191-201.

Abstract

The metaverse, an emerging virtual universe, allows real-time interactions and solid social links between humans, akin to the physical world. However, today's cloud-based metaverse infrastructure struggles to meet the metaverse's low latency and high bandwidth requirements. This is where edge computing steps in, moving processing closer to consumers and applications and overcoming these challenges. The metaverse, as a new distributed computing paradigm for computationally intensive tasks, can be offloaded to the network's edge. In this paper, we first outline the architecture of the metaverse and the driving technologies and underscore the pivotal role of edge computing in the digital infrastructure for realizing the metaverse. We then propose an edge computing-enabled metaverse, focusing on its performance in terms of rendering, latency, resource allocation, and communication. Finally, we delve into the challenges of implementing edge techniques, ensuring a comprehensive understanding of the topic.

Keywords: Metaverse, Edge computing, Distributed computing, Latency.

1 | Introduction

It is anticipated that the metaverse will take over every area of our lives and transform the conventional Internet. Its potential uses in social interaction, education, gaming, real estate, business, and commerce are promising. Users can use their avatars to engage with 3D virtual environments in the metaverse, where they can work, learn, or pass the time. The users can participate in an immersive virtual experience with accurate feedback sensors. Metaverse applications must comply with particular standards, including ultra-low latency, high resource needs, application interoperability, and privacy and security concerns [1], [2].

Most metaverse implementations use a centralized cloud-based approach for avatar physics emulation and graphical rendering. This has the disadvantages associated with long latency for cloud access and low-quality visualization. For example, Second Life has many virtual worlds but still is based on a centralized architecture. Each world is further divided into small regions maintained by dedicated servers called region servers. Thus,

Corresponding Author: jpourmail@gmail.com

https://doi.org/10.22105/metaverse.v1i1.19

most computationally intensive tasks—physics emulation, 3D animation, collision detection, and so on—are resident in the centralized server for each region. Therefore, the limit on the server's computational and communication capacity limits the number of users accessing each region [3].

The challenges to cloud-based metaverse platforms are apparent. The data movement between users and servers in metaverse platforms may be affected by web traffic or request complexity, introducing delay/break-up into login activities because of buffering or other types of delays. Bandwidth insufficiency will result in issues for the user and abandonment of applications. There may be performance and scalability problems due to the large number of users logged onto the central server, with the possibility that several requests overlap simultaneously. If it is vulnerable to an outage or downtime, this hurts the users' experience. Security concerns are always paramount since, if hackers infiltrate the cloud-stored data server, all information will be lost without a reliable backup [4].

Edge computing has successfully mitigated the issues faced by cloud-based systems by moving some of the heavy computational work closer to the user, hence decentralizing it across edge devices. Computationally intensive tasks are shifted from the core data centers to distributed edge servers at the base stations. This type of distributed computing paradigm significantly reduces communications latency while offering comparatively large amounts of computational resources compared to conventional cloud computing models [5], [6].

Improving the quality of interactions within AR/VR environments for metaverse users, bringing processing close to where the data is generated, provides seamless, immersive experiences with minimal latency. Edge computing is a more scalable and effective way to manage the massive amounts of data generated within the metaverse, which makes it indispensable for distributed and decentralized applications. This holds significant importance in the metaverse since it can lower operating costs while simultaneously improving the scalability, performance, and dependability of metaverse apps. The swift growth of the metaverse has caused edge computing to become more closely integrated with this virtual environment, which has redefined the range of digital interactions and created a bridge between the real and virtual worlds [7].

The impact of edge computing is far-reaching, cutting across various industries but particularly in the significant observation of improving user experience in areas like entertainment, health, education, and even online shopping [8] (see *Fig. 1*). The entertainment industry is witnessing transfers of high-end 3D content, live virtual events, and immersive gaming experiences powered by edge computing. In healthcare, on the other hand, edge computing enables real-time data transmission, effectively allowing healthcare providers to provide the best care remotely and enabling virtual reality in telemedicine for consultation, training, and even remote surgery. While in the education sector, it will pave the way for immersive virtual classrooms, personalized learning experiences, and real-time, interactive sessions. And finally, in e-shopping, edge computing allows the responsiveness of online shops to resemble the real shop experience. In combination with edge computing, the potential of the metaverse allows exciting futures for user experiences across a wide range of domains.

The remainder of the paper is organized as follows. Section 2 provides related studies in the context of an edge-enabled metaverse. Section 3 introduces the metaverse's architecture and driving technologies. Section 4 explains the edge-empowered metaverse and its edge functionalities. Section 5 describes the challenges encountered in implementing edge computing in the metaverse. Finally, the paper concludes.

2 | Related Work

Many publications discuss various facets of edge computing and metaverse technology. This section covers the featured work that uses edge computing to improve metaverse scalability, efficiency, security, and latency.

Wang and Zhao [6] Contributed an exhaustive survey on integrating MEC into metaverse, focusing on how these two technologies converge. Then, they discussed architectures that let MEC cooperate with cloud computing and fog computing, elaborating on how such collaborations enhance performance and efficiency for metaverse applications. The paper provided detailed research and application scenarios, especially augmented reality, virtual reality, and mixed reality, clearly pointing out how MEC can tremendously improve user experiences in these areas.

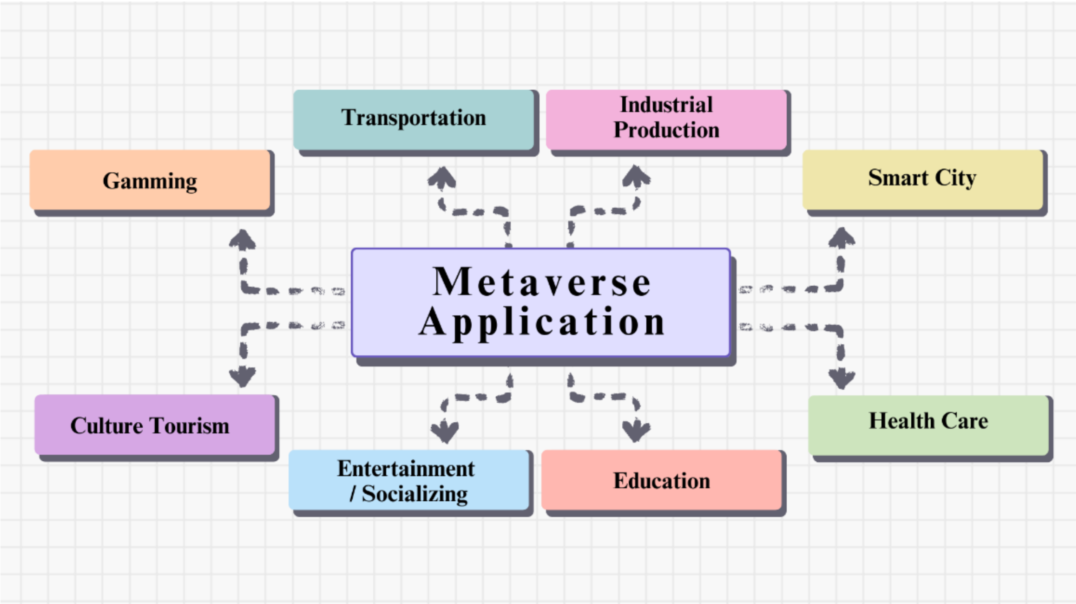

Fig. 1. The metaverse application spectrum.

To employ edge devices to complete the necessary computations for demanding tasks like 3D physics computation and virtual universe collision detection, Ahsani et al. [9] developed a Fog-Edge computing architecture for metaverse implementation. According to simulation results, the suggested design could reduce visualization latency by half compared to conventional cloud-based metaverse apps.

Lee et al. [10] covers future issues with MEC-based metaverse, including computer resource allocation, user experience, data, mobility management, delay, and privacy. Mobile edge computing is a distributed computing concept that can offload computation-intensive tasks to the network's edge.

In his study, Chang [11] concentrated on an edge-enabled metaverse. They also carefully examined the blockchain problems and networking relevance. The implementation of metaverse at mobile edge computing networks from the perspectives of computation, heterogeneity, communication, and interoperability are among the challenges explored, including shared metaverse. The suggested solutions utilize the computational power of mobile edge networks, physical and virtual synchronization, and digital reproduction of real-world entities in the metaverse.

Xu's [12] research integrates fundamental components to create a sixth-generation mobile edge framework, empowering the metaverse. Additionally, it expands on cutting-edge communication paradigms to satisfy metaverse user demands. Deploying the 6G architecture in metaverse presents a number of issues, including integrating disparate technologies, enhancing user experience, and addressing privacy and security.

3 | Metaverse Architecture

Creating an immersive metaverse ecosystem requires an efficient production platform, scalable infrastructure for high-performance support, and technical solutions for digital objects and environment content in terms of production, transmission, and interaction. A typical metaverse design comprises the layers of infrastructure, digital engine, content generation, perceptual interaction, and application. *Fig. 2* depicts a five-layer metaverse construction.

The metaverse ecosystem is constructed on the infrastructure layer, which primarily supports computation, networking, and storage [13], [14]. Application engines, including development platforms, 3D modeling tools, and rendering engines, are part of the digital engine layer and help accelerate the creation of metaverse apps. To create the fundamental architecture of the metaverse, the content generation layer uses digital generation technologies like Digital Twins (DTs) and AI agents to simulate the real world or create novel virtual settings that do not exist in reality. Human-Computer Interaction (HCI) devices, such as AR/VR headsets, are part of the perceptual interaction layer. They enable individuals to freely access virtual environments, engage in productive interactions, and enjoy immersive user experiences. The application layer makes the metaverse apps and the fully immersive digital existence possible.

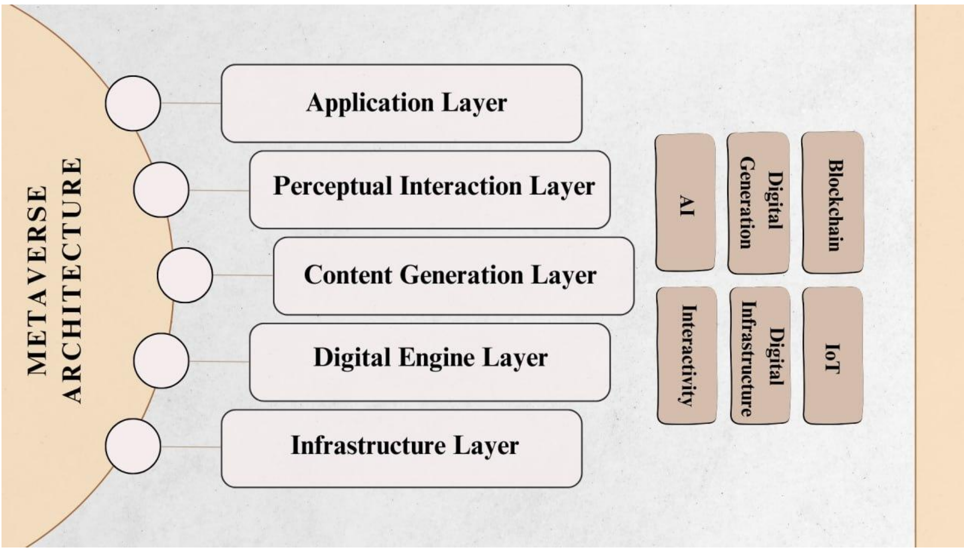

Fig. 2. The metaverse layers and driving technologies.

The metaverse digital ecosystem is created from the collaboration of a wide range of enabling advanced technologies that assure the development of metaverse applications in a fast, smart, reliable, and secure manner. In summary, the enabling technologies are discussed below:

I. Blockchain technology has given rise to a decentralized creator economy [15] and has come to be seen as one of the technologies harboring the most promise in fleshing out this conceptual metaverse, where virtual and real life could transact and meld.

II. Digital twins, 3D modeling, computer vision, and real-time rendering are some enabling techniques covered by digital generation. These techniques enable the creation of large-scale, intricate, and highly accurate immersive sceneries, including 3D reconstructions of massive digital items (like avatars) and surroundings [16].

III. The physical world and digital space are connected through interaction. To provide an immersive 3D experience, the metaverse is primarily presented through VR/AR devices. Extended reality (XR), in particular, has the potential to replace primary access devices and deeply integrates AR, VR, and mixed reality (MR) techniques. Furthermore, the human-computer interface directly operates external devices by gathering and interpreting brain signals [17].

IV. The Internet of Things (IoT) ensures that everything in the metaverse is connected to the network, enabling human-machine interaction and interconnection. This includes the real-time sharing of massive amounts of data collected by various IoT devices (e.g., sensors) over the Internet [18].

V. AI has influenced every facet of metaverse production and applications. The three primary AI approaches, Deep Learning (DL), Machine Learning (ML), and Reinforcement Learning (RL)—make use of their respective advantages to enable digital content creation, rendering, interaction, and other areas with efficiency and performance. For instance, DL can assist in speeding up the depiction of large-scale scenes, ML-based techniques are used for sophisticated data analysis and processing, and RL algorithms can handle difficult decision-making situations [19].

VI. Digital infrastructure offers highly scalable computing and storage capabilities and solid and dependable communication assurances for metaverse applications. This involves utilizing distributed computing paradigms to attain extremely low latency and offer seamless metaverse experiences.

4 | The Edge-Empowered Metaverse

Using a traditional cloud-based metaverse architecture to execute virtual operations and services by sending large amounts of data, including avatar movements and environmental physical characteristics, to a central server is not beneficial. Creative metaverse architectures based on edge computing have produced optimization and acceptable performance to counteract the detrimental effects of constraints. Put differently, a new generation of edge computing technology results from the convergence of edge computing and metaverse [20], [21]. This technology breaks the dependence of devices on centralized cloud servers and enhances the system's high real-time performance and security.

The edge-enabled metaverse frameworks can benefit the edge server resources regarding computing and communication. High-performance GPU requirements for real-time rendering and interaction orchestration in the metaverse must render immersive virtual worlds and interact with hundreds of players. To meet this requirement, user devices such as HMDs have to connect to powerful edge servers for remote rendering. This is necessary because the metaverse will be accessible to everyone through edge computation that provides ubiquitous computing and intelligence for users and service providers in the metaverse. This way, the overhead and the latency can be reduced by edge servers to execute expensive foreground render, which requires fewer graphical details but tends to be faster [22].

The fidelity, reliability, and latency requirements for AR/VR and haptic immersive streaming ensure no break-in-present of metaverse services for users [23]. Cutting-edge communication and networking solutions should be provided for the immersive experience of the edge-enabled metaverse. The edge communication and networking to support the metaverse should prioritize user-centric considerations in the content delivery of communication and networking support. The semantic/goal-oriented communication solutions [24] open the gate toward metaverse-native communications that can alleviate the spectrum scarcity for next-generation multimedia services. For the metaverse to be constructed, it is essential to have bidirectional physical–virtual synchronization in real-time.

This section aims to define and examine the functionality of edge computing technology that will be effective in the metaverse immersion experience, how it can enhance the metaverse's user-friendly features, and important components and services for metaverse service providers to better service delivery.

4.1 | Efficient AR/VR Rendering

In addition to wired devices, the edge-enabled metaverse offers mobile users in the physical world the ability to experience virtual worlds via AR/VR by using VR HMDs and AR Goggles. On the one hand, HMDs generate sensory images that constitute the virtual worlds [25]. For the metaverse to operate smoothly, users need to be able to render the sensory images in real-time. Metaverse users benefit most from AR applications when they are physically present in the real world, such as while on the job or working with a computer. However, it is essential to note that users' devices have limited computational capacity, memory storage, and battery life. These devices cannot support the intense AR/VR applications needed for the immersive metaverse. To overcome these challenges, users' devices accessing the metaverse can leverage ubiquitous computing resources to render and offload tasks remotely via edge collaborative computing [26].

The edge collaborative computing architecture in edge-computing technologies enables mobile users to perform computations, such as analytics, rendering, and avatar computing, where the data are created [27]. A vehicle can, for instance, send the data to nearby vehicles or roadside units rather than offloading it to the cloud when the user interacts with avatars in the metaverse to perform task computations, dramatically reducing the end-to-end latency. The metaverse should be accessible no matter where mobile users are located. By shifting computations away from the core networks, mobile edge computing also reduces network traffic. An edge server provides computing resources to mobile edge users at edge networks [28].

4.2 | Latency Optimization

In edge computing systems, latency is minimized by dynamically allocating processing work based on user proximity. This method expedites data processing and lessens the waiting time that users of the metaverse encounter. The term "latency" describes how long it takes for a metaverse action to appear in a user's experience. Dynamically optimizing latency requires prioritizing the intelligent distribution of computing workloads according to edge computing nodes' proximity to users. Data processing locations are determined in real-time based on job priority, computing load, and network delay. Thus, as close to the user as possible, perceived latency in data processing is minimized, guaranteeing that metaverse applications react quickly to user inputs [29].

A node's suitability for carrying out a particular task is determined by considering the dynamic conditions of the network. A more engaging user experience is produced, making the metaverse more dynamic and flexible. Enhancing the quality of metaverse applications, especially those that need low latency, like augmented reality, virtual conferences, and online gaming, is significantly affected by this. Users' digital experience is improved by flexibility and real-time decision-making, guaranteeing they don't experience delays in the metaverse.

4.3 | Resource Allocation

Edge computing nodes in the metaverse employ predictive models to optimize resource sharing, guaranteeing effective resource distribution according to workload demands. This method ensures optimal use of computing resources by minimizing waste and maximizing efficiency. In the metaverse, efficient resource allocation is crucial to satisfying the changing needs of various applications while preserving the highest performance.

It is essential in metaverse to distribute data processing tasks efficiently among various edge computing nodes. The division of available resources in real time could help prevent bottlenecking due to underutilization and overload. Resource allocation would ensure that the right assets are allocated to the correct task at the optimum time for maximum performance and optimal resource usage. This is important, especially when the metaverse develops with users who can change quickly and with a fast-evolving application landscape [30]. Optimizing resource distribution in metaverse edge computing systems aims to increase scalability and resource utilization. This is accomplished through resource allocation based on dynamic conditions, real-time demand prediction, and continuous workload monitoring.

Adaptability is achieved thanks to edge predictive modeling; therefore, it handles most workloads varying within a very wide range, effectively utilizing the available resources. This forms a critical base needed for the performance requirements of the massive digital ecosystems in the metaverse.

4.4 | Networking and Communication

A successful AR/VR environment requires a seamless, dependable, and low-latency network infrastructure for communication [31]. The transmission rate required to facilitate interactions between the virtual and physical worlds, as well as interaction latency, which impacts the degree of realism in immersive experiences, must be taken into account [32–34]. Users who are fully immersed in the metaverse are also affected by the dependability of the physical network services and the frequency of outages [35], [36].

With the above requirements, a developed edge networking and communication infrastructure can become critical to exchanging large chunks of data between the virtual and physical worlds. This can trade off data transfer rate, reliability, and latency for the user of 3D multimedia services while moving from the physical to the virtual world and vice versa. The edge networks ensure that players join massively multiplayer online games with minimal latency.

In the process, edge resource allocation for AR/VR services is a critical concern to any virtual or physical service provider. Their interest is in accommodating the dynamic reliability requirements of AR/VR applications and users.

5 | Challenges in Edge-Enabled Metaverse

In the context of metaverse, edge computing technologies support efficient immersive streaming and social interaction for users. The AI technologies ensure that communication resources are used optimally by changing traditional edge network architecture into intelligent edge networks. Edge computing enables adaptive AR/VR edge co-rendering between metaverse users' devices. Moreover, on-demand and generalized model compression supports ubiquitous intelligence in metaverse edge devices. On the other hand, user-centric computing acts as a key enabler of virtual-real synchronization in the metaverse. Similarly, metaverse user data is utilized to optimize metaverse services.

The previous discussion mentioned that edge computing services can enable metaverse developers to offer high-immersion metaverse applications. Implementing metaverse services using edge technology comes with challenges and requirements that will be deeply analyzed in the next sections of this paper.

5.1 | Efficient Immersive Streaming and Interaction

The metaverse distributes content in multimodal formats through tactile Internet technologies, AR, and VR. Unlike conventional AR/VR, which focuses on single-user experiences, the metaverse enables multi-user interaction and coexistence in virtual environments. This calls for effective resource allocation at the network's edge to maximize service delivery. In addition, users will have to work with real-time 3D Field of View (FoV) and perform rendering and real-time communication network calculations.

5.2 | AI for the Intelligent Edge Communication

Network management is becoming more complex and dynamic, so AI techniques must be used to manage communication resources. The "AI for edge" paradigm focuses on using AI to optimize resource allocation at the network edge, like task offloading and bandwidth management. Service providers can reduce communication costs by combining AI with conventional optimization tools. However, one major challenge is the computational cost of training and storing AI models on devices with limited resources.

5.3 | Data Leakage

The edge computing-based metaverse architecture differs significantly from the decentralized Bitcoin architecture in several ways. Passwords, digital assets, and currency are just a few examples of the private and sensitive information sent from end devices to the edge cloud. However, adversaries could potentially use these devices for malicious purposes, such as tracking blind spots, controller cursor manipulation, and improper use of assisted display for content sharing [21]. Data quality is a key factor in improving users' experiences; high data quality leads to a notable improvement in user experience, while low data quality has the opposite effect. Jitters that arise during the propagation of data and phony IDs are examples of sources and processes that can produce untrustworthy data. Thus, it is necessary to prevent data leaks and improve the quality and reliability of data in the metaverse since these are essential requirements for creating and implementing the metaverse idea.

5.4 | AR/VR Edge Rendering

By leveraging ubiquitous computing and intelligence in edge networks, AR/VR tasks can be offloaded to network nodes with the necessary processing power to render them. The performance bottlenecks in AR/VR rendering, such as stragglers at edge networks, heterogeneous tasks, stochastic demand, and network conditions, must be adaptively overcome within the cloud-edge-end collaborative computing paradigm.

5.5 | On-demand and Generalized Model Compression

Model compression can be advantageous for local devices when interacting with the metaverse. Despite potential limitations, such as storage, processing power, and energy constraints on some devices, additional model compression may be essential to accommodate these restrictions. A balanced on-demand model compression necessitates considering the accuracy vs. user quality of experience trade-off. Moreover, a generalized model compression method can be used to determine the best compression level or method for various tasks, thereby improving the computational interoperability of the metaverse.

5.6 | User-Centric Computing

User-centric computing must prioritize responsible user privacy enforcement to guarantee that the metaverse can be trusted without jeopardizing user privacy. This will make it possible to protect the real and virtual worlds simultaneously. Applications must protect sensitive data while being computed on edge devices in virtual worlds. Furthermore, in the actual world, privacy protection should be extended to data like GPS coordinates, voice recordings, and eye movements recorded by external devices (like AR/VR headsets).

5.7 | Computational Privacy and Security

Applications of the metaverse, like AR/VR, have the potential to change our lifestyles and transform several industries while posing new privacy and security challenges for edge computing technologies. User protection policies must be implemented as the metaverse is used more and more. Additionally, because of the importance of security and data protection, users risk experiencing new effects. AR applications should not be allowed to access sensor data to protect edge devices [37]. Users upload images or video streams to deliver AR content. These can be shared with third-party servers, potentially leaking private information. To preserve an immersive experience and safeguard their data, users shouldn't be exposed to extraneous data, such as gestures and voice commands. An attacker can obtain the user's data without authentication by mimicking vocal instructions and hand motions. Voice-spoofing protection systems can be used to defend voice access by identifying if the voice command originates from the user or the surrounding environment [38].

6 | Conclusion

This research was carried out with a focus on how latency and bandwidth limitations have an expense on user immersion in cloud-based metaverse frameworks and how it can be solved or minimized by edge networks through communication resources and distributed computing near the user and data source. It explored ways to strengthen the metaverse using edge computing and assessed the impact of edge on various aspects of metaverse performance. The study has also discussed some challenges of edge computing implementation within a metaverse environment.

Acknowledgments

We sincerely thank the editor and the reviewers for their valuable suggestions.

Author Contributions

Author Javad Pourqasem prepared the draft of the paper. Author Leila Sharifi, as the professor, provided overall guidance and supervision throughout the research process.

Funding

This research received no specific grant from any financial organization.

Conflicts of Interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

References

[1] Wang, G., Badal, A., Jia, X., Maltz, J. S., Mueller, K., Myers, K. J., … & Zeng, R. (2022). Development of metaverse for intelligent healthcare. *Nature machine intelligence*, *4*(11), 922–929. https://doi.org/10.1038/s42256-022-00549-6

[2] Ali, S., Abdullah, Armand, T. P. T., Athar, A., Hussain, A., Ali, M., … & Kim, H. C. (2023). Metaverse in healthcare integrated with explainable AI and blockchain: Enabling immersiveness, ensuring trust, and providing patient data security. *Sensors*, *23*(2), 565. https://doi.org/10.3390/s23020565

[3] Hoang, D. T., Nguyen, D. N., Nguyen, C. T., Hossain, E., & Niyato, D. (2023). *Metaverse communication and computing networks: Applications, technologies, and approaches*. John Wiley & Sons. https://doi.org/10.1002/9781394160013

[4] Kulkarni, S., Dwivedi, J. N., Pramanta, D., & Tanaka, Y. (2024). *Edge computational intelligence for AI-enabled IoT systems*. CRC Press. https://doi.org/10.1201/9781032650722

[5] Kashyap, R. (2022). Machine learning, data mining for IoT-based systems. In *Research anthology on machine learning techniques, methods, and applications* (pp. 447–471). IGI Global. https://doi.org/10.4018/978-1-6684-6291-1.ch025

[6] Wang, Y., & Zhao, J. (2022). A survey of mobile edge computing for the metaverse: Architectures, applications, and challenges. *2022 IEEE 8th international conference on collaboration and internet computing (CIC)* (pp. 1–9). IEEE. https://doi.org/10.1109/CIC56439.2022.00011

[7] Bavkar, D., Kashyap, R., & Khairnar, V. (2023). Deep hybrid model with trained weights for multimodal sarcasm detection. *International conference on information, communication and computing technology* (pp. 179–194). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-5166-6_13

[8] Zhang, J., Chen, B., Zhao, Y., Cheng, X., & Hu, F. (2018). Data security and privacy-preserving in edge computing paradigm: Survey and open issues. *IEEE access*, *6*, 18209–18237. https://doi.org/10.1109/ACCESS.2018.2820162

[9] Ahsani, V., Rahimi, A., Letafati, M., & Khalaj, B. H. (2023). *Unlocking metaverse-as-a-service the three pillars to watch: Privacy and security, edge computing, and blockchain*. http://arxiv.org/abs/2301.01221

[10] Lee, L. H., Braud, T., Zhou, P., Wang, L., Xu, D., Lin, Z., … & Hui, P. (2021). *All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystem, and research agenda*. http://arxiv.org/abs/2110.05352

[11] Chang, L., Zhang, Z., Li, P., Xi, S., Guo, W., Shen, Y., ... & Wu, Y. (2022). 6G-enabled edge AI for metaverse: challenges, methods, and future research directions. *Journal of communications and information networks*, *7*(2), 107–121. https://doi.org/10.23919/JCIN.2022.9815195

[12] Xu, M., Ng, W. C., Lim, W. Y. B., Kang, J., Xiong, Z., Niyato, D., … & Miao, C. (2023). A full dive into realizing the edge-enabled metaverse: Visions, enabling technologies, and challenges. *IEEE communications surveys and tutorials*, *25*(1), 656–700. https://doi.org/10.1109/COMST.2022.3221119

[13] Manushri, S. K., Santhiya, J., Roobasri, A. E., Keshav Shanmukhanathan, E., & Sanjai, V. (2022). Metaverse-the future of virtual world. *International journal of engineering technology and management sciences*, *6*(5), 779–783. https://doi.org/10.46647/ijetms.2022.v06i05.121

[14] Zhu, H. Y., Hieu, N. Q., Hoang, D. T., Nguyen, D. N., & Lin, C. T. (2024). A human-centric metaverse enabled by brain-computer interface: A survey. *IEEE communications surveys and tutorials*, 1–1. https://doi.org/10.1109/COMST.2024.3387124

[15] Cao, B., Wang, Z., Zhang, L., Feng, D., Peng, M., Zhang, L., & Han, Z. (2023). Blockchain systems, technologies, and applications: A methodology perspective. *IEEE communications surveys and tutorials*, *25*(1), 353–385. https://doi.org/10.1109/COMST.2022.3204702

[16] Alkhateeb, A., Jiang, S., & Charan, G. (2023). Real-time digital twins: Vision and research directions for 6G and beyond. *IEEE communications magazine*, *61*(11), 128–134. https://doi.org/10.1109/MCOM.001.2200866

[17] Dhillon, P. K. S., & Tinmaz, H. (2024). Immersive realities: A comprehensive guide from virtual reality to metaverse. *Journal for the education of gifted young scientists*, *12*(1), 29–45. https://doi.org/10.17478/jegys.1406024

[18] Azeem, W., Malik, A. A., & Yar, M. A. (2019). Internet of things: Architectural components, protocols and its implementation for ubiquitous environment. *Lahore garrison university research journal of computer science and information technology*, *3*(3), 51–55. https://doi.org/10.54692/lgurjcsit.2019.030384

[19] Taye, M. M. (2023). Understanding of machine learning with deep learning: architectures, workflow, applications and future directions. *Computers*, *12*(5), 91. https://doi.org/10.3390/computers12050091

[20] Zhang, W., Chen, J., Zhang, Y., & Raychaudhuri, D. (2017). *Towards efficient edge cloud augmentation for virtual reality mmogs* [presentation]. Proceedings of the second ACM/IEEE symposium on edge computing (pp. 1–14). https://doi.org/10.1145/3132211.3134463

[21] Dhelim, S., Kechadi, T., Chen, L., Aung, N., Ning, H., & Atzori, L. (2022). Edge-enabled metaverse: The convergence of metaverse and mobile edge computing. *TechRxiv*. https://doi.org/10.36227/techrxiv.19606954.v1

[22] Guo, F., Yu, F. R., Zhang, H., Ji, H., Leung, V. C. M., & Li, X. (2020). An adaptive wireless virtual reality framework in future wireless networks: A distributed learning approach. *IEEE transactions on vehicular technology*, *69*(8), 8514–8528. https://doi.org/10.1109/TVT.2020.2995877

[23] Park, J., & Bennis, M. (2018). URLLC-embb slicing to support VR multimodal perceptions over wireless cellular systems. *Proceedings-IEEE global communications conference (GLOBECOM)* (pp. 1–7). IEEE. https://doi.org/10.1109/GLOCOM.2018.8647208

[24] Yang, W., Liew, Z. Q., Lim, W. Y. B., Xiong, Z., Niyato, D., Chi, X., … & Letaief, K. B. (2022). Semantic communication meets edge intelligence. *IEEE wireless communications*, *29*(5), 28–35. https://doi.org/10.1109/MWC.004.2200050

[25] Duan, H., Li, J., Fan, S., Lin, Z., Wu, X., & Cai, W. (2021). *Metaverse for social good: a university campus prototype* [presentation]. Proceedings of the 29th acm international conference on multimedia (pp. 153–161). https://doi.org/10.1145/3474085.3479238

[26] Chen, Y., Zhang, N., Zhang, Y., Chen, X., Wu, W., & Shen, X. (2019). Energy efficient dynamic offloading in mobile edge computing for internet of things. *IEEE transactions on cloud computing*, *9*(3), 1050–1060. https://doi.org/10.1109/TCC.2019.2898657

[27] Sunyaev, A. (2020). Fog and edge computing. *Internet computing: principles of distributed systems and emerging internet-based technologies*, 237–264. https://doi.org/10.1007/978-3-030-34957-8

[28] Beck, M. T., Werner, M., Feld, S., & Schimper, T. (2014). *Mobile edge computing : A taxonomy* [presentation]. Proc. of the sixth international conference on advances in future internet. (pp. 48–54). https://www.researchgate.net/publication/267448582_Mobile_Edge_Computing_A_Taxonomy

[29] Lam, N. T. (2021). Developing a framework for detecting phishing URLs using machine learning. *International journal of emerging technology and advanced engineering*, *11*(11), 61–67. https://doi.org/10.46338/IJETAE1121_08

[30] Liu, X., Zheng, J., Zhang, M., Li, Y., Wang, R., & He, Y. (2024). Multi-user computation offloading and resource allocation algorithm in a vehicular edge network. *Sensors*, *24*(7), 2205. https://doi.org/10.3390/s24072205

[31] Saad, W., Bennis, M., & Chen, M. (2020). A vision of 6G wireless systems: Applications, trends, technologies, and open research problems. *IEEE network*, *34*(3), 134–142. https://doi.org/10.1109/MNET.001.1900287

[32] Quang Hieu, N., Nguyen, D. N., Hoang, D. T., & Dutkiewicz, E. (2022). *When virtual reality meets rate splitting multiple access: A joint communication and computation approach*. https://doi.org/10.48550/arXiv.2207.12114

[33] Letaief, K. B., Chen, W., Shi, Y., Zhang, J., & Zhang, Y. J. A. (2019). The roadmap to 6G: AI empowered wireless networks. *IEEE communications magazine*, *57*(8), 84–90. https://doi.org/10.1109/MCOM.2019.1900271

[34] Mao, Y., Dizdar, O., Clerckx, B., Schober, R., Popovski, P., & Poor, H. V. (2022). Rate-splitting multiple access: Fundamentals, survey, and future research trends. *IEEE communications surveys & tutorials*, *24*(4), 2073–2126. https://doi.org/10.1109/COMST.2022.3191937

[35] You, X., Wang, C. X., Huang, J., Gao, X., Zhang, Z., Wang, M., … & Liang, Y. C. (2021). Towards 6G wireless communication networks: Vision, enabling technologies, and new paradigm shifts. *Science china information sciences*, *64*(1), 1–74. https://doi.org/10.1007/s11432-020-2955-6

[36] Tataria, H., Shafi, M., Molisch, A. F., Dohler, M., Sjoland, H., & Tufvesson, F. (2021). 6G wireless systems: Vision, requirements, challenges, insights, and opportunities. *Proceedings of the IEEE*, *109*(7), 1166–1199. https://doi.org/10.1109/JPROC.2021.3061701

[37] Jana, S., Molnar, D., Moshchuk, A., Dunn, A., Livshits, B., Wang, H. J., & Ofek, E. (2013). *Enabling fine-grained permissions for augmented reality applications with recognizers* [presentation]. Proceedings of the 22nd usenix security symposium (pp. 415–430). https://www.usenix.org/conference/usenixsecurity13/technical-sessions/presentation/jana

[38] Shang, J., & Wu, J. (2019). Enabling secure voice input on augmented reality headsets using internal body voice. *2019 16th annual ieee international conference on sensing, communication, and networking (SECON)* (pp. 1–9). IEEE. https://doi.org/10.1109/SAHCN.2019.8824980