IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 15 February 2023, accepted 3 March 2023, date of publication 10 March 2023, date of current version 16 March 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3255510

SURVEY

The Role of Network Slicing and Edge Computing in the Metaverse Realization

SUPUN KARUNARATHNA [1], SHALITHA WIJETHILAKA [2], (Student Member, IEEE), PASIKA RANAWEERA [2], (Member, IEEE), KASUN T. HEMACHANDRA [1], (Member, IEEE), THARAKA SAMARASINGHE [1], (Senior Member, IEEE), AND MADHUSANKA LIYANAGE [2], (Senior Member, IEEE)

[1]Department of Electronic and Telecommunication Engineering, University of Moratuwa, Moratuwa 10400, Sri Lanka
[2]School of Computer Science, University College Dublin, Dublin 4, D04 V1W8 Ireland

Corresponding author: Shalitha Wijethilaka (mahadurage.wijethilaka@ucdconnect.ie)

This work was supported in part by the CONFIDENTIAL-6G Project under Grant 101096435, in part by the Science Foundation Ireland under CONNECT Research Center under Grant 13 RC/2077_P2, and in part by the European Commission in SPATIAL Project under Grant 101021808.

ABSTRACT Metaverse is the latest technological hype in the modern world due to its potential for revolutionizing the digital visual perspective. With the COVID-19 pandemic, most industries have moved towards digitization, and the metaverse is identified as one of the most promising platforms for such a transition, as it provides a three-dimensional (3D) immersive experience for the users. Currently, most digital service providers and organizations are actively working on metaverse- based applications. In addition, there has been a rapid increase on research work involving metaverse realization. Launching a large scale metaverse in the real world is a challenging task. However, fifth-generation (5G) and beyond 5G (B5G) technologies are envisioned to improve the feasibility of pragmatic deployments. Although, there are several conceptual designs available, actual adaptations of the concepts are still limited. This survey focuses on providing a practical approach for metaverse realization using 5G and B5G technologies. Specifically, We discuss the importance of network slicing (NS) and multi-access edge computing (MEC) as emerging 5G technologies for enabling the realization of the metaverse. We first introduce the motivation behind metaverse for future envisaged technologies. Next, we present a holistic high-level framework for metaverse realization based on network slicing and edge computing. Moreover, we discuss the futuristic metaverse applications, their technical requirements, and methods to satisfy the requirements. Finally, we highlight the deployment challenges and possible approaches to overcome them for an actual metaverse realization.

INDEX TERMS Augmented reality, multi-access edge computing, metaverse, network slicing, virtual reality, extended reality.

I. INTRODUCTION

Metaverse is amalgamating digital reality and virtually enhanced physical reality into a particular domain, contrived of many advanced features and enablers. It can be considered as the next level of the internet, as the term itself was initially introduced in the scientific fiction Snow Crash, written by Neal Stephenson in 1992 [1]. Nowadays, users expect higher interactive capabilities from the existing internet-based digital communication technologies. However, the real world is limited by its geographical constraints and the availability of resources. The metaverse, on the other hand, is infinite in scale and can be extended until the imaginative limits of its creators. Furthermore, this virtual domain enables its users to experience or explore adventurous activities that may not be physically realizable in the real world. It is a massive network of virtual worlds in which users can actively collaborate and experience. To access the metaverse, a user should possess either augmented reality/virtual reality (AR/VR) devices, smart glasses, gaming consoles,

The associate editor coordinating the review of this manuscript and approving it for publication was Mehdi Sookhak.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

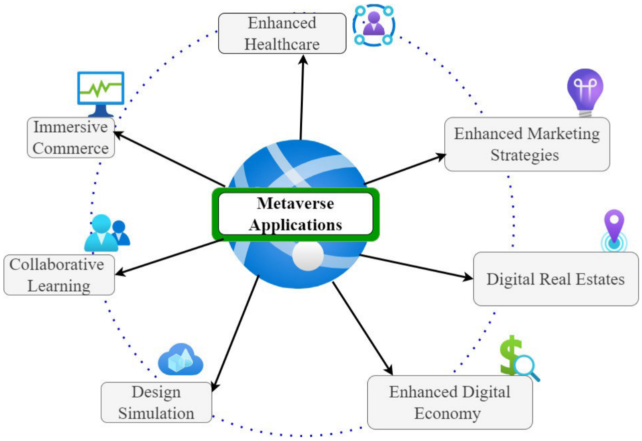

FIGURE 1. Metaverse applications.

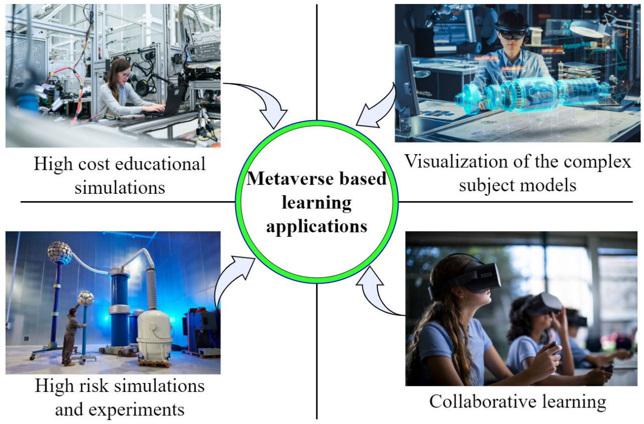

FIGURE 2. Metaverse enabled learning applications.

haptic devices, mobile devices, a computer, or a Laptop [2]. Extended reality (XR) approaches with the combination of AR and VR technologies have better potential on improving the user experience in the metaverse [3]. A single vendor or an owner does not own metaverse. Thus it is considered a collaborative space between service providers and users [4]. The leading technologies of the metaverse include artificial intelligence (AI), blockchain, computer vision, advanced networking technologies, user interactivity, XR, internet of things (IoT), and robotics [5], [6]. It is expected that the market value and share of the companies that operate in metaverse will increase exponentially the next decade [7].

The users in the metaverse are identified by their unique avatars, which are capable of adapting to the real user interactions [8]. Their transactions are facilitated through non-fungible tokens (NFT), which are secure digital assets that the owner can transfer. These NFTs are owned digitally, and at the same time, shareable in the metaverse [9]. Although the metaverse development is still in its initial stages, it envisages great potential for novel feature implementations and many research avenues.

Due to the metaverse's versatility, various technologies and services can be implemented on top of its virtual platform. Fig. 1 shows a few possible applications which can be launched in metaverse. Presently, businesses mainly focus on digitization and automation to reduce their capital and operational expenditures. However, people also prefer simplification of everyday tasks and accessibility to the services at a low cost. With Metaverses' virtual worlds which consist of enhanced visualization, services can be offered for many concurrent users in different geographical locations [11]. Therefore, metaverse-based platforms can be used for education, healthcare, social networks, industry applications, smart marketing, architecture design, smart businesses engineering design, and autonomous vehicle simulations [12], [13], [14], [15], [16], [17].

Metaverse also facilitates collaborations between different internet-based services. Currently, these collaborations are constrained by the inability of having 100% virtual presence in remote access situations. Metaverse relaxes these constraints by enhancing the quality of service through more service collaborations. More services can be integrated as a value addition to the primary service to extend the current limits of the quality of experience (QoE). For instance, a user can try out an outfit from a clothing store while matching its compatibility with an already selected watch from another store, allowing the user to check both items simultaneously before buying.

The COVID-19 pandemic has opened up many new avenues for metaverse as people are forced to work remotely. For example, in the educational sector with institutions focusing more on active collaborations, metaverse-based learning can strengthen distance learning methods by providing a more interactive and feedback-oriented learning process with immersive visualization in a virtual environment. As shown in Fig. 2, future learning will be more enriched with metaverse-enabled applications.

Immersive media can be used effectively in the education sector to improve teaching and learning experience [18], [19], [20]. Metaverse-based educational platforms can be used to deliver important educational content that requires more visual aids and cost intensive realistic simulations.

Importance of the point of presence will become less prominent with the advancement of the metaverse. Especially, boundaries for many fields will disappear, and many new fields may initiate. Metaverse-based approaches will play an important role in the work from home (WFH) culture, which is already popular in the world. Moreover, the metaverse will be more effective in tourism, and it will introduce the opportunity to tour any place virtually, irrespective of time. Applications such as connected vehicles and vehicle to everything (V2X) are the prominent use cases in 5G, and AR/VR-based metaverse approaches are envisioned to enhance these applications as well [21]. Modern prototypes of the metaverse are already available for games, social experience platforms, online collaboration, simulations, designs, and creator economy. Furthermore, there will be many use cases created in relation to virtual real-estate applications inside the metaverse.

TABLE 1. Issues in metaverse integration.

Technical Issues	Non-Technical Issues
• Real-time synchronization between the metaverse and real world. • Accuracy of the real-time data when passing from the metaverse to the real world(e.g., AR-based navigation). • Identity and uniqueness of the user. • QoS depends on the access device. • Lack of standardized protocol, tools, and frameworks [10]. • Metaverse generates a large amount of data, including the biometric data of users. Data storage should be gigantic, and high security is required. • Lack of compatibility with the existing networks and the application platforms. • XR headsets and haptic devices require latency as low as tens of milliseconds to maintain an immersive user experience [11].	• Countrywise restrictions need to apply inside the metaverse too. Then the fairness of the application or relevant service may differ from the exact expected outcome [10]. • Affordability and the complexity of the access devices. • Less user awareness about the metaverse concept and functionality can cause a bad user experience, affecting platform acquisition [11]. • Defining the governing bodies of the metaverse for the continuity of the functions and maintenance. • Money transactions and digital payments in between the real world and the Metaverse.

All components of the network layer, aggregation layer, and core layer, along with sub-layers, and applications, need to be supported for the metaverse requirements. It is obvious that 5G and B5G networks are an imperative requisite for the realization of the metaverse [22], [23]. Another mandatory requirement is the availability of access devices that have the ability to contrive the required 3D visualization, and extract the user feedbacks, which transfer through haptic devices [24]. According to 3rd generation partnership project (3GPP) release 15 phase 1, a maximum end-to-end (E2E) latency of 7-15 ms, and a data rate of 250 Mbps is required for AR/VR/XR services [25]. After the implementation, service providers are responsible in maintaining the service functionality. Mainly, two kinds of service providers are involved in the metaverse realization: virtual service providers who provide the content, and physical service providers who operate the physical infrastructure required for the metaverse engine [26]. Apart from the technical requirements, non-technical requirements such as rules, regulations, and fair use play a key role in the metaverse adoption as well.

Metaverse can be integrated with the physical world, utilizing a virtual copy of the real-world objects/elements that replicate not only its dimensions, but also its functionality via simulations, referred to as a digital twin [27]. Issues can arise when integrating the metaverse with the physical world systems. These issues can be categorized into two parts as technical and non-technical. A brief summary of those issues is presented through Table 1. Apart from these concerns, application-specific issues may exist as well.

It is important to recognize that metaverse requires advanced network requirements such as high bandwidth, end-to-end congestion control, guaranteed quality of service (QoS), and ultra-low latency. Satisfying such network requirements using a shared network can be extremely challenging [28], [29]. Network slicing, where multiple end-to-end networks are created on shared physical infrastructure, acts as a solution to this problem. Different network slices can be used for a specific application or a service [30]. Network slices can also scale up and down according to the service requirements [31], [32]. Network resources to metaverse applications can be allocated according to the demand to facilitate the recommended QoE to the user, while optimizing the resource usage in the network. Since isolation between the slices is possible, security and reliability can be enhanced significantly [33]. Therefore, network slicing enables performance improvement, security and privacy, and management characteristics such resource management, which are key requirements of the metaverse [34].

The metaverse is massive in scale, and consists of a large number of virtual worlds that require interoperability with each other. Virtual worlds must be rendered in real-time and synchronized with the physical world. Edge computing provides distributed infrastructure located near the user and connected to the network using high-speed backhaul connectivity. The backhaul connectivity can be wired, wireless, or hybrid. In [26], Lim et al. highlight features of the metaverse architecture that consist of cloud-edge assisted rendering, cloud-edge AI model training, and cloud-edge blockchain mining, available under the computations. Further, it highlights the base station edge AI model, device-to-device data caching, and optimal cache replacement, which an edge storage facility can provide. Edge computing enables the implementation of ultra-high definition (UHD) video streaming, VR/ XR/ mixed reality (MR) based applications, which are the key underlying technologies for the metaverse [35].

A. RELATED WORK

Although novel, a considerable number of surveys and research studies are still available on this topic. However, studies focusing on the realization of metaverse with a telecommunication technological approach are limited. The metaverse's ecosystem and technological background are discussed in the survey [5]. It provides a comprehensive review of the development and the building blocks of the metaverse in technical and non-technical aspects. However, [5] provides only a brief overview of the telecommunication technologies for metaverse realization. The authors in [36] present the implementation feasibility of metaverse at mobile edge networks, considering the computational, communication, networking, and blockchain perspectives. They discuss a reference architecture, developments, and tools of the metaverse, and provide a brief overview on the telecommunication technologies for metaverse realization. Although the edge computing approach is discussed, it focuses mainly on edge intelligence-based techniques. In [26], Lim et al. discuss the edge intelligence-based approaches, that consist of edge computing combined with artificial intelligence for the metaverse realization. Also, it provides a holistic view of the metaverse ecosystem and proposes a framework for virtual city development, highlighting the cost and resource allocation. Furthermore, [26] identifies redefining user QoE, beyond 5G (B5G) and the metaverse, interoperability standards, security and privacy, and economics of the edge-driven metaverse as open research challenges. A general overview of the technological aspect of the metaverse, and the implementation challenges are highlighted in [24]. The authors of [37] provide an overview of the metaverse concept and how 6G is important for the metaverse implementation.

The comparison of related work and this paper is presented in Table 2. To the best of our knowledge, there has not been a study of the role of future telecommunication technologies in the metaverse realization, considering network slicing and edge computing.

B. CONTRIBUTION

Although network slicing and edge computing with the B5G are potential techniques for metaverse realization, studies on network slicing and edge computing for metaverse realization, are rare. Therefore, it is important to discuss the technical approach to realize the metaverse with the novel and rapid changes of the telecommunication sector in 5G and B5G technologies. Our technical survey investigates the importance of network slicing and mobile edge computing for metaverse realization.

Specific contributions of this paper can be enumerated as follows.

1. An overview of how network slicing and mobile edge computing can be used to improve the feasibility of the metaverse is presented.

2. Technical challenges in edge computing and network slicing as enabling technologies for metaverse realization are discussed, and the possible solutions are presented.

3. A holistic framework for metaverse realization using edge computing and network slicing is proposed and comprehensively analyzed.

4. A discussion on futuristic applications of the metaverse is presented, and the technical requirements for these applications are discussed.

5. An analysis is conducted on the technical requirements for the metaverse realization under edge computing and network slicing.

6. The requirements for deploying a metaverse in practice are discussed.

7. Insights on the metaverse realization and implementation are provided, considering network slicing and edge computing.

C. ORGANIZATION

This paper consists of eight sections and is organized as follows. Fundamentals, concepts of the metaverse and contribution of the paper are discussed in Section I. Background on network slicing and edge computing are presented in Section II. In Section III, an edge computing and network slicing-based holistic framework is presented for the metaverse realization, together with a discussion of its functions. Section IV presents possible futuristic applications. Technical requirements of the metaverse, and possible solutions using network slicing and edge computing are discussed in the section V. Metaverse deployment challenges are discussed in Section VI. Insights gained are presented in section VII, and Section VIII concludes the paper. Fig. 3 illustrates the summary of the paper organization.

II. BACKGROUND

The background information related to edge computing, network slicing, and metaverse is presented in this section.

A. EDGE COMPUTING

Edge computing can be identified as an open platform available near the data source or near the network's edge. It can provide networking, storage, computing, and edge intelligence to achieve user requirements such as low latency real-time applications, application optimization, and many more [41], [42]. Furthermore, it helps to enhance the services by optimizing the network resources while minimizing network congestion [43]. Earlier, cloud computing emerged as a centralized approach with disadvantages such as high bandwidth requirements, high cost, and high centralized power requirements [44]. Edge computing emerged as an extension of cloud computing, with a decentralized architecture, resulting in advantages such as low cost, less bandwidth requirement, and less processing power [45]. The decentralized architecture of edge computing enables the distribution of computational power, storage space, and other network resources among the edge nodes, enabling flexible and robust deployments for various services. With edge computing, the last-mile latency is reduced to enhance the performance of latency-aware applications [46]. Moreover, with MEC,

TABLE 2. Related works and controbution.

Ref	Context	Importance of edge computing	Importance of network slicing	Technical challenges in edge computing	Technical challenges in network slicing	Deployment challenges	Futuristic Applications
[5]	A comprehensive survey on metaverse, which includes a review of technological background, and ecosystem aspects.	✓	✓	✓	✓	✗	✓
[36]	Discuss the overview of the metaverse and the realization of technologies and implementation challenges. The paper describe the feasibility of the metaverse realization through edge enabling.	✓	✗	✓	✓	✗	✓
[26]	Discuss an edge intelligence-based infrastructure for the metaverse.	✓	✗	✓	✓	✗	✓
[24]	Discuss the technological aspects of the metaverse and implementation challenges.	✗	✗	✗	✗	✓	✓
[38]	Discuss the general architecture and the available prototypes of the metaverse. The paper's primary focus is one the security and privacy aspects of the metaverse.	✓	✗	✓	✓	✗	✓
[23]	Discuss the importance of edge computing for enhancing the user experience.	✓	✗	✗	✓	✗	✗
[39]	Discuss the technological background of the metaverse along with the current development status. Furthermore, this paper highlights the available implementation challenges.	✓	✗	✗	✓	✗	✓
[40]	Discuss the computational arts and the implementation in the metaverse.	✓	✗	✗	✓	✗	✓
[37]	Discuss the technical requirements of the metaverse and the importance of 6G for metaverse realization.	✓	✗	✓	✗	✓	✓
	This paper.	✓	✓	✓	✓	✓	✓

latency values less than 10 ms can be expected [47]. A high-level diagram of edge computing is presented in Fig. 4.

Key features of edge computing include dense geographical distribution, mobility support, location awareness, ultra-low latency, masking cloud outage, high bandwidth, virtualization, and proximity [48], [49], [50], [51]. Edge computing can be mainly categorized into fog computing, mobile edge computing, and cloudlets [52]. In Fog computing, the networking plane consists of two planes: the control plane and the user plane. According to [53], the endpoint with processing power and storage can be considered a fog node. Cloudlet is a small cloud deployed in a localized and stateless server that runs single or multiple virtual machines [54]. Cloudlets mainly focus on providing low latency high bandwidth cloud services for mobile devices such as tablets, smartphones, and wearable smart devices [55].

Edge computing is a technology capable of implementing micro operating system (OS) and approaches as a container or robust deployment and implementing lightweight libraries and algorithms [56]. Also, this edge-based approach can be used to facilitate V2X communications, location services, video analytics, augmented reality, IoT, local content distribution, and data caching [57], [58], [59]. European telecommunications standards institute (ETSI) standards on MEC started in 2015 as phase 1, phase two in 2018, and phase 3 which began in 2021 is ongoing. 3GPP is planned to provide native support for edge computing in Release 17 for all aspects, covering the application layer architecture, core network enhancement, security, media processing, and management [60], [61].

B. NETWORK SLICING

In network slicing, a physical network is divided into logical networks running different applications, that have heterogeneous requirements [62]. Each network slice is associated with network functions and consists of resources such as computing, networking, and storage [63]. Network slicing enables virtual end-to-end networks with complete isolation, although using shared infrastructure. It is possible to configure each slice with different attributes, such as high

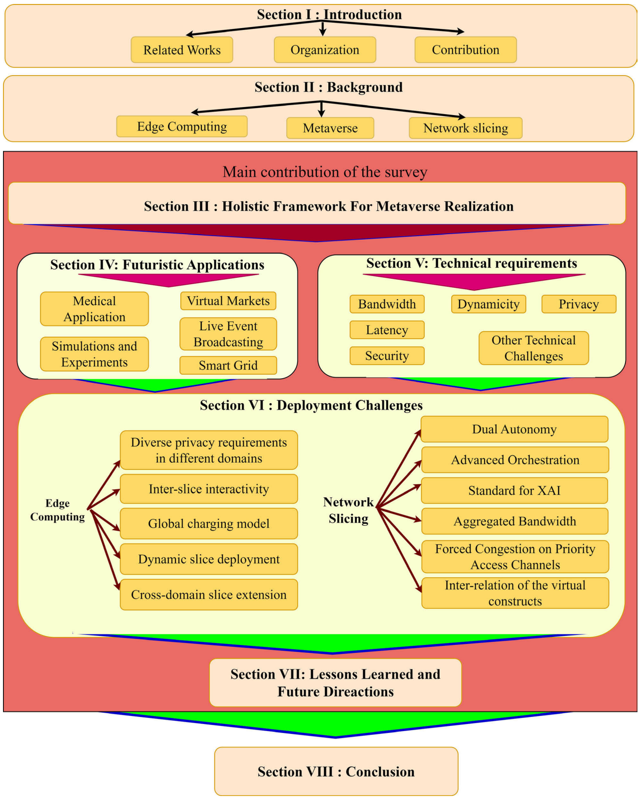

FIGURE 3. Paper organization.

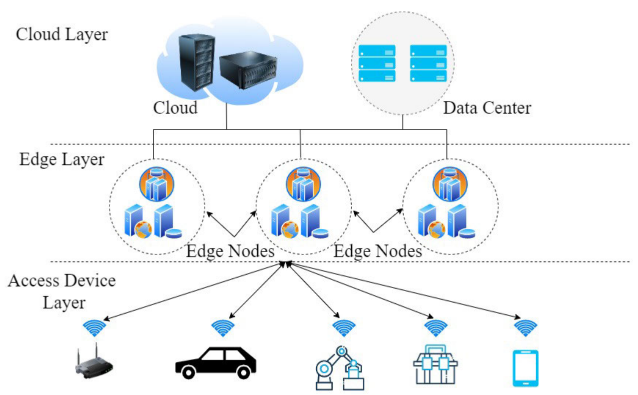

FIGURE 4. A high level diagram for edge computing.

bandwidth, ultra-low latency, and high availability, based on the requirements of the application it is catering to [64]. The users can access multiple slices simultaneously with the same user equipmet (UE) and the same access network. Key enablers of network slicing are software-defined networking, network functions virtualization, edge computing, and cloud computing [65], [66]. A high-level diagram of network slicing is represented by Fig. 5.

Network slicing involves slice creation, slice isolation, and slice management phases. Further, in [67], Afolabi et al. describe that isolation, elasticity, automation, customization, programmability, and hierarchical abstraction as the main principles of network slicing. Slicing is done mainly to achieve QoS requirements and infrastructure sharing purposes [68], [69]. Several standardization bodies, including internet engineering task force (IETF), open network foundation (ONF), next generation mobile networks (NGMN), and 3GPP, have addressed the network slicing concepts towards standardization, with the specifications 23.501, 23.502, and 23.503 [70], [71], [72]. In 5G, network slicing is a key feature in deploying the standalone core network. The four phases in the life cycle of network slicing can be identified as preparation, commissioning, operation, and decommissioning [73]. According to the NGMN, network slicing architecture consists of three layers service instance layer, network slice instance layer, and resource layer [74].

C. METAVERSE

Metaverse can be defined as a large-scale virtual world that connects many virtual worlds to provide an immersive experience to its ecosystem. It is a kind of multi-layer network with high scalability to grow faster than other networks [7]. There are two main possible visions of the metaverse available. The first one is the open, decentralized thing which is maintained and powered by the users and the creators who use it. The second option is a central, closed practice that is owned and maintained by a limited number of contributors and creators, resulting in low flexibility and ownership to the general user. Metaverse consists of characteristics such as immersiveness, sustainability, interoperability, scalability, hyper spatiotemporality, and heterogeneity [38]. User interactive equipment such as game controllers, smart glasses, brain-computer interfaces, smart contracts, haptics, and mobile devices are used to access the metaverse. The below technologies enable the metaverse and its functionalities.

- AI: It is a key technology in the metaverse since the scale of the metaverse, and its applications and functions are high. Automation and AI are needed to manage the ecosystem. AI techniques can be implemented in natural language processing, machine vision, blockchain, networking, digital twin, and neural interface to enhance the functionalities [75].
- Blockchain: Blockchain is a distributed database that stores data digitally with digital asset tracing. It functions as a digital ledger content in the decentralized ledger that can be functional without having any central authority [76], [77]. Blockchain enables accounting and ensures integrity and privacy. Due to these reasons, user data, transactions, and all the ecosystems of the metaverse depend on the blockchain [78].
- Computer vision : Computer vision is a technique used to extract information from images and videos. It includes analyzing, processing, and understanding the content subject [79]. The metaverse extracts the user's surroundings, including activities, and generates a properly enhanced environment and decision-making.
- Networking: Networking is a broad aspect of a metaverse which includes network infrastructure and the chain of the virtual worlds of the metaverse. According

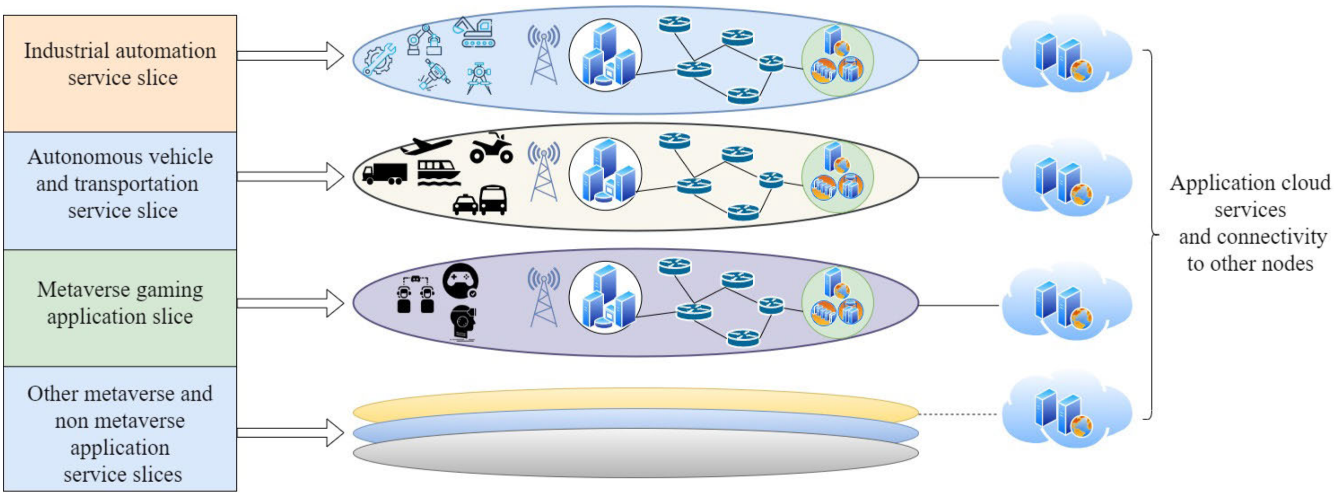

FIGURE 5. A high level diagram for network slicing.

to the metaverse requirements, it needs to deploy or upgrade existing networks since more specific network requirements are available than the existing ones. B5G, guaranteed QoS, network-aware applications, network slicing, and congestion control are the major requirements in the networking section [5].

- Edge computing: In edge computing, a portion of the network's resources are put forward to the provider edge to supply a high-quality service with low latency. This technology has a distributed architecture and is a preferred networking approach for metaverse realization.
- Extended reality: Extended reality means any kind of special computing technology consisting of augmented, virtual, and mixed reality technologies. A special collaboration for interactive data transfer in education and business is identified as the future predictions on XR and metaverse.
- IoT & Robotics: 5G and B5G networks have massive type connections, including IoT. In the metaverse, IoT can extract data from the physical world and transfer it to the virtual world. Robotics are also heavily useful to enable automated functions in the real world that link to the metaverse.
- AR/VR: In VR, users are virtual and have no interaction with the physical world. AR is a technology where computer-generated interactive objects reside in the physical world. Both these technologies can enable via access devices and can access the metaverse with high QoE.

Several use cases of the metaverse are available, and many use cases remain emerging with the improvements. A few of the use cases are mentioned below.

- Gaming: Many interactive games are released frequently, and the audience for the game keeps increasing. Immersive features of the metaverse can increase the QoE in an advanced manner.
- Immersive commerce: Immersive shopping experiences based on VR and experience in virtual real etates can be identified as metaverse-based applications with huge potential.
- Learning and education: Interactive classroom learning and simulation-based learning methods can be enabled in distance learning. Further skill-based self-learning is also possible to implement.

Due to the novelty of the metaverse concept and less adaptation to the existing ecosystems, still, standards are lacking. Metaverse standards forum is one of the leading forums created for accelerating metaverse adaption and open standard development of the metaverse with the cooperation of many companies interested in the metaverse and its services [80]. Due to the advanced features and the sensitive involvement of the user, it is important to develop proper standards and regulations that can minimize the activities prohibited by law and fair use.

Metaverse platforms can be deployed in three main formats open, close, and hybrid. A brief description of each format is mentioned below.

1) OPEN METAVERSE

An open metaverse is a decentralized and shared space for all users and service providers. Decentralized implementation reduces censorship while distributing the ownership among the users to achieve a high diversity [81]. In this platform, internal structure, codes, and all network building blocks need to be open source, and transparency of the flows should be there. Content creation and all the functions need not depend on the central owner; users and service owners can deliver them subject to the agreed code of ethics. Compared to the other networks, the metaverse is more likely to be more advanced in the sense of features as well as enabling technologies. The open metaverse approach may allow more freedom to users in the network, such as permissionless access, service creation, and content creation. Such features may strengthen the deployment, but the regulatory framework needs to be applied to all the layers, the service function, and the openness for better network sustainability.

2) CLOSE METAVERSE

A close metaverse is mainly centralized and consists of features with more limitations than an open metaverse. Ownership is distributed among a few stakeholders, and users have minimum ownership of the virtual platform. Here, the platform's internal structure, codes, and building blocks are private, and only users are allowed to use application-level output. Content creation and all other functions done by the users are subjected to specific terms and conditions imposed by the owners of the close metaverse.

3) HYBRID METAVERSE

This approach consists of both features related to the open and close metaverse. Some of the features discussed under the open metaverse are too ideal for implementing actual implementation. For example, user access to the metaverse needs to be monitored or appropriately governed. Ownership can be distributed within the community, but few central authorities related to the same community require regulation for decision-making. Maintaining this platform requires a considerable cost, especially for optimization, partnerships, network infrastructures, and many others. A close metaverse can efficiently allocate money and infrastructure since ownership is distributed among a few stakeholders. However, in an open metaverse, it is difficult since no specific governing body or responsible party is involved in this function. So, it is essential to define the structure and governing bodies for an open metaverse.

III. NETWORK SLICING AND EDGE COMPUTING ENABLED METAVERSE: A HOLISTIC FRAMEWORK

A holistic framework for metaverse is presented in this section which is based on the network slicing and edge computing.

A proper framework is essential in realizing the metaverse and deploying metaverse applications in a live functional network. Due to the requirement that the metaverse is heterogeneous, specific network characteristics must be used. As previously discussed, metaverse realization cannot be achieved with exact requirements and QoE in long term evolution advanced (LTE-A) or previous versions of networks. Launching metaverse-related applications only in 5G and B5G networks is possible. All the main layers of the mobile network, access layer, aggregation layer, and core network layer, should be compatible with achieving the required QoS and network criteria.

According to the ETSI MEC framework, edge management can be mainly identified at two levels, i.e., system level and host level. The host level enables and provides the virtualization infrastructure and application functionality. System-level facilitates the abstraction of the MEC system, and it manages the third-party access. Generally, edge service orchestration events can be identified as life cycle management and initiating and terminating of an application [82]. As shown in Fig. 7, edge computing and network slicing have life cycle phases. Those phases must be appropriately synchronized to avoid service deployment or QoS issues related to metaverse applications. This proposed framework uses a resource manager for that requirement which can internally match the life cycle phases of both edge computing and network slicing depending on the metaverse application requirement. In this framework, it needs to intensely discuss the automation and programmability of life cycle event management. A commercial network may consist of several metaverse and non metaverse services, which require different QoS and network requirements. End-to-end processes must be adequately automated to provide such requirements with high availability. Furthermore, optimization is vital regarding network resources, resource allocation time, service migrations and operational functionalities.

Network slicing-based approaches are helpful in hardening privacy issues available in the metaverse. It is possible to configure the different security levels and policies for the slices in which metaverse applications are deployed. A particular network slice can be mainly sliced as a core network slice and radio access network slice [73]. The slice pairing function used in the network slicing architecture can pair slices, and the network slice manager does all slice management. In the metaverse realization procedure, it is also vital to consider network ownership and orchestration purposes. There can be infrastructure as multi-operator use shared resources as well. It needs to consider the edge network deployment with this fact because sometimes edge devices, e.g. cache servers deployed by the application provider itself. One slice of the core network should be possible to intercommunicate with many radio network slices, and Compatibility needs to support both directions. In this framework, all network slices are associated with on premises or cloud based application servers to continue their particular services and data transmission.

In this proposed framework shown by Fig. 6, the combined network slicing and edge computing approach is used to implement the realization of metaverse applications. The physical network is virtualized, and network slices are defined here for metaverse and non-metaverse applications. The metaverse slices are capable of communicating between metaverse slices as well as the non metaverse slices. As per the proposed framework, users can access metaverse applications such as medical, sports, and transportation applications using an access device. The networking slicing manager is introduced to manage all slice management function maintenance, and an edge computing resource manager is included to handle the edge computing resources in line with the slicing manager changes. AI, ML platform integrated with the resource manager to implement and be aware of possible future changes such as high user spikes and emergencies based on the old data. AI and ML platform is suggested to integrate with the resource manager to predict and analyze the resource allocation since allocation between slicing,

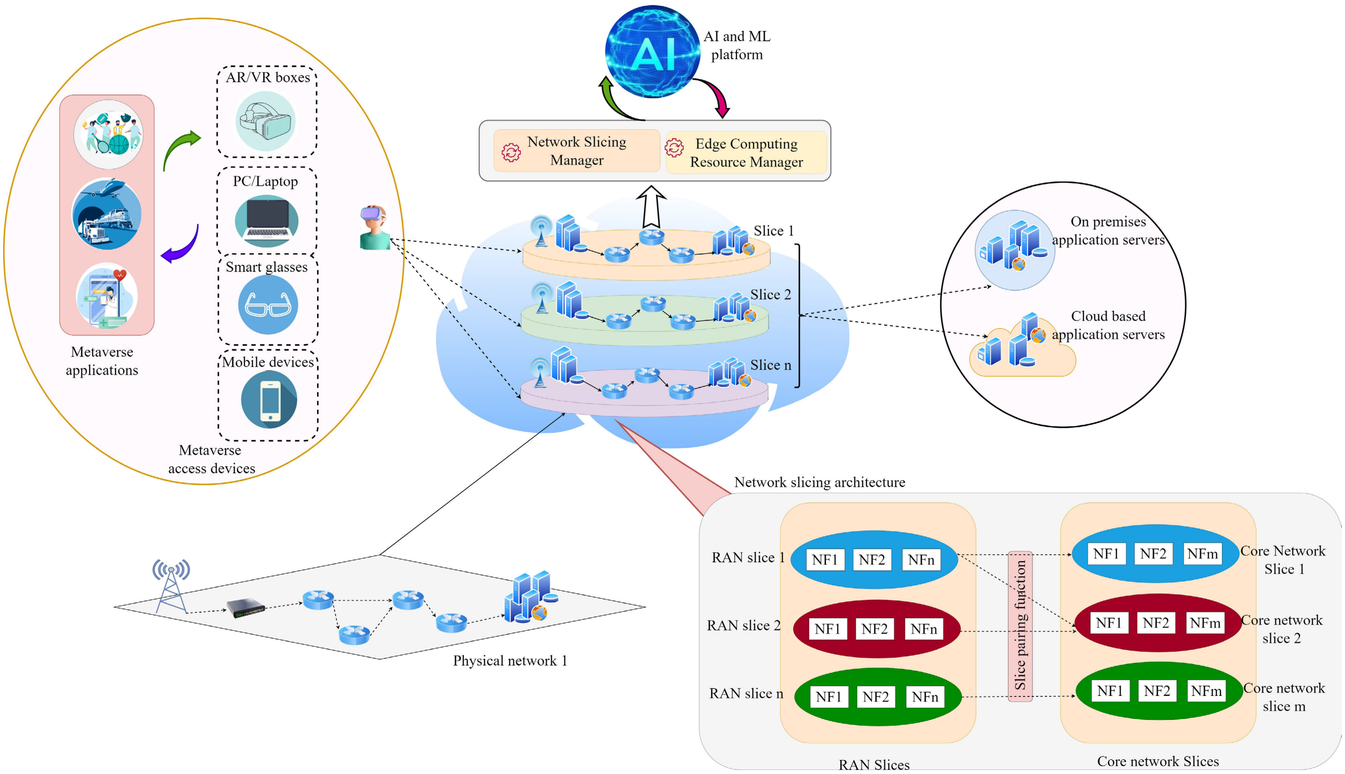

FIGURE 6. Sample metaverse realization framework.

and edge computing combination is complex and fast phase dynamic. This platform can be powered with advanced optimized algorithms and predictive methods to predict the future behaviours of the metaverse network. Further, it can feed the user behaviour data of metaverse applications to AI, ML platform for better output.

In this framework, all network slices are associated with on premises or cloud based application servers on continuing their particular services and data transmission. This framework needs to be more focused on end-to-end slice isolation due to core and access slice data communications. It is proposed to pre-configure the network slice parameters with a range of values such that network resource thresholds sustain. There can be many challenges when implementing this framework, and identified concerns are mentioned below.

- Integration with the existing networks with the same network operator.
- Greenfield deployment and interconnect between other network operators.
- Optimally and possible vulnerabilities of the proposed framework.

IV. FUTURISTIC APPLICATIONS

It is essential to identify the practical use cases of a concept as well as the realization of the concept. When considering the metaverse's potential, it can provide many use cases depending on the requirement. The main concern for some implementations is the lack of solid infrastructure, including access equipment and an overall framework. Futuristic applications which can be implemented on top of the metaverse are discussed in this section.

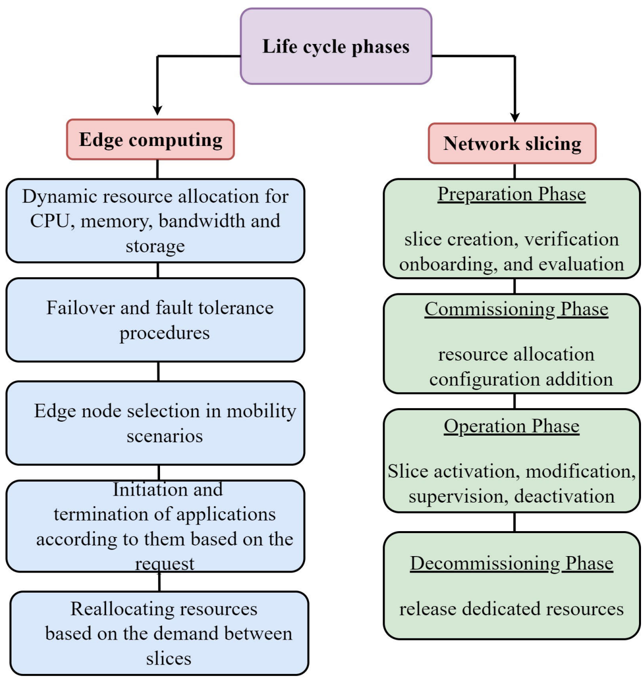

FIGURE 7. Life cycle synchronization in between edge computing and network slicing.

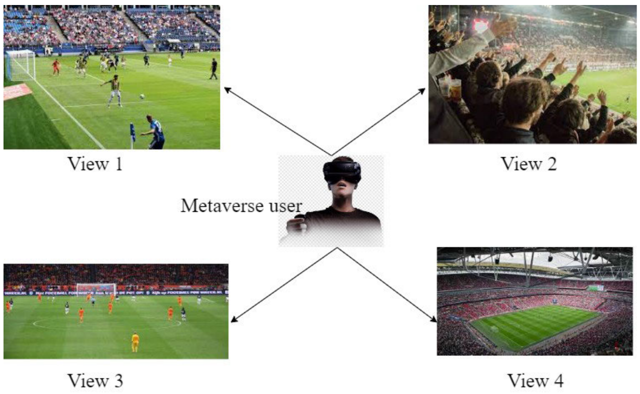

FIGURE 8. Metaverse for broadcasting applications.

A. BROADCASTING OF LIVE EVENTS

There is a high demand for live events in sports like football, cricket, the Olympics, and many more. Many spectators may need to watch a game at the venue where the game is played. However, only a limited amount of space is available, and many of the spectators who wish to watch the game may be unable to attend the event. It is possible to provide a service in the metaverse for such scenarios via VR technology, with an immersive experience. It may unlock the boundaries and allow many to watch the game live from all over the world. Similar to the prices of the tickets related to the specific location of the stadium, it can categorize the price and packages based on the QoS provided to the user. Separate packages can be included with the quality of data rates, multiple event views such as the ones shown in Fig. 8, repeat facility, zoom-in zoom-out facility, interaction with the other spectators, separate places to watch the event, and many more features. The maximum QoS threshold can be defined based on the configurations of the metaverse service slices. Furthermore, this application can use edge computing nodes for caching and rendering purposes. The number of allowable users can be estimated based on the usage, and if any resources unutilized, it can be notified to the users who wish to watch the event. The same procedure can be implemented for live events such as musical concerts and large gatherings.

B. SMART GRIDS

Smart grid applications have become famous for efficient energy usage and energy saving. Metaverse features can be effectively integrated with the smart grid functions. This can be implemented from the user and sub-domain perspectives such as operations, bulk generations, transmission, distribution, service, and service providers [83]. Energy management, demand management, and advanced metering systems can be effectively launched through the metaverse while facilitating a digital money transaction between a user and the service providers. As an example scenario, consider that there is a user having multiple buildings, and the electricity is supplied from multiple service providers based on demand management. Metaverse-based smart grid application can be deployed as shown in Fig. 9. Through the metaverse

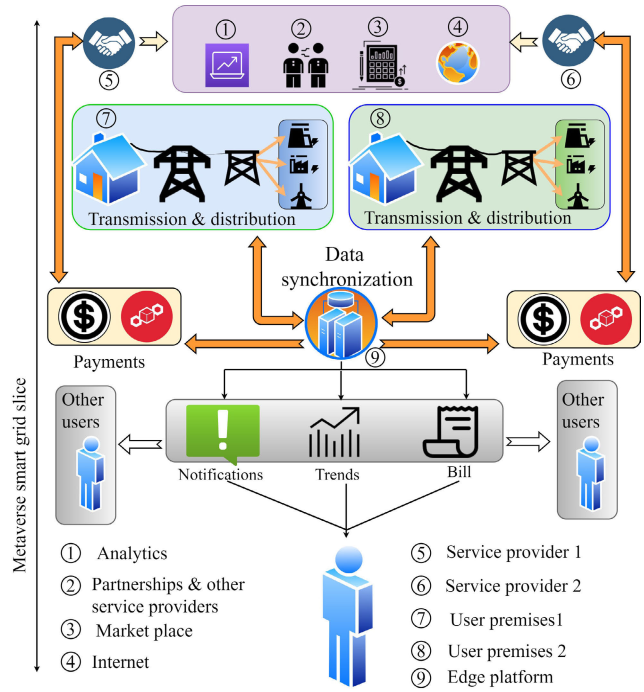

FIGURE 9. Metaverse based smart grid applications.

application, providers can use smart metering techniques to provide the total bill amount of the user, visualize the statistics and trends, and pay the bill by a digital payment method such as NFT. Further, it is possible to adjust the demand management preferences via the same application in an interactive manner.

C. MEDICAL APPLICATIONS

Telemedical applications are becoming very popular, mainly due to the availability of remote patient data collection methods. Currently, there are many remote-based medical approaches available such as telemedicine, telesurgery, telemonitoring, and even more focused on the cloud-based IoT e-health applications [84]. Metaverse-based medical facilities can be provided more efficiently without the point presence of the patient in a particular location. It can enable consultation from foreign countries without travelling, and periodical checks can be done quickly, removing the geographical barriers [85]. Approaches such as holographic construction, holographic emulation, and virtual reality integration can be used in the metaverse for telemedicine purposes [86], [87]. These metaverse medical applications can also be extended up to a level of remote surgery. These applications are essential in pandemic situations such as COVID-19. In such scenarios, remote isolation centres can be equipped with the required wearable and remote measuring equipment, and consultation can be done via the metaverse application for the patients. Fig. 10 shows the example implementation of a metaverse-based medical application for remote patient monitoring. The medical examiner and the patient are located at two geographical locations and are connected via the metaverse

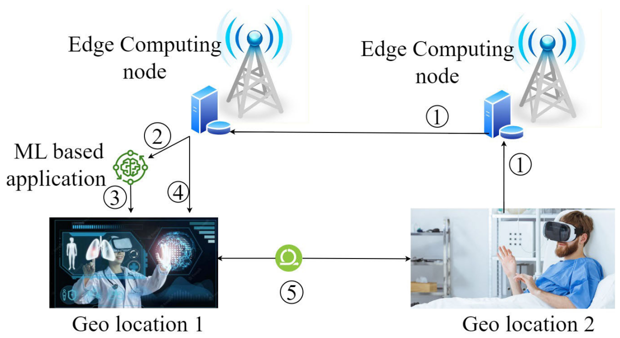

FIGURE 10. Metaverse-based medical application for remote patient examination.

medical application. The user may be equipped with wearable devices for clinical data collection, and the collected data is transferred to the medical examiner for analysis. Collected data is subjected to an intelligent analysis that can provide insights about the disease, which can be obtained using this patient's old records and common patient databases. The output of the ML application and patient's data records are fed to an interactive dashboard which the examiner can easily refer to.

Different guaranteed QoS and SLA are required based on the type of medical purpose. Surgeries and emergency check-ups can be assigned high QoS and high priority over other medical scenarios. More value addition can be done for the healthcare services because those are associated with many other service chains. For example, it is possible to deliver checkup reports and medicines to a particular location after the patient's medical examination. Payments for the services and health insurance facilities can be provided by linking with the metaverse healthcare applications. Further, collected data can be efficiently used for predictions using AI and ML techniques, and it helps to warn the patients. For example, if a heart patient's heart rate becomes abnormal with an ongoing activity, it can be used to warn the user or the nominated caregiver quickly. Furthermore, many other applications such as awareness programs can be integrated.

D. VIRTUAL MARKETS

Virtual marketplaces in the metaverse is a topic with a large scope and includes various services. In this, services and products can both be considered for metaverse-based implementation. Due to the productivity of the metaverse-based market platforms, a worldwide trend for virtual marketplaces can be expected. This approach allows some products to be checked and tested virtually before the actual usage. This can be identified mainly as two parts: trading virtual assets in metaverse such as virtual real-estate, virtual buildings, virtual outfits, and things related to each application and trading which link with the physical world businesses. As an example for the first scenario, it is possible to trade a virtual real-estate which is built in the metaverse for the buyers.

Blockchain-based digital currency can be used for money transactions, and ownership of the particular virtual real-estate should be transferred to the buyer. Importantly, the virtual asset's ownership should not be altered by any kind of method without the permission of the owner. For the second scenario, if anyone orders a dress from a foreign country, metaverse makes it possible to fit on and check the dress before it delivered. It is easy to build interactive virtual show-rooms instead of the multiple high cost physical showrooms. Money transactions in the virtual marketplace can be done via blockchain-based currencies, which assure the authenticity of the money.

Furthermore, it is required to link the money transactions with the relevant company outlet, and the goods need to be delivered to the proper places physically as ordered. This kind of virtual market-based application can be run on top of selected metaverse slices according to the network requirement such as bandwidth and latency. Edge computing can be integrated with network slicing for caching, asset authentication, transactions, and many more. It should be possible to extend the particular slice in which services are deployed towards the service receiver, or if it is not possible to provide the connectivity via the slice, it needs to be informed to the user via the application before use.

E. SIMULATIONS AND EXPERIMENTS

Simulations and experiments are important for new findings and technological advancement in every field. There are many constraints for experiments and simulations such as high cost, unavailability of resources, health and social impact, limited space, and many more. Due to these reasons, technological advancements and developments are hindered due to the unavailability of enough experimental setups. Educational institutions can effectively use virtual experiments to perform physical world activities that are affected by the previously mentioned boundaries. They can also reuse the same model of the simulation or experiment by enabling minimum recreation of the scenario. The fields which need prior visualization can productively use this approach to develop the real-world object with fewer modifications from the real world. The automobile industry needs a large number of simulations in every process of production. A considerable amount of expenditure can be saved by adopting the virtual model simulations in the metaverse.

Further, architectural design also requires visualization and the ability to experiment with the design before finalizing it. The majority of architectural firms use these simulations that are implemented using computer-aided design programs [88]. Enterprises can implement metaverse simulations to improve supply chains. Virtual models can be implemented in the metaverse and can be trained on real-world data. As an example, IoT-based real life data collection can be used in a synchronous manner with a virtual model for better output results in the simulations.

V. TECHNICAL REQUIREMENTS

The technical requirements of the metaverse realization are discussed here with network slicing and edge computing perspective and identified technology requirements are mentioned here with the possible implementation solutions. There can be many challenges due to ongoing technological advancements as well as due to the network topology of each operator, service restrictions in the region, rules and regulations in the country, etc. Technological issue fixing can speed up the metaverse implementation in real networks. Technical requirements are discussed below under bandwidth, security, scalability, dynamicity, privacy, and latency.

A. BANDWIDTH

Bandwidth affects the amount of data transmitted through a network within a specific period. Metaverse applications are expected to be bandwidth hungry applications, through both uplink and downlink [100]. Since metaverse consists of high-quality video content, graphics, and large number of transactions, a high bandwidth is required for maintaining the QoE and QoS levels. A large amount of metadata created by sensors also acquire a considerable amount of bandwidth for transferring the data [101]. Ideally, symmetric high bandwidth links need to be supplied from the network operator or the provider end, to transport and synchronize the data between the user and the application. Providing high, fixed bandwidth for several users may become a challenge from the network provider's perspective when the number of metaverse-based application users keeps increasing. It is not possible to upgrade the backbone network to provide more bandwidth within a short period, as it requires considerable time for planning and implementation. The bandwidth for an operator includes the bandwidth inside the network and the international bandwidth used through high-speed fibre, satellite, or submarine cables. Though operational expenditure (OPEX) and capital expenditure CAPEX can be reduced and the return on investment (RoI) can be increased by optimizing both bandwidths without over-idling or over-congesting, it is a challenging task to fulfil the dynamic resource requirements.

VR technologies require large bandwidth througout the session for a quality user experience. The experience factors of cloud VR are based on the sense of reality, interaction, and pleasure. In cloud VR, the following factors are affected by the bandwidth.

- Frame rate
- Color depth
- Resolution
- Transmission mode
- Coding and compression technology

According to real test simulations and theoretical analysis of Huawei, it is found that a data rate above 260 Mbps is required for a comfortable cloud experience in 4K panorama, and over 1 Gbps is required for an ideal experience. Metaverse application users use other applications and services with different QoS. Also, the same internet connection may serve other services while serving metaverse services. Providing bandwidth for such scenarios under different QoS levels is also quite challenging. Specific techniques need to be used for bandwidth allocation and management in or near the customer premises.

Possible Gains From Integrating NS and EC: The metaverse requires bandwidth for signaling traffic as well as payload traffic. By deploying edge computing nodes, the amount of data transfer over transmission links to the central servers hosted in the core or public cloud servers can be reduced. This edge-based implementation can effectively use data management methods such as caching, processing, collecting, and storing [102]. Below are a few possible bandwidth-saving approaches that can be implemented on edge computing nodes.

- Function Automation: Some of the service functions can be automated and arranged to obtain decisions at the edge and transmit back to user devices without transmitting throughout the transmission network. For example, service functions of metaverse-based smart manufacturing and smart home applications can easily automated while reducing the response time.
- Data Replication: Data replication is a method used to keep replicas in multiple locations for high reliability and fast access [103]. Proper data replication mechanism implementation at edge nodes can improve the QoS while reducing the bandwidth consumption [104].
- Data Caching: Data caching is a method that stores multiple copies of data in a location to improve accessibility. In the metaverse, the same content can be used repeatedly, such as in the user's background in a virtual world. Optimized caching implementation can improve the QoS and latency while saving the bandwidth and the access cost [105].

Further data dissemination and analysis methods can be implemented on edge nodes to save bandwidth as a solution.

B. SECURITY

There are many security-related challenges in the metaverse as well. Since all the transactions happen through NFT and digital currencies, it requires high security to avoid fraud. Since the metaverse is an extensive distributed network, the attack surface is higher than a typical distributed network. Many areas such as user device security, network security, application-level security aspects, data management security concerns need to be addressed under the security of the metaverse. In [38], Wang et al.. classify the security threats under the main seven categories as identity, data, privacy, economy, physical, social effects, and government.

TABLE 3. Role of network slicing and edge computing for metaverse and its pertinent deployment requirements.

Metaverse Futuristic Application	Edge Computing and Slicing based Solution	Technical requirements						Deployment Challenges
		Security	Scalability	Privacy	Dynamysity	Bandwidth	QoS	
Live events broadcasting [89], [90]	Network slicing can be used for the on-demand slice creation for the metaverse applications, and edge nodes can be used for caching and rendering purposes.	L	H	L	H	H	H	Resource allocation can be unpredictable due to high user addition in a limited time.
Smart Grids [91], [92]	Deploying a separate slice for slice management that can intercommunicate with the slices of the other services. Using edge nodes for data analytics, report generation, and monitoring data synchronization with relevant applications.	M	L	M	L	L	M	Interworking with the non-metaverse applications, as well as legacy nodes, due to all the systems not working in the metaverse application.
Medical and healthcare [93]–[95]	Separate network slice deployment for the service and allocation of edge resources with the SLA for minimum network requirements.	H	L	H	M	M	H	Guaranteed minimum QoS needs to be provided constantly with a backup plan due to service criticality, e.g., telesurgery.
Virtual Markets [96], [97]	Network slice deployment in a way that supports high data transactions between the other service slices. Contributing edge nodes for the caching and authentication services.	H	L	H	M	L	L	High security is required since real-time money transactions need to be performed and interaction between the other service slices is high.
Simulations and Experiments [98], [99]	Allocation of different slices with the QoS specified for the application. Using edge nodes to provide services with low latency and optimization.	L	M	M	M	H	H	Particular services are required only for a specific time and need dynamic resource allocation.

H High Impact M Medium Impact L Low Impact

Identity-related security threats are common due to many data transactions between the user device and the metaverse applications. Common data-related security vulnerabilities are integrity breaches [106], falsified data injection replacing the actual data, and theft of sensitive biometric data. Privacy data leakages can be identified as another security issue in the metaverse. Metaverse access devices such as AR & VR head mount devices can have vulnerabilities that can cause exploitation by an unauthorized party. In such a scenario, an unauthorized party can compromise the data that flows into and out of the device [107]. Many metaverse devices will be waiting to connect to the metaverse, and it is possible to deliver DDoS attacks toward the application servers by generating high traffic. Such kind of high traffic will cause network congestion, and it will lead to network service interruptions as well.

Metaverse can be used to create many things, including avatars, virtual buildings, real estate, and typically any digital twin of a physical world. These things can be considered digital assets in the metaverse. Validation and authentication of these digital assets is also a complex task as a massive amount of digital assets are available under different users, and the ownership changes often. Digital assets can be recreated easily, leading to deep fakes too [107]. So it is a huge challenge to protect the digital asset from copies and the redistribution throughout the metaverse [5]. In the metaverse,

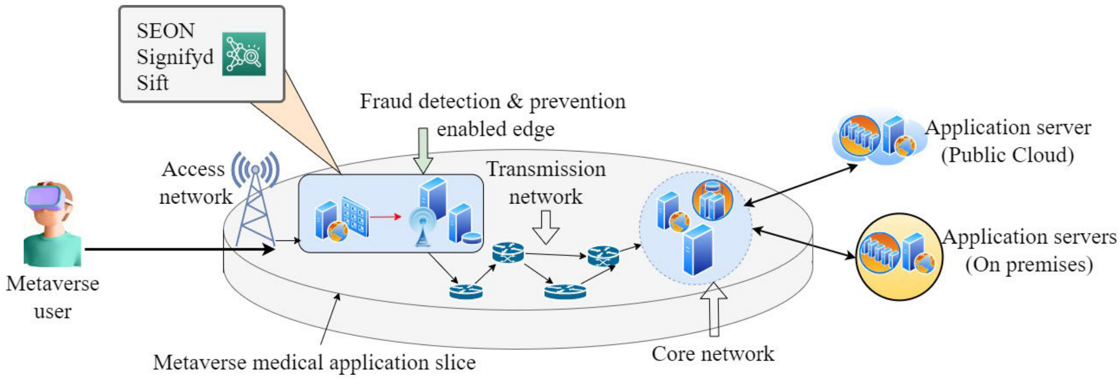

FIGURE 11. **Fraud detection in a metaverse medical application.**

there are no proper standards or authority to detect or prevent fraud. Due to the lack of regulatory measures, fraudsters easily launch defrauding attempts toward the users and application providers. Account takeovers, irreversible transactions, scam projects, fake reviews, affiliate frauds, multi-accounting frauds, and market manipulation frauds can be identified as some of the frauds related to the metaverse.

Possible Gains From Integrating NS and EC: Metaverse requires an efficient and secure identity management procedure that can solve most identity-related security concerns. Typically, digital identities three fold [38]. First is the central identity that manages identities by the primary node [108]. The second one is the federated identity which drives the digital identity by more nodes or accounts. Finally, a self-sovereign identity that manages the identity ultimately by each user [109]. Blockchain-based data storage can mitigate data tampering, theft, and many data leakage issues mentioned previously. This decentralized approach of blockchain enhances the security, fault tolerance, privacy, and controllability of the data as well [110]. Edge computing can be effectively used for providing blockchain-based services such as blockchain as a service (BaaS). Already, Microsoft provides BaaS in Azure cloud services. In [111], Xiong et al. provide a prototype for mobile blockchain in edge computing infrastructure. According to this approach and the proposed approach in [110], an edge computing-based blockchain approach can be provided to minimize security concerns.

Edge computing nodes are less likely to be attacked due to the small scale and distributed architecture compared to the centralized cloud infrastructure [112]. The Attack surface of the data is higher when information is transmitted to the core network, core servers, or cloud situated at the far end of the network. Hence edge computing can store compassionate data, authenticate the user at the edge itself, and only transfer the sensitive data for compulsory requirements. This approach may harden the security of the sensitive data, reduce the attack surface, and reduce the possibility of data exploitation. Guo et al. [113] proposed a distributed authentication system to improve asset authentication based on the blockchain and edge computing. This proposed method uses edge computing as a blockchain edge layer to provide name resolution and edge authentication based on smart contracts. Frauds can't be mitigated completely because the fraudsters evlove by identifying new methods. As shown in Fig. 11, fraud identification and prevention applications can be implemented for specific metaverse application slices to identify and prevent fraud. The application can be implemented as owned by a specific network operator or another global vendor. In this implementation, edge computing servers can be equipped with fraud prevention and detection applications such as SEON, Signfyd, Sift or any other custom made application. This service can be implemented as a separate service add, allowing users to subscribe based on their preferences. If the user does not select the particular service, then user traffic should bypass the fraud detection and prevention server.

C. SCALABILITY

Scalability is an important characteristic as well as a technical challenge for the implementation of the metaverse. The metaverse consists of sub-metaverses, and the number of sub-metaverses may increase exponentially. This is more like a scale-free network like the internet and the blockchain. Scalability of metaverse means the possibility of maintaining the services by providing configured QoS according to the agreed SLAs. Scalability needs to be provided using the underlying network infrastructure. Scalability is required both ways as scale-up and scale down, and all the QoS parameters in a metaverse platform should keep uniform under variations of scalability requirements. Scalability can be identified as scaling up and down the resources without affecting the end user experience [114]. The physical world is enormous and has many dimensions which need to synchronize with the virtual world. Therefore, scalability can be challenging when the amount of content and the number of users become massive [115]. Changes in the number of online sub-metaverses inside the metaverse, the number of concurrent users, the quality of the services, and the number of interactions can be considered as the factors that affect the scalability. It is required to predict the network growth for the next few years by creating a proper scalability plan and a strategy since the metaverse grows exponentially. Furthermore, service providers need to allocate and plan the future network capacity according to the scalability of the metaverse in terms of bandwidth, QoS parameters, storage resources, content delivery servers, number of active users, and network technologies.

Large-scale real-time resource allocation for a distributed application can be identified as one challenge for scalability [116]. Furthermore, simultaneous QoS maintenance for users with a typical application can be quite complicated, with the number of users changing. Service providers with different operational characteristics also add more complexity to the scalability. In a concurrent user increment scenario, scene complexity increases, and updates need to be sent to all the users. Hence the resources need to allocated with the incrementing user numbers to maintain the agreed QoS. This is a scale-up scenario, and CPU, memory, bandwidth, and all the processing requirements need to scale up. In this scenario, CPU utilization of the application servers can lead to low QoS due to the reduction in frames per second rate, which occurs due to the lack of processing resources. Network traffic also increases in a quadratic manner, and serving traffic to other services under guaranteed QoS becomes challenging.

Possible Gains From Integrating NS and EC: Above mentioned challenges are barriers to actual implementation, and possible solutions are discussed here with network slicing and edge computing-based approaches. Distributed scene graph (DSG) approach can be used with the edge computing architecture to achieve high performance in scaling by providing the required scene complexity. Lake et al. [117] introduced a DSG-based method to enable more concurrent users and scale the virtual environment successfully. The exact implementation can be used with distributed edge servers by allowing them to handle separate parts of the scene without using a centralized server. Shared resource allocation can be initiated by this method without any degradation of the QoE and the user's QoS. Bruschi et al. [118] Provide a SDN-based slicing mechanism for edge networks to achieve high scalability. In their work, OpenFlow based approach includes fewer rules in the implementation stage but provides high scalability compared to a legacy network.

D. DYNAMICITY

Metaverse is a dynamic platform, and all the functions inside it are subjected to change rapidly. This include Mobility of the users, applications functionality, resource allocation, and all the ecosystems of the metaverse. Most adapted metaverse interfaces are wearable devices such as AR glasses, headsets, and mobile smartphones [5]. These devices are mainly supported for the dynamicity of the user. Dynamicity introduces many challenges for the metaverse, such as maintaining the guaranteed service under the mobility scenario. In wireless technology, the dynamicity of the device brings many challenges to the operator to maintain the QoS. Similarly, maintaining minimum latency, authenticating the user, and providing a minimum bit rate for the device need to be assessed quite profoundly. Handovers during the mobility

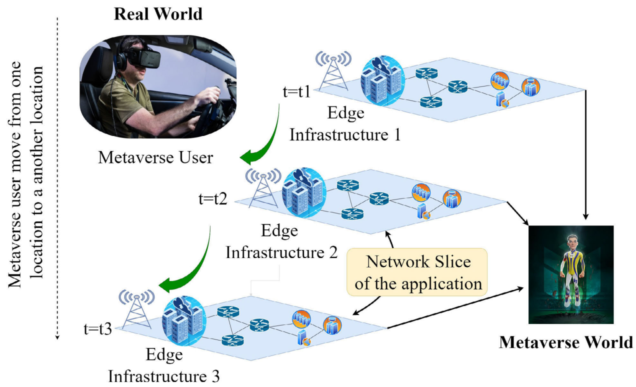

FIGURE 12. High mobility user application in metaverse.

affect the QoS parameters and the stability of the network as well [119]. Dynamic resource allocation for endpoint users with high mobility while maintaining the guaranteed service attributes is a complex procedure. A user or a device which travels on the highway, like a bullet train or high-speed vehicle, may change their access points at high frequency, and other indoor slow mobility users and devices change the access points at very low frequency. So, resource allocation for the user needs to be defined and addressed based on the user's mobility behaviour while maximising the user's service continuity.

Possible Gains From Integrating NS and EC: For example, a user is moving from one location to another with high mobility while using a particular application that needs to replicate his movement and interact with the metaverse. The application needs guaranteed QoS from the start to the end point. As Fig. 12 shows, metaverse users move from one location to another in the real world while using a metaverse application service. Though users move in the real world, the metaverse service should be continued and not be affected by the user's mobility. For this, the serving edge infrastructure need to be changed, as shown in the diagram, according to the user location and the wireless coverage while serving the same network slice for the application. The edge point needs to change with mobility while providing the proper authentication and identification to the user with the agreed QoS. Ouyang et al. [120] proposed an optimized mobility-aware service and resource allocation framework for edge computing. Zhang et al. [121] proposed a logical resource allocation and management framework for 5G considering the handovers of the user. Various mobility-aware slicing scenarios are considered in [121], and QoS requirements are also acknowledged for the resource allocation.

E. PRIVACY

As the metaverse provides an immersive experience and various services, privacy concerns arise more than ever. In the metaverse, details about the user will be shared with the other users, such as the user's actual behavior, gestures, and interaction with the surroundings [122]. Biometric and personal data leakages during the data collection, transmission, and

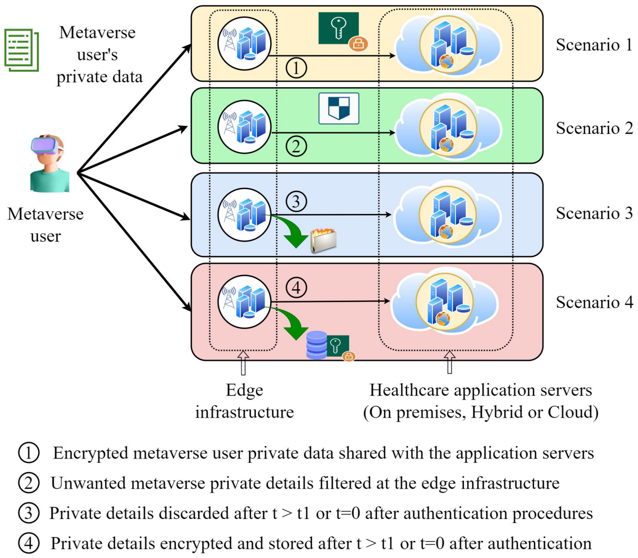

FIGURE 13. **Privacy data management in metaverse healthcare application.**

processing, hacked end device data leakages, and unauthorized access to the user's data can be identified as possible metaverse privacy threats.

A large amount of data is generated from the sensors of the user devices including biometric, physical, and social data. Protecting users' privacy with data distributed throughout the network is a significant challenge. Also, all users may not be adequately aware of the functionality, and there can be users with different technical skills who may not have proper awareness. Such users are more vulnerable to attacks, and those users can be easily tricked into revealing private data such as personal information, passwords, bank account details, and many more. Risks of phishing attacks is also high with the excess amount of user data and due to the large attack surface. In the metaverse, collecting user data, as well as the background data of the places, can be considered the main privacy issue. Some details about the restricted secure places of a country or an organization can be leaked via metaverse when synchronizing the background data related to the specific user. It is also possible to represent fake digital entities, such as buildings and streets, that are not in the real world. Privacy detail misuse can lead to deep fakes and alternative representations of the users as well [5].

Possible Gains From Integrating NS and EC: Data processing at the edge computing nodes can be considered a solution for privacy data misuse. Authentication can be done at the edge, and further, those data can be retained at the edge without being transmitted to the central servers. If authentication data is no more required, those data can be discarded at the edge servers. This reduces the likelihood of the data being exposed to other parties. Privacy data management scenarios related to a metaverse healthcare application are depicted in Fig. 13. Depending on the possibility of offloading some functions, the application can be associated with a combination of edge infrastructure and the core application servers. Four scenarios related to user privacy data management are highlighted, and a summary of these scenarios is given below.

Scenario 1: In this scenario, metaverse users' private data, such as biometric data, and personal health measurement data, are transfered to the edge cloud. Next, data processing authentication functions happen at the core application server, and data need to be transmitted for processing. Thus, data is encrypted with robust encryption methods and transferred to the application servers.

Scenario 2: As in scenario 1, authentication and some processing functions are deployed in the edge infrastructure in this scenario as well. After using private data for processing, those processed data are filtered and transmitted with other relevant data to the core application servers.

Scenario 3: In this scenario, authentication and some processing functions are also deployed in the edge infrastructure. $t1$ is the amount of time for which private data is required for the application functionality. After $t1$ elapses, private data is discarded such that there is no extended use of such data.

Scenario 4: In this scenario, authentication and some processing functions are also deployed in the edge infrastructure, and user private data need to be stored for future processing requirements. So after the relevant processing in which private data used, data is encrypted and stored securely for future use.

Generally, for any scenario, private data need to be shared with the end servers. These servers can apply robust encryption methods to protect the data from adversaries. Since one user generates a large amount of data while using the heterogeneous features for a short time, even the user may not be aware of the information generated. Therefore, edge servers based on private data filtration applications can be hosted and allowed to activate the service based on the requirement. This can act as a protective shield for the user to preserve privacy. Federated learning is a distributed machine learning method deployed using the edge network servers or with the user's edge servers without sharing private details [123]. This technique can be used on the edge infrastructure to secure privacy details without sharing.

Network slicing-based approaches are beneficial in hardening privacy issues available in the metaverse. Configuring different security levels and policies for the metaverse application-related network slices is possible [124]. Slice isolation provides privacy-preserving data isolation between metaverse applications. Furthermore, cryptographical primitives can be used to enhance the privacy of the slices as well [125].

F. LATENCY

Latency is the time to travel data from one point to another and back to the same point [126]. Latency is one of the key important network requirements which should be maintained at desired values for a good QoS and QoE. Most applications require less than 20 *ms* latency, and some need even less latency for real-time synchronization [127]. Especially, 1 *ms* is the maximum expected latency in tactile internet, which is used for haptic device communication [128]. High latency can cause lags in the application and even dizziness and nausea in VR applications [129]. Difficulties in dynamic state and event synchronization between virtual worlds and the natural world is a significant problem caussed by latency [5]. Further, device latency also affects the overall aggregation latency. Motion-to-photon (MTP) latency should be maintained below the perceptible human level to provide an immersive experience in the metaverse applications.

Possible Gains From Integrating NS and EC: Traditional cloud offloading leads to considerable amount of latency in the applications [5]. The majority of existing cloud-distributed networks are not capable of providing the MTP latency requirements. Edge computing can be used for computational purposes and data storage instead of default cloud offloading. Achieved Experimental results with LTE mobile edge than LTE cloud deployments demonstrate the significance of edge computing for reducing the overall latency. Furthermore, edge-based cloud deployments can be efficiently used to reduce the computational power on the user device by offloading heavy computational tasks to the edge servers [130]. Chen et al. showed by an experiment that the LTE cloudlets provide user expectations for more applications than the default and public cloud offloading [131]. Several hops from the edge infrastructure to the application-hosted server can also add more latency. Therefore, the latency can also be reduced by reducing the hops to the network infrastructure in which the application is hosted.

Metaverse applications and services must be deployed with the operator's other services. Network slicing enables the possibility of deploying services based on the different SLAs. Zanzi et al. provides a latency-driven network slicing orchestration that can be implemented in B5G networks to achieve predefined SLAs such as latency, and throughput [132]. Though SLAs can be predefined in this method, it directly affects the OPEX of businesses as well as the OPEX of the service providers. Thus, latency-aware resource allocation methods need to be employed from a business perspective while predicting and providing the minimum latency requirements for applications. A similar approach is introduced by Oladejo and Falowo, which is a latency-aware dynamic resource allocation method used in multi-tier 5G networks [133]. Some of the low latency applications require ultra-low latency, and central cloud infrastructure-based network slicing is not suitable for such applications [134]. To overcome this complication, it is possible to use central and edge mix cloud-based infrastructure for resource allocation as proposed in [135].

G. OTHER TECHNICAL REQUIREMENTS

Apart from the above-discussed challenges, many other technical challenges exist for the metaverse realization. A summary of all technical challenges is given in Fig. 14. The interoperability of virtual worlds can be identified as one of the main challenges in the metaverse. Interoperability is an important fact in strengthening the functions of the metaverse as well as for its network growth. It should be possible to move a user from one virtual world to another, create the content, and distribute it over the virtual worlds. Authentication and identification in the virtual world need to perform swiftly and securely to allow users to move from one virtual world to another seamlessly. For a better experience for the user, the changing point of the virtual world to the other virtual worlds should be managed properly. Importantly, every virtual world can have specific rules, regulations, and restrictions. It can be the content, activities, appearance, transactions, and many others. Therefore, care should be taken when moving between the virtual worlds.

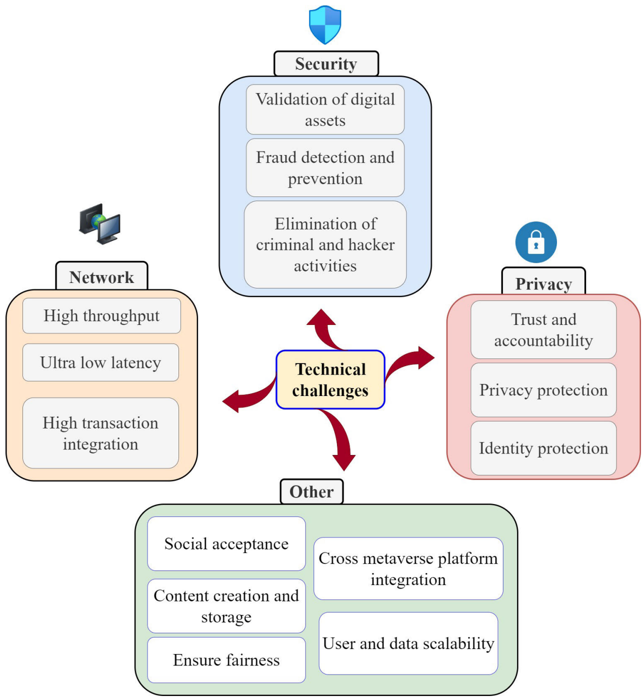

FIGURE 14. **Technical requirements for metaverse realization.**

As for interoperability, we also need to deeply assess the cross-metaverse platform integration. Metaverse is a scale-free network, and the number of platforms may increase rapidly with the advancement of technology and implementation possibilities. Users expect to experience more features and services simultaneously provided by different platforms. This requires defining or developing proper procedures for maintaining QoS, digital transactions, identification, service initiation & termination, content sharing, and other platform requirements. Fig. 14 shows a summary of the technical requirements as network, security, privacy and other technical challenges that must be fulfilled when implementing a metaverse network. Basic technical requirements are highlighted here and they can change based on the metaverse implementation procedure. An illustration of the cross-domain interoperability in the metaverse is depicted in Fig. 15. This figure describes a scenario where a metaverse user moves from an

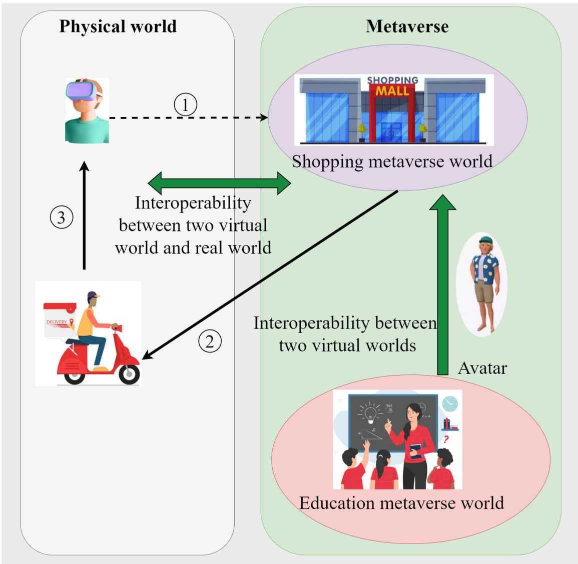

FIGURE 15. Interoperability and cross-platform integration between metaverse and physical world.

educational metaverse application to a shopping application. After moving to the shopping application, the user requests an order through the application based on the available items in the metaverse world. The particular order is delivered to the user in the physical world as the user selects it from the metaverse world. This scenario highlights the interoperability between virtual worlds and between the virtual and physical worlds.

VI. DEPLOYMENT CHALLENGES

Metaverse deployment is a complex process since it has many domains and functionalities. Several deployment challenges are available for the metaverse deployment, and challenges for the network slicing and edge computing approaches are discussed here. As discussed in the previous sections, many solutions can be implemented using edge computing and network slicing. However, still, there are many challenges that need to be overcome in practical deployments.

A. FOR NETWORK SLICING

1) INTER-SLICE INTERACTIVITY

Network slice communication can mainly be categorized into two parts as inter slice communication and intra slice communication. Rather than intra-slice communication, inter-slice communication is quite complex since different slices are configured for different services. As shown in Fig. 16, one metaverse application slice may need to communicate with many metaverse slices and non-metaverse slices in the same region or in a different region. For example, consider sharing personal health data stored in a particular health application slice with a metaverse application is required. For this requirement, the metaverse application slice should be

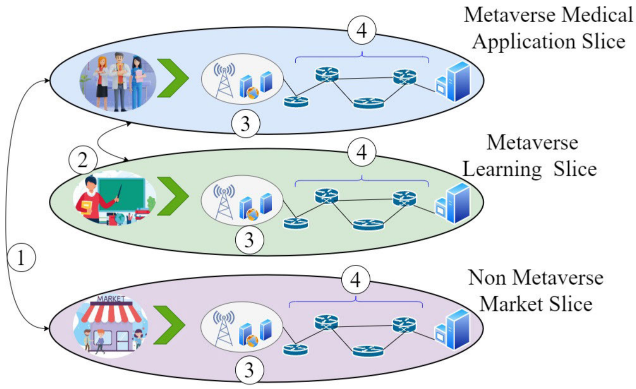

FIGURE 16. Interslice interactivity in metaverse.

capable of communicating with the network slice deployed for the health application. For another example consider that a user in a metaverse gaming application buys or rents gaming accessories such as outfits from another metaverse application deployed in another metaverse network slice. In this scenario, the virtual resource or service is shared between two slices, and the money transaction happens between the slices. Similarly, several interactions will be required between the different slices for a good experience. Suárez et al. [136] provide a mathematical model considering the network slice security attributes for inter-slice communication for a 5G network. Also, Bordel et al. [137] provide Networking slicing operations and propose a method for inter-slice communication event management based on queuing and the graph theory.

A similar method is required for the metaverse application slices to communicate with other metaverse or non-metaverse slices. When one network slice communicates and transfers data with the other slices, additional resources must be allocated depending on the number of inter-slice transactions. Maintaining the SLAs and the guaranteed QoS in a slice while allowing inter-slice communication is important. Improper inter-slice communication can lead to security breaches and attacks such as malware distribution, DoS attacks, and more [138]. As a solution, a virtual secure link can be established between the slices for the communication period, and the requester needs to be authenticated with the provider prior to the communication. Furthermore, access control lists can be implemented to enhance security.

2) CROSS-DOMAIN SLICE EXTENSION

Not all internet-based applications are available across the world in all regions. However, it is possible to expand or scale down based on the requirement and the network infrastructure availability. Similarly, metaverse applications also should be capable of distributing the services for the expected

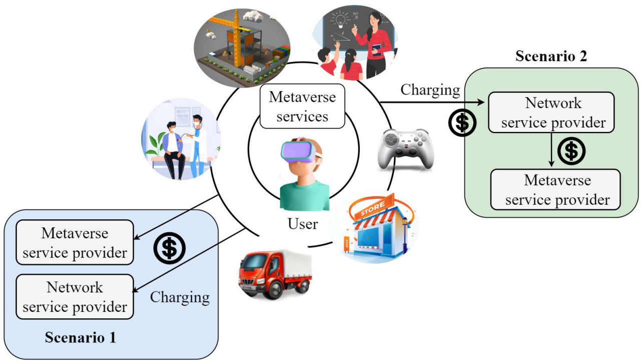

FIGURE 17. Metaverse sample charging model.

regions under the possible networking approaches. Metaverse application users may increase exponentially after the proper deployment and the availability of the access devices. So it is essential to assess the ability to expand among all the users within a limited period. Some network operators use the latest technologies, while others lag behind the latest ones. So, it is pretty challenging to design a framework for slice expansion over the expected regions. Under service extension, it is needed to examine the possibility of extending the same slice, such as a global slice. This service extension of a slice needs to be studied from different perspectives, such as how to slice ownership and how the management can be done for a global slice, how to continue the slice over different operators, slice attributes, and end-to-end specification continuation. Public cloud networks are possible since they have the minimum dependencies with a deployed mobile network.

3) GLOBAL CHARGING MODEL

Charging and rating for the services are essential for all parties in the metaverse ecosystem. Mainly, there are two parties available in the metaverse who provide the services for a user as metaverse application & content providers and network service providers. Network service providers facilitate the required network slices with the relevant network capabilities to launch the metaverse applications. The slice creation process and the on-demand resource facilitation, quality of the service, value addition from the network such as optimization systems, regulations, government taxes, type of vendor, and many other reasons can make the charging for the metaverse application differ from operator to operator or from region to region. Metaverse users need to pay for the services they use, and the charging procedure can be divided into two scenarios, as depicted in Fig. 17. Furthermore, the payment methods can be defined as a monthly subscription, pay-as-you-go or other charging methods. These charging scenarios are briefly discussed below.

- Scenario 1: Charging separately for the metaverse-based services and for providing the network infrastructure, and account them for the service providers and the network operators, respectively. In this approach, the operator has less responsibility for the metaverse application since the user pays separately for the services. An operator can provide services based on different attributes, such as usage and QoS.
- Scenario 2: Charging only for the network operator and operator pay for the metaverse service providers based on the total usage. In this approach, the operator has more responsibility for the metaverse applications and network services. Charging need to be defined by considering the specific status of the user in the case of inbound and outbound roamers.

There can be capacity and resource limitations in the network slices. Based on the number of users and the serving user's resource requirement, it may need to create network slices based on demand. In such a scenario, charging needs to be triggered based on the user's subscription. For example, a subscription can be prepaid, postpaid, or pay-as-you-go and may differ from operator to operator.

4) DIVERSE PRIVACY REQUIREMENTS IN DIFFERENT DOMAINS

Though the metaverse provides its services to the users, it should be bound by rules and regulations of different regions. As shown in Fig. 18, the metaverse application content and some services inside it can be filtered according to the regulations in each region. Hence, metaverse users may access allowed user content only within an application. This is important for network slicing since some applications and services are deployed based on regional regulations. Some content and services must be blocked, and some may need partial access. A proper mechanism is needed to pre-identify the relevant content which needs to be blocked or filtered. The slice deployment can be decided based on that identification, and the figure shows a sample process for such identification. Further, it should be possible to block content based on the order of the regulatory body of a region. For example, one metaverse application has virtual world content prohibited by the country's privacy law. The regulatory body requests to block that content only from the application or remove access to that application. Deployed network slices should be terminated or the relevant content should be blocked by modifying the service slice features.

5) DYNAMIC SLICE DEPLOYMENT

Since the metaverse provides several services, several applications can host those services worldwide from the network-slicing perspective to create and terminate the network slices based on the demand. The network slice deployment and termination times are critical for operations in many ways, as described below.

- User Experience: In metaverse applications, users are more sensitive to the delay due to the immersiveness and other advanced features available from the user experience. So, the delay should be minimum and less than the application's minimum delay thresholds.
- Operational Cost: Slice creation and termination delay directly affect the operational expenditure. A large-scale

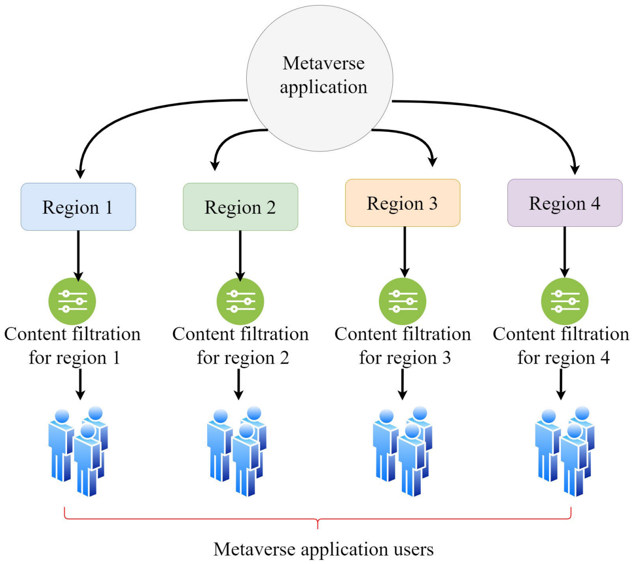

FIGURE 18. **Metaverse privacy and content filtering in different regions.**

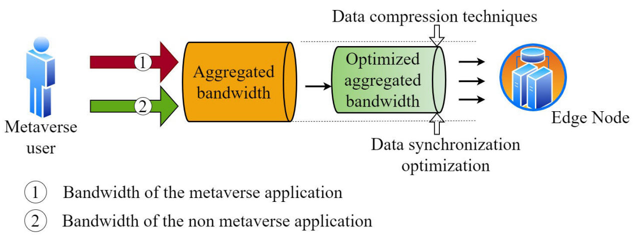

FIGURE 19. **Aggregated bandwidth optimization for metaverse user.**

deployment needs to optimize the slice deployment time in the sense of optimizing cost, while fulfilling the users' and the application's minimum requirements.

B. FOR EDGE COMPUTING

1) AGGREGATED BANDWIDTH

As an example, consider a scenario where there is a lot of background syncing and data transfers happening in every device which is connected to the internet to continue the relevant applications. Similarly, additional such bandwidth is required for the metaverse applications, as there is frequent device synchronization and background process synchronization. As previously discussed, one metaverse application may interact with a few other metaverse and non-metaverse applications. Therefore, additional bandwidth may be required for such communication apart from the core requirements of the application. This concern needs to be considered in actual deployments of the edge network entities. Furthermore, the metaverse application, maximum bandwidth capability of the network, and the transport backbone network should be designed accordingly. Identifying the processes that require additional bandwidth and the possible techniques to reduce that additional bandwidth is crucial for this process.

- Data compression techniques: A significant amount of aggregated bandwidth savings can be expected by improving the image and video compression techniques. However, other factors such as latency which that gets affected by compression need to be considered. For a given bandwidth, the latency changes according to the type of compression [139].
- Data synchronization and optimization: Data synchronization can be identified as synchronization with regards to the ongoing application, and synchronization with the other applications and services of the metaverse, such as updates, configuration changes, and data sharing. This needs to be prioritized to control the aggregated bandwidth and serve the prioritized applications according to the user requirements, and can be introduced in a configuration preference selection, that users can change or adjust accordingly. Still, it should indicate the prioritization of the application and the effect of the choice on the user.

Fig. 19 shows a high level implementation of aggregated bandwidth optimization for metaverse users. This can be done at the device and edge node levels before transferring traffic to the transmission network, which connects the edge node and the core network. Both non metaverse and metaverse application bandwidths need to be considered for the optimization.

2) FORCED CONGESTION ON PRIORITY ACCESS CHANNELS DUE TO METAVERSE SERVICE GUARANTEES

Though it could be possible to allocate resources at the edge for each service channel, resources are limited and scarce. For example, deploying a large-scale data center infrastructure for resource allocation at the edges is infeasible since multiple nodes are available in one geographical area. Currently, the chalnge for most operators and service providers is dimensioning the network to cater forecasted traffic for many upcoming years. Similarly, it is challenging to design edge networks for metaverse applications. Since metaverse applications need high bandwidth, they can congest the other application channels in high utilization scenarios. The traffic patterns can change due to many scenarios, such as emergencies, specific events, and continuous subscriber growth. An important fact is that it is complicated to predict the subscriber growth patterns, which is related to the metaverse applications and the minimum network requirements of the upcoming applications. As an example, consider a famous worldwide event that people can participate freely in a metaverse application. Users of that application may try to participate, and more new users may try to engage with that event within a limited period. It May need to allocate more network slices for the application from the available resources due to high traffic. Such a scenario can trigger congestion and low resource availability for other applications.

Dynamic resource-sharing methods based on congestion prediction can solve this concern. Reference [47] highlights the importance of using intelligent video acceleration mechanisms based on the edge servers to reduce congestion control in 5G networks. Such an approach for video and other data types can be adhered to in a metaverse application.

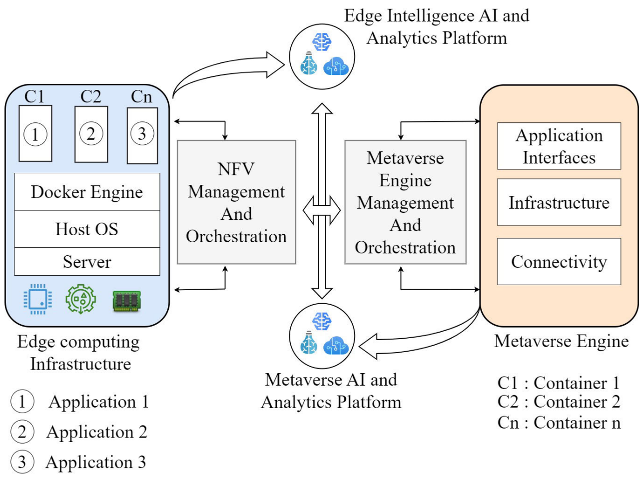

FIGURE 20. AI-based platform synchronization for dual autonomy in metaverse.

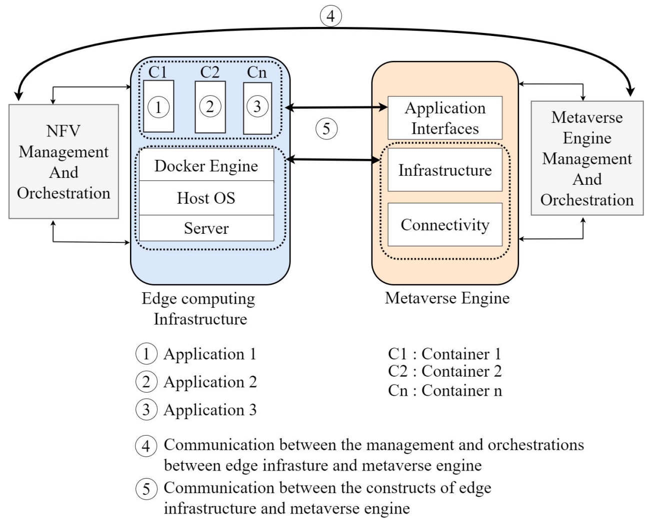

FIGURE 21. High level of interrelation of the metaverse virtual constructs to the edge computing virtualization constructs.

Along with the congestion avoidance approaches, it is also more important to introduce predictive congestion methods. ML-based traffic pattern identification methods help identify traffic variation over time based on incidents and trends. As an example, [140] provide an ML-based approach to identify the traffic patterns of mobile users in a metro area. A similar approach may be combined with data analytics to predict traffic variation and possible high-traffic scenarios based on external constraints. Another possible solution is to migrate the user or VM migration to a less congested node. Kikuchi et al. [141] propose a mobile edge computing-based VM migration method to improve the QoS of an application. As previously discussed, this can be combined with the prediction for an effective outcome. The edge network serves both metaverse and non-metaverse applications, with SLA for both scenarios. Based on this categorization, it can design a resource allocation scheme based on a priority order to serve all applications in a worst-case scenario.

3) DUAL AUTONOMY

Due to the dynamicity of the metaverse, it isn't easy to manage the operations manually. So, operations at the edge platforms and the metaverse should be automated for better performance. It is challenging to deploy such self-sustained ecosystem and network functions. Robotic automation processes, ML, and AI may help to achieve this autonomy without or with minimum manual human interaction. Automating all functions, such as resource allocation, the functionality of an application, regulation, protection, and transactions should be automated. Computer vision can be used with the bots to identify the visual space elements and the interaction between the elements as well [142]. Fig. 20 shows a possible sample implementation for automation that can fulfil the dual autonomy of both the edge platform and the metaverse engine. In this, edge computing nodes and the metaverse engine consists of AI analytic platforms, which analyses all the functions and processes for automation. Automation decisions can be delivered to bots or any process that performs the task in the metaverse platform. Further, these AI platforms are synchronized with the edge platform and metaverse management and orchestration for further automation.

4) INTER-RELATION OF THE METAVERSE VIRTUAL CONSTRUCTS TO THE EDGE COMPUTING VIRTUALIZATION CONSTRUCTS

Interrelations and communication between the virtual constructs of the metaverse and edge computing should be clearly defined. Both architectures can be different, but the intercommunication needs to be performed under a common operational architectural model. Most of the network virtualization standards that are used for edge computing virtualization are already defined. Still, common metaverse standards and models are being developed. For example, meta has deployed its closed metaverse, which is supposed to be in the common open metaverse as a closed one. Since they have their architecture in deployment, it is challenging to deploy a service provider network that supports end-to-end. Only application level connectivity will not be effective in an edge-enabled metaverse, and an advanced model is required to communicate with the metaverse engine and the infrastructure. The illustration of the high level of inter-relation of the metaverse virtual constructs to the edge computing virtualization constructs is depicted in Fig. 21.

5) ADVANCED ORCHESTRATION

Unlike the internet, more ownership is distributed among the metaverse users. Though the metaverse is distributed by infrastructure and ownership, it needs advanced orchestration for management. At the edge, it needs to clearly define who provides the governing directions and which entity of the edge network cooperates with those governing directions. Since there is no set of owners, it is challenging to define the governing body of the metaverse. First, it is required to develop proper standardization related to all the functions of

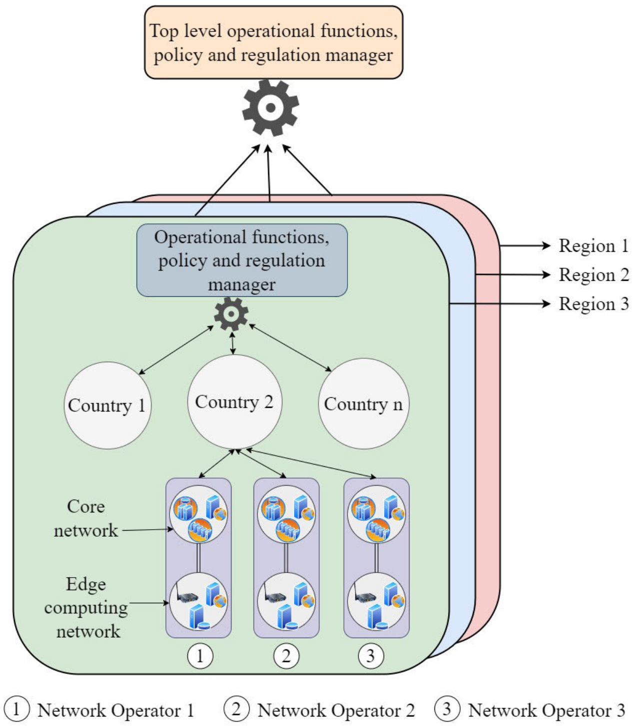

FIGURE 22. High-level advanced orchestration of metaverse.

the metaverse. Once the standardization process is complete, all the service providers, including the access devices, can align to standards to deliver the services. Metaverse standard forum is working on an open standardization process by collaborating with other standardization organizations, and any organization can join without any cost. As previously discussed, the metaverse functionality should be autonomous up to the best level. Primary functionalities of the metaverse need to be clearly defined, which can be applied to all the ecosystems in the metaverse.

On top of that, the regulation and policies should be defined based on the countries or regions. As shown in Fig. 22, each region consists of several countries, and each country may have a few network operators with their networks. Each region consists of a policy and regulation manager who manages the region's countries and connects the region to the top level policy and regulation manager. As a first step, it can deploy automated policies and functions for each region, including specific policies and functionalities based on the region. These regional policies and functionalities can be defined by the regulatory bodies of the countries responsible for their own country. An appointed technical committee can manually review the functionality of that automated manager. Depending on the success, it can be allowed as fully automated with the ability to add changes manually if there is any requirement. Finally, it synchronizes all regions with each other and automates at a high level for service continuation.

6) STANDARD FOR XAI

AI may play a huge role in developing and implementing metaverse applications. Edge intelligence can be

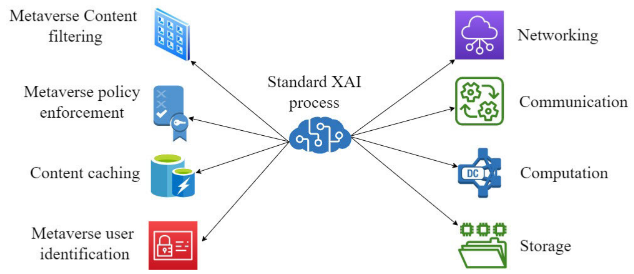

FIGURE 23. XAI standardisation for metaverse.

implemented for both edge infrastructure and application levels. An edge infrastructure can use AI efficiently for resource and process optimization in the main functions such as communication, computation, networking, and storage [26]. Many users interact with the contents in the virtual world, as well as many instances such as object creation, removal, policy enforcement, content filtering, edge caching, and user identification that must be performed in a large-scale environment. To obtain such performance, those functions need to be automated, as previously mentioned, and AI is the best approach. Explainable artificial intelligence (XAI) is an AI that can make available an explainable model that humans can understand. This is effectively used for many functions to obtain a better result and improve the user experience [143]. XAI explains to the end user, assuming that the end user depends on the recommendation or the decisions provided. However, the explanation depends on the task, abilities, and expectations of the end user [144].

The primary objective of any metaverse application is to provide a more realistic experience similar to the real world. XAI provides the outputs with more gravity toward transparency, which enriches the realistic nature of the user experience. In this slicing and edge-based metaverse realization process, more intelligence is concentrated at the edge, and XAI approaches can be effectively implemented. Since many service providers have their way of implementation, it requires a proper XAI standardization for metaverse implementations that all operators and the connected ecosystems support, as shown in Fig. 23. Currently, IEEE is developing standards for the XAI to achieve the interoperability of the systems designs [145]. Sometimes, metaverse implementations can be more specific and advanced and can be changed from application to application. However, all deployments should adhere to one standardization framework. For example, for a particular application user, avatar management, which includes all the incidents related to the avatar, should be the same for the other users, regardless of location, service provider, or any other constraints. After the standardization, applications, devices, operators, or other parties can do any value addition for the processes via available interfaces.

VII. LESSONS LEARNED AND FUTURE DIRECTIONS

In this section, the lessons learned from the previous sections are presented. The existing internet and the ecosystems associated with it are more likely saturated at the present moment in the sense of development. User expectations and service requirements are growing with regards to new features and development. The metaverse concept emerges as a solution for this with more potential of providing a variety of services to the users in novel ways, that improve user experience. The rapid development of the communications technology and its capabilities open a pathway for such new concept realization. Several technologies are required for the metaverse realization, such as IoT, robotics, AI, edge computing, network slicing, low latency communication, and more. In this paper, we focus on the importance of network slicing and edge computing for metaverse realization.

Edge computing facilitates the resources near the user to enable high-capacity processing depending on the allocated resources. Metaverse comprises of high processing requirements such as rendering, 3D animation, avatar management, and data caching. By implementing an edge computing node, those processes can be done at the edge, reducing communication latency. In metaverse applications, latency is a crucial factor affecting the user experience, and edge-based decentralized network deployment may perform better than a centralized deployment. Network slicing is the other main telecommunication technology discussed here, which provides end-to-end separate network slices isolated from the other network slices. Since more user data, such as biometric data and user details, is involved in the metaverse applications, security and privacy need to be guaranteed within the metaverse. Network slicing can provide such isolation while providing the specific network QoS per each slice. Several standards are already available for both technologies, and an extension or a new set of standards is required to be defined for the metaverse implementation. A combination of these two technologies provides a strong background for metaverse realization.

A. HOLISTIC FRAMEWORK FOR METAVERSE REALIZATION

1) LESSONS LEARNED

We have proposed a high-level, holistic framework for metaverse realization mainly based on edge computing and network slicing technologies. A framework is an essential requirement for metaverse implementation in the real world. Features like high availability, QoS, and user mobility will be vital in a metaverse implementation. So, a framework should be optimized such that the primary user and network requirements are fulfilled. As highlighted in the framework, metaverse functions need to be autonomous to provide a highly available scale-free network. Both edge computing and network slicing functions suggest automating under the network slicing manager and edge computing manager. Furthermore, the importance of predictions based on intelligence data analysis is highlighted by the AI and ML platforms, which provide the inputs to the function manager.

2) KEY RESEARCH PROBLEMS

Frameworks for the metaverse are not fixed; still, research communities are working on these. The research problems are formed considering the interoperability and the co-existence of the existing networks and applications. The main questions of interest are

- How to integrate metaverse with the existing networks?
- How is metaverse complying with available standards?

3) PRELIMINARY SOLUTIONS

Though some existing older technologies cannot deliver metaverse services, metaverse needs to coexist with those technologies. As a solution, metaverse applications and frameworks can be deployed based on 5G and B5G networks. Since existing metaverse supporting networks, such as 5G networks, support edge computing and network slicing, it can mainly deploy the metaverse network according to the proposed framework as in Fig. 6. Since 5G and B5G networks support backward operability with old telecommunication technologies such as 4G and 3G, application service flow will not get affected, and the service continuity between the metaverse and non-metaverse applications will be preserved. Metaverse standards are still developing, and they must match the existing standards. Edge computing and network slicing standards and metaverse standards must be aligned properly to avoid integration and standards mismatch issues.

4) FUTURE DIRECTIVES

Metaverse implementation should be fair such that all the users can use the same quality of service if the network conditions are met. However, the main problem is that different networks have different capabilities. Some networks must be ready for 5G and run on legacy networks. Therefore, it needs to propose a method for implementation possibility of metaverse services and the way to migrate the services when a network changes a particular technology. Metaverse standards are still under discussion, and end-to-end standardization needs to be implemented. Metaverse architecture, ownership management, access devices, edge network deployment, network slicing for different metaverse applications, and many service functions are still open for research. Importantly, standards need to be the sense of systems interoperable with each other. The feasibility of implementing existing protocols and the requirement for new protocols need to be analyzed as well.

B. TECHNICAL REQUIREMENTS

1) LESSONS LEARNED

The metaverse's technical requirements are significant to appropriately identify for deploying a metaverse network. In this paper, we discussed the selected vital technical requirements and the challenges available for the metaverse implementation. Mainly identified technical challenges can be categorized into application-related challenges and network-related challenges. The main challenges, such as bandwidth, latency, scalability, and dynamicity, can be categorized under the network layer. Security, application management, and privacy are the main challenges identified under the application layer. Possible approaches and solutions for these challenges are discussed to address these issues under section V, and it will assist in minimizing implementation complexity.

2) KEY RESEARCH PROBLEMS

Technical requirements must be overcome for the metaverse realization, and each requirement needs to be deeply assessed. Identified key research problems are mentioned.

- What are the essential technical requirements for metaverse realization?
- How can network slicing, and edge computing facilitate the technical requirements?

3) PRELIMINARY SOLUTIONS

Edge computing provides the nearest access to the metaverse services by providing the desired QoS to the user, and allowing network operators to optimally use vital resources by offloading the functions to the edge. At the same time, network slicing allows specified network requirements for the particular metaverse services based on their requirements. Furthermore, both technologies can implement functions to enhance security and privacy while supporting the user dynamicity and scalability of the resources.

4) FUTURE DIRECTIVES

Technical requirements of the metaverse are dynamic and possible to change with the technology advancement and application complexity. Though requirements and possible solutions are highlighted concerning edge computing and network slicing, still many possible novel solutions are open to research. The full potential of the metaverse can be obtained with the B5G networks such as 6G [37], [146], [147], [148], [149], and they can be used for more optimized solutions. Especially, network requirements must match the upcoming metaverse access devices' capabilities. Studies on security and privacy of the metaverse will be extremely significant as well.

C. FUTURISTIC APPLICATIONS

1) LESSONS LEARNED

Metaverse is capable of delivering advanced applications that cannot be delivered under existing network technologies. The metaverse's immersive feature may unlock various applications by providing a high user experience. For example, education, industrial systems, and healthcare applications can be redeployed as metaverse applications with more advanced features. Most of the services and user expectations are limited due to geographical limitations, and metaverse eliminates that factor by providing access to users irrespective of location. Digital currencies strengthen the virtual economy, and more applications will be based on user satisfaction and feelings, and will not depend on physical objects. High-level implementation scenarios for a few futuristic applications are discussed in this paper, and metaverse can launch many other futuristic applications. The application complexity may depend on the deployed metaverse network capabilities significantly.

2) KEY RESEARCH PROBLEMS

Futuristic metaverse applications require proper analysis of the realization, such as proper assessment and planning on technical requirements and the implementation procedure. The most important part of futuristic applications is its implementation in a real environment. The below research problems focus on the importance of realizing the application in a real environment.

- What is the significance of network slicing and edge computing for the realization of metaverse futuristic applications?
- What are the key research areas for futuristic applications?

3) PRELIMINARY SOLUTIONS

Edge computing and network slicing can facilitate base requirements which each futuristic application requires, such as network requirements and guaranteed service quality. Since edge computing and network slicing are both technologies that can be integrated and are associated with many other novel technologies for automation, it is possible to implement the application with the desired features more robustly. Metaverse futuristic applications are not limited and open to any application that needs more interaction and real-time user experience. Especially, the applications that have geo-location barriers can effectively implement immersive metaverse features.

4) FUTURE DIRECTIVES

Though initial implementation concepts of metaverse applications are limited, several applications still need to be discovered. Healthcare, military, education, and e-commerce will be key areas for futuristic applications. Furthermore, existing applications can be modified to support metaverse features and add more value to the persisting applications. This paper highlights that network slicing and edge computing will be key enablers of such novel applications.

D. DEPLOYMENT CHALLENGES

1) LESSONS LEARNED

Mainly, metaverse can be deployed based on three main approaches, as open metaverse, close metaverse, or a hybrid with the features of both open and closed approaches. Furthermore, the approach can be categorized as distributed or centralized implementation with regards to practical implementations. A decentralized implementation is more suitable for metaverse deployments due to the ease of deployment and easy governance. Edge computing enables distributed implementation while network slicing supports providing dedicated QoS and other requirements to metaverse applications. Deployment challenges must be identified in every implementation phase, such as the initial deployment and service management phase. Many challenges persist for actual implementation, including network implementation, function orchestration, privacy, data security, authentication, user management governance, regulation, and ownership [150]. Edge computing and network slicing-based solutions can be effectively implemented to overcome these challenges, and possible scenarios are discussed in this paper. Furthermore, one of the significant challenges is the interconnectivity of metaverse with the existing systems applications by consistency in the standards. The existing systems may need modifications or upgrades to match the metaverse capabilities for some interconnectivity with metaverse applications. Identified challenges are discussed in this paper with the possible solutions under the deployment challenges section. We have proposed a high-level architecture for the metaverse advanced orchestration, which can be implemented for a distributed open metaverse deployment. The importance of automation in the metaverse and the possible technologies for automation are also discussed.

2) KEY RESEARCH PROBLEMS

The deployment phase is one of the most critical phases where the metaverse is deployed in a real working environment. Identified research problems for the deployment challenges are highlighted below.

- How to implement a metaverse network globally?
- How do metaverse applications interact with non-metaverse applications?

3) PRELIMINARY SOLUTIONS

Cross-domain network slice extension can be used to extend and implement the metaverse services globally. Advanced orchestration can be implemented using edge computing infrastructure at the lowest level, and then define the orchestration hierarchy to a global level. Both metaverse and non-metaverse applications can be defined based on different network slices, and inter-slice communication can be implemented via a secure link for communication.

4) FUTURE DIRECTIVES

Different countries have their networks with different capabilities, and deploying a standard metaverse network that supports all the possible scenarios in the sense of edge computing, and network slicing still needs to be developed. Automation and programmability will be key features in the metaverse deployment process, which can add more robustness and optimality to the metaverse network.

VIII. CONCLUSION

Metaverse is becoming the next hype in the future tech world due to its high potential in providing advanced services to users. Most tech companies are already focusing on and working on metaverse realizations, and addressing the metaverse adaptation challenges. The realization process may speed up with new technological innovation on metaverse access equipment, and the fast development in telecommunications. In this paper, we have comprehensively analyzed the role of edge computing and network slicing as future telecommunication technologies in the metaverse realization. First, we have discussed the metaverse concept, ecosystem, and the components of the metaverse, along with the related works that focus towards our research topic. Next, we have provided background for edge computing, network slicing and the metaverse, highlighting their key features. Furthermore, we have proposed a holistic framework based on edge computing and network slicing, and have discussed the possible implementation of a high-level view. Possible metaverse futuristic applications that can be realized using edge computing and network slicing to cater future use cases have also been discussed. We also have highlighted and discussed the technical requirements necessary to realize a metaverse, and how network slicing and edge computing contribute to fulfilling these requirements. Next, we have discussed deployment challenges associated with network slicing and edge computing, with possible solutions. Finally, we have highlighted the lessons learned and the future research directives to help future research and developments. The content of this work will strengthen the metaverse community in their ongoing research work and metaverse-related implementations.

REFERENCES

[1] J. Joshua, "Information bodies: Computational anxiety in Neal Stephenson's snow crash," *Interdiscipl. Literary Stud.*, vol. 19, no. 1, pp. 17–47, Mar. 2017.

[2] S. Dhelim, T. Kechadi, L. Chen, N. Aung, H. Ning, and L. Atzori, "Edge-enabled metaverse: The convergence of metaverse and mobile edge computing," 2022, *arXiv:2205.02764*.

[3] N. Xi, J. Chen, F. Gama, M. Riar, and J. Hamari, "The challenges of entering the metaverse: An experiment on the effect of extended reality on workload," *Inf. Syst. Frontiers*, pp. 1–22, Feb. 2022.

[4] M. Damar, "Metaverse shape of your life for future: A bibliometric snapshot," *J. Metaverse*, vol. 1, no. 1, pp. 1–8, 2021.

[5] L.-H. Lee, T. Braud, P. Zhou, L. Wang, D. Xu, Z. Lin, A. Kumar, C. Bermejo, and P. Hui, "All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystem, and research agenda," 2021, *arXiv:2110.05352*.

[6] T. Maksymyuk, J. Gazda, G. Bugár, V. Gazda, M. Liyanage, and M. Dohler, "Blockchain-empowered service management for the decentralized metaverse of things," *IEEE Access*, vol. 10, pp. 99025–99037, 2022.

[7] R. Moro-Visconti, "From physical reality to the internet and the metaverse: A multilayer network valuation," *J. Metaverse*, vol. 2, 2022.

[8] J. Yang, Y. Zhou, H. Huang, H. Zou, and L. Xie, "MetaFi: Device-free pose estimation via commodity WiFi for metaverse avatar simulation," 2022, *arXiv:2208.10414*.

[9] K. Christodoulou, L. Katelaris, M. Themistocleous, P. Christodoulou, and E. Iosif, "NFTs and the metaverse revolution: Research perspectives and open challenges," in *Blockchains and the Token Economy*. Cham, Switzerland: Springer, 2022, pp. 139–178.

[10] J. Anderson and L. Rainie, "The metaverse in 2040," *Pew Res. Center*, Jun. 2022.

[11] J. Y. Lee, "A study on metaverse hype for sustainable growth," *Int. J. Adv. Smart Converg.*, vol. 10, no. 3, pp. 72–80, 2021.

[12] S. Papagiannidis, M. Bourlakis, and F. Li, "Making real money in virtual worlds: MMORPGs and emerging business opportunities, challenges and ethical implications in metaverses," *Technol. Forecasting Social Change*, vol. 75, no. 5, pp. 610–622, Jun. 2008.

[13] M. M. Inceoglu and B. Ciloglugil, "Use of metaverse in education," in *Proc. Int. Conf. Comput. Sci. Appl.* Springer, 2022, pp. 171–184.

[14] S. H. Moon, "The impact of metaverse development and application on industry and society," *The J. Converg. Culture Technol.*, vol. 8, no. 3, pp. 515–520, 2022.

[15] A. Moneta, "Architecture, heritage, and the metaverse," *Traditional Dwellings Settlements Rev.*, vol. 32, no. 1, pp. 37–49, 2020.

[16] S.-V. Rehm, L. Goel, and M. Crespi, "The metaverse as mediator between technology, trends, and the digital transformation of society and business," *J. Virtual Worlds Res.*, vol. 8, no. 2, pp. 1–8, Oct. 2015.

[17] X. Wang, J. Wang, C. Wu, S. Xu, and W. Ma, "Engineering brain: Metaverse for future engineering," *AI Civil Eng.*, vol. 1, no. 1, pp. 1–18, Aug. 2022.

[18] E. Erturk and G.-B. Reynolds, "The expanding role of immersive media in education," in *Proc. Int. Conf. E-Learn.*, 2020, pp. 191–194.

[19] C. J. Dede, J. Jacobson, and J. Richards, "Introduction: Virtual, augmented, and mixed realities in education," in *Virtual, Augmented, and Mixed Realities in Education*. 2017, pp. 1–16.

[20] J. Díaz, C. Saldaña, and C. Avila, "Virtual world as a resource for hybrid education," *Int. J. Emerg. Technol. Learn.*, vol. 15, no. 15, pp. 94–109, 2020.

[21] 3GPP. *Enabling Edge Computing Applications in 3GPP*. Accessed: May 17, 2022. [Online]. Available: https://www.3gpp.org/release-16

[22] S. E. Bibri and Z. Allam, "The metaverse as a virtual form of data-driven smart cities: The ethics of the hyper-connectivity, datafication, algorithmization, and platformization of urban society," *Comput. Urban Sci.*, vol. 2, no. 1, pp. 1–22, Dec. 2022.

[23] L.-H. Lee, P. Zhou, T. Braud, and P. Hui, "What is the metaverse? An immersive cyberspace and open challenges," 2022, *arXiv:2206.03018*.

[24] S.-M. Park and Y.-G. Kim, "A metaverse: Taxonomy, components, applications, and open challenges," *IEEE Access*, vol. 10, pp. 4209–4251, 2022.

[25] J. Tanveer, A. Haider, R. Ali, and A. Kim, "Machine learning for physical layer in 5G and beyond wireless networks: A survey," *Electronics*, vol. 11, no. 1, p. 121, Dec. 2021.

[26] W. Y. B. Lim, Z. Xiong, D. Niyato, X. Cao, C. Miao, S. Sun, and Q. Yang, "Realizing the metaverse with edge intelligence: A match made in heaven," 2022, *arXiv:2201.01634*.

[27] Y. Wu, K. Zhang, and Y. Zhang, "Digital twin networks: A survey," *IEEE Internet Things J.*, vol. 8, no. 18, pp. 13789–13804, Sep. 2021.

[28] F. Tang, X. Chen, M. Zhao, and N. Kato, "The roadmap of communication and networking in 6G for the metaverse," *IEEE Wireless Commun.*, early access, Jun. 24, 2022, doi: 10.1109/MWC.019.2100721.

[29] C. T. Nguyen, D. T. Hoang, D. N. Nguyen, and E. Dutkiewicz, "MetaChain: A novel blockchain-based framework for metaverse applications," in *Proc. IEEE 95th Veh. Technol. Conf. (VTC-Spring)*, Jun. 2022, pp. 1–5.

[30] B. Chatras, U. S. Tsang Kwong, and N. Bihannic, "NFV enabling network slicing for 5G," in *Proc. 20th Conf. Innov. Clouds, Internet Netw. (ICIN)*, Mar. 2017, pp. 219–225.

[31] A. Medeiros, A. Neto, S. Sampaio, R. Pasquini, and J. Baliosian, "Enabling elasticity control functions for cloud-network slice-defined domains," in *Proc. IEEE/IFIP Netw. Oper. Manage. Symp. (NOMS)*, Apr. 2020, pp. 1–7.

[32] M. Bagaa, D. L. C. Dutra, T. Taleb, and H. Flinck, "Toward enabling network slice mobility to support 6G system," *IEEE Trans. Wireless Commun.*, vol. 21, no. 12, pp. 10130–10144, Dec. 2022.

[33] X. Li, M. Samaka, H. A. Chan, D. Bhamare, L. Gupta, C. Guo, and R. Jain, "Network slicing for 5G: Challenges and opportunities," *IEEE Internet Comput.*, vol. 21, no. 5, pp. 20–27, Sep. 2017.

[34] J. Ordonez-Lucena, P. Ameigeiras, D. Lopez, J. J. Ramos-Munoz, J. Lorca, and J. Folgueira, "Network slicing for 5G with SDN/NFV: Concepts, architectures, and challenges," *IEEE Commun. Mag.*, vol. 55, no. 5, pp. 80–87, May 2017.

[35] P. Ranaweera, A. D. Jurcut, and M. Liyanage, "Survey on multi-access edge computing security and privacy," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 2, pp. 1078–1124, 2nd Quart., 2021.

[36] M. Xu, W. C. Ng, W. Y. B. Lim, J. Kang, Z. Xiong, D. Niyato, Q. Yang, X. S. Shen, and C. Miao, "A full dive into realizing the edge-enabled metaverse: Visions, enabling technologies, and challenges," 2022, *arXiv:2203.05471*.

[37] B. Siniarski, C. De Alwis, G. Yenduri, T. Huynh-The, G. Gür, T. R. Gadekallu, and M. Liyanage, "Need of 6G for the metaverse realization," 2022, *arXiv:2301.03386*.

[38] Y. Wang, Z. Su, N. Zhang, R. Xing, D. Liu, T. H. Luan, and X. Shen, "A survey on metaverse: Fundamentals, security, and privacy," 2022, *arXiv:2203.02662*.

[39] H. Ning, H. Wang, Y. Lin, W. Wang, S. Dhelim, F. Farha, J. Ding, and M. Daneshmand, "A survey on metaverse: The state-of-the-art, technologies, applications, and challenges," 2021, *arXiv:2111.09673*.

[40] L.-H. Lee, Z. Lin, R. Hu, Z. Gong, A. Kumar, T. Li, S. Li, and P. Hui, "When creators meet the metaverse: A survey on computational arts," 2021, *arXiv:2111.13486*.

[41] X. Hong and Y. Wang, "Edge computing technology: Development and countermeasures," *Strategic Study Chin. Acad. Eng.*, vol. 20, no. 2, pp. 20–26, 2018.

[42] M. T. Beck, M. Werner, S. Feld, and S. Schimper, "Mobile edge computing: A taxonomy," in *Proc. 6th Int. Conf. Adv. Future Internet*. Princeton, NJ, USA: Citeseer, 2014, pp. 48–55.

[43] P. Porambage, J. Okwuibe, M. Liyanage, M. Ylianttila, and T. Taleb, "Survey on multi-access edge computing for Internet of Things realization," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 2961–2991, 4th Quart., 2018.

[44] M. Armbrust, R. Griffith, A. Joseph, R. Katz, A. Konwinski, G. Lee, D. Patterson, A. Rabkin, and I. Stoica, "Above the clouds: A Berkeley view of cloud computing," Dept. EECS, Univ. California, Berkeley, CA, USA, Tech. Rep. UCB/EECS-2009-28, 2009.

[45] K. Cao, Y. Liu, G. Meng, and Q. Sun, "An overview on edge computing research," *IEEE Access*, vol. 8, pp. 85714–85728, 2020.

[46] Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief, "A survey on mobile edge computing: The communication perspective," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2322–2358, 4th Quart., 2017.

[47] Y. C. Hu, M. Patel, D. Sabella, N. Sprecher, and V. Young, "Mobile edge computing—A key technology towards 5G," *ETSI White Paper*, vol. 11, no. 11, pp. 1–16, 2015.

[48] M. Satyanarayanan, "The emergence of edge computing," *Computer*, vol. 50, no. 1, pp. 30–39, 2017.

[49] Y. Ai, M. Peng, and K. Zhang, "Edge computing technologies for Internet of Things: A primer," *Digit. Commun. Netw.*, vol. 4, no. 2, pp. 77–86, 2018.

[50] P. Ranaweera, A. Jurcut, and M. Liyanage, "MEC-enabled 5G use cases: A survey on security vulnerabilities and countermeasures," *ACM Comput. Surv.*, vol. 54, no. 9, pp. 1–37, Dec. 2022.

[51] P. Ranaweera, C. de Alwis, A. D. Jurcut, and M. Liyanage, "Realizing contact-less applications with multi-access edge computing," *ICT Exp.*, vol. 8, no. 4, pp. 575–587, Dec. 2022.

[52] W. Z. Khan, E. Ahmed, S. Hakak, I. Yaqoob, and A. Ahmed, "Edge computing: A survey," *Future Gener. Comput. Syst.*, vol. 97, pp. 219–235, Aug. 2019.

[53] S. Yi, C. Li, and Q. Li, "A survey of fog computing: Concepts, applications and issues," in *Proc. Workshop Mobile Big Data*, 2015, pp. 37–42.

[54] A. Bahtovski and M. Gusev, "Cloudlet challenges," *Proc. Eng.*, vol. 69, pp. 704–711, Jan. 2014.

[55] M. Babar, M. S. Khan, F. Ali, M. Imran, and M. Shoaib, "Cloudlet computing: Recent advances, taxonomy, and challenges," *IEEE Access*, vol. 9, pp. 29609–29622, 2021.

[56] B. Varghese, N. Wang, S. Barbhuiya, P. Kilpatrick, and D. S. Nikolopoulos, "Challenges and opportunities in edge computing," in *Proc. IEEE Int. Conf. Smart Cloud (SmartCloud)*, Nov. 2016, pp. 20–26.

[57] F. Giust, X. Costa-Perez, and A. Reznik, "Multi-access edge computing: An overview of ETSI MEC ISG," *IEEE 5G Tech Focus*, vol. 1, no. 4, p. 4, Dec. 2017.

[58] A. C. Baktir, A. Ozgovde, and C. Ersoy, "How can edge computing benefit from software-defined networking: A survey, use cases, and future directions," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2359–2391, 4th Quart., 2017.

[59] Q.-V. Pham, F. Fang, V. N. Ha, M. J. Piran, M. Le, L. B. Le, W.-J. Hwang, and Z. Ding, "A survey of multi-access edge computing in 5G and beyond: Fundamentals, technology integration, and state-of-the-art," *IEEE Access*, vol. 8, pp. 116974–117017, 2020.

[60] 3GPP. *Enabling Edge Computing Applications in 3GPP*. Accessed: Jun. 18, 2022. [Online]. Available: https://www.3gpp.org/news-events/2152-edge_sa6

[61] M. Liyanage, Q.-V. Pham, K. Dev, S. Bhattacharya, P. K. R. Maddikunta, T. R. Gadekallu, and G. Yenduri, ''A survey on zero touch network and service management (ZSM) for 5G and beyond networks,'' *J. Netw. Comput. Appl.*, vol. 203, Jul. 2022, Art. no. 103362.
[62] T. Umagiliya, S. Wijethilaka, C. De Alwis, P. Porambage, and M. Liyanage, ''Network slicing strategies for smart industry applications,'' in *Proc. IEEE Conf. Standards Commun. Netw. (CSCN)*, Dec. 2021, pp. 30–35.
[63] A. Kaloxylos, ''A survey and an analysis of network slicing in 5G networks,'' *IEEE Commun. Standards Mag.*, vol. 2, no. 1, pp. 60–65, Mar. 2018.
[64] P. Subedi, A. Alsadoon, P. W. C. Prasad, S. Rehman, N. Giweli, M. Imran, and S. Arif, ''Network slicing: A next generation 5G perspective,'' *EURASIP J. Wireless Commun. Netw.*, vol. 2021, no. 1, pp. 1–26, Dec. 2021.
[65] F. Z. Yousaf, M. Bredel, S. Schaller, and F. Schneider, ''NFV and SDN—Key technology enablers for 5G networks,'' *IEEE J. Sel. Areas Commun.*, vol. 35, no. 11, pp. 2468–2478, Nov. 2017.
[66] P. McEnroe, S. Wang, and M. Liyanage, ''A survey on the convergence of edge computing and AI for UAVs: Opportunities and challenges,'' *IEEE Internet Things J.*, vol. 9, no. 17, pp. 15435–15459, Sep. 2022.
[67] I. Afolabi, T. Taleb, K. Samdanis, A. Ksentini, and H. Flinck, ''Network slicing and softwarization: A survey on principles, enabling technologies, and solutions,'' *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2429–2453, 3rd Quart., 2018.
[68] M. A. Habibi, B. Han, and H. D. Schotten, ''Network slicing in 5G mobile communication architecture, profit modeling, and challenges,'' 2017, *arXiv:1707.00852*.
[69] S. Marinova, V. Rakovic, D. Denkovski, T. Lin, V. Atanasovski, H. Bannazadeh, L. Gavrilovska, and A. Leon-Garcia, ''End-to-end network slicing for flash crowds,'' *IEEE Commun. Mag.*, vol. 58, no. 4, pp. 31–37, Apr. 2020.
[70] T. Saboorian, A. Xiang, and L. Thiébaut, ''Network slicing and 3GPP service and systems aspects (SA) standard,'' *IEEE Softw.*, vol. 7, Dec. 2017.
[71] J. Ordonez-Lucena, O. Adamuz-Hinojosa, P. Ameigeiras, P. Muñoz, J. J. Ramos-Muñoz, J. F. Chavarria, and D. Lopez, ''The creation phase in network slicing: From a service order to an operative network slice,'' in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Jun. 2018, pp. 1–36.
[72] D. Kim and S. Kim, ''Network slicing as enablers for 5G services: State of the art and challenges for mobile industry,'' *Telecommun. Syst.*, vol. 71, no. 3, pp. 517–527, Jul. 2019.
[73] S. Wijethilaka and M. Liyanage, ''Survey on network slicing for Internet of Things realization in 5G networks,'' *IEEE Commun. Surveys Tuts.*, vol. 23, no. 2, pp. 957–994, 2nd Quart., 2021.
[74] NGMN Alliance, ''Description of network slicing concept,'' *NGMN 5G P*, vol. 1, no. 1, pp. 1–11, 2016.
[75] T. Huynh-The, Q.-V. Pham, X.-Q. Pham, T. T. Nguyen, Z. Han, and D.-S. Kim, ''Artificial intelligence for the metaverse: A survey,'' 2022, *arXiv:2202.10336*.
[76] Q. Yang, Y. Zhao, H. Huang, Z. Xiong, J. Kang, and Z. Zheng, ''Fusing blockchain and AI with metaverse: A survey,'' 2022, *arXiv:2201.03201*.
[77] M. Crosby, P. Pattanayak, S. Verma, and V. Kalyanaraman, ''Blockchain technology: Beyond Bitcoin,'' *Appl. Innov.*, vol. 2, nos. 6–10, p. 71, 2016.
[78] T. R. Gadekallu, T. Huynh-The, W. Wang, G. Yenduri, P. Ranaweera, Q.-V. Pham, D. B. da Costa, and M. Liyanage, ''Blockchain for the metaverse: A review,'' 2022, *arXiv:2203.09738*.
[79] K. G. Nalbant and C. S. Uyanik, ''Computer vision in the metaverse,'' *J. Metaverse*, vol. 1, no. 1, pp. 9–12, 2021.
[80] *The Metaverse Standards Forum*. Accessed: Jun. 20, 2022. [Online]. Available: https://metaverse-standards.org/
[81] A. S. L. Harkavy and E. Lazzarin. *7 Essential Ingredients of a Metaverse*. Accessed: Jun. 20, 2022. [Online]. Available: https://future.com/7-essential-ingredients-of-a-metaverse/
[82] T. Taleb, K. Samdanis, B. Mada, H. Flinck, S. Dutta, and D. Sabella, ''On multi-access edge computing: A survey of the emerging 5G network edge cloud architecture and orchestration,'' *IEEE Commun. Surveys Tuts.*, vol. 19, no. 3, pp. 1657–1681, 3rd Quart., 2017.
[83] M. L. Tuballa and M. L. Abundo, ''A review of the development of smart grid technologies,'' *Renew. Sustain. Energy Rev.*, vol. 59, pp. 710–725, Jun. 2016.
[84] B. Farahani, M. Barzegari, F. S. Aliee, and K. A. Shaik, ''Towards collaborative intelligent IoT eHealth: From device to fog, and cloud,'' *Microprocessors Microsystems*, vol. 72, Feb. 2020, Art. no. 102938.
[85] R. Wootton, ''Telemedicine,'' *BMJ*, vol. 323, no. 7312, pp. 557–560, 2001.
[86] D. Yang et al., ''Expert consensus on the metaverse in medicine,'' *Clin. eHealth*, vol. 5, pp. 1–9, Dec. 2022.
[87] M. Sun, L. Xie, Y. Liu, K. Li, B. Jiang, Y. Lu, Y. Yang, H. Yu, Y. Song, C. Bai, and D. Yang, ''The metaverse in current digital medicine,'' *Clin. eHealth*, vol. 5, pp. 52–57, Dec. 2022.
[88] L. Ma, ''Multimedia simulation-based architecture CAD system model,'' *Comput.-Aided Des. Appl.*, vol. 18, no. S1, pp. 53–64, May 2020.
[89] A. H. Payberah, H. Kavalionak, V. Kumaresan, A. Montresor, and S. Haridi, ''CLive: Cloud-assisted P2P live streaming,'' in *Proc. IEEE 12th Int. Conf. Peer-to-Peer Comput. (P2P)*, Sep. 2012, pp. 79–90.
[90] J. Han, D. Farin, and P. H. N. de With, ''A mixed-reality system for broadcasting sports video to mobile devices,'' *IEEE Multimedia*, vol. 18, no. 2, pp. 72–84, Feb. 2011.
[91] P. Kansal and A. Bose, ''Bandwidth and latency requirements for smart transmission grid applications,'' *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1344–1352, Sep. 2012.
[92] Y.-H. Jeon, ''Qos requirements for the smart grid communications system,'' *Int. J. Comput. Sci. Netw. Secur.*, vol. 11, no. 3, pp. 86–94, 2011.
[93] R. Chengoden, N. Victor, T. Huynh-The, G. Yenduri, R. H. Jhaveri, M. Alazab, S. Bhattacharya, P. Hegde, P. K. R. Maddikunta, and T. R. Gadekallu, ''Metaverse for healthcare: A survey on potential applications, challenges and future directions,'' 2022, *arXiv:2209.04160*.
[94] L. Petrigna and G. Musumeci, ''The metaverse: A new challenge for the healthcare system: A scoping review,'' *J. Funct. Morphol. Kinesiol.*, vol. 7, no. 3, p. 63, Aug. 2022.
[95] M. A. I. Mozumder, M. M. Sheeraz, A. Athar, S. Aich, and H.-C. Kim, ''Overview: Technology roadmap of the future trend of metaverse based on IoT, blockchain, AI technique, and medical domain metaverse activity,'' in *Proc. 24th Int. Conf. Adv. Commun. Technol. (ICACT)*, Feb. 2022, pp. 256–261.
[96] E. Hopkins, ''Virtual commerce in a decentralized blockchain-based metaverse: Immersive technologies, computer vision algorithms, and retail business analytics,'' *Linguistic Phil. Invest.*, vol. 21, no. 21, pp. 203–218, 2022.
[97] H. Jeong, Y. Yi, and D. Kim, ''An innovative e-commerce platform incorporating metaverse to live commerce,'' *Int. J. Innov. Comput., Inf. Control*, vol. 18, no. 1, pp. 221–229, 2022.
[98] H. Lee, D. Woo, and S. Yu, ''Virtual reality metaverse system supplementing remote education methods: Based on aircraft maintenance simulation,'' *Appl. Sci.*, vol. 12, no. 5, p. 2667, Mar. 2022.
[99] L. O. Alpala, D. J. Quiroga-Parra, J. C. Torres, and D. H. Peluffo-Ordóñez, ''Smart factory using virtual reality and online multi-user: Towards a metaverse for experimental frameworks,'' *Appl. Sci.*, vol. 12, no. 12, p. 6258, Jun. 2022.
[100] K. Li, Y. Cui, W. Li, T. Lv, X. Yuan, S. Li, W. Ni, M. Simsek, and F. Dressler, ''When Internet of Things meets metaverse: Convergence of physical and cyber worlds,'' 2022, *arXiv:2208.13501*.
[101] R. Cheng, N. Wu, S. Chen, and B. Han, ''Will metaverse be NextG internet? Vision, hype, and reality,'' 2022, *arXiv:2201.12894*.
[102] J. Sakhdari, B. Zolfaghari, S. Izadpanah, S. H-Mahdizadeh-Zargar, M. Rahati-Quchani, M. Shadi, S. Abrishami, and A. Rasoolzadegan, ''Edge computing: A systematic mapping study,'' 2021, *arXiv:2102.02720*.
[103] N. Mansouri, ''Adaptive data replication strategy in cloud computing for performance improvement,'' *Frontiers Comput. Sci.*, vol. 10, no. 5, pp. 925–935, Oct. 2016.
[104] N. Bhalaji, ''Efficient and secure data utilization in mobile edge computing by data replication,'' *J. ISMAC*, vol. 2, no. 1, pp. 1–12, Mar. 2020.
[105] X. Xia, F. Chen, Q. He, J. Grundy, M. Abdelrazek, and H. Jin, ''Online collaborative data caching in edge computing,'' *IEEE Trans. Parallel Distrib. Syst.*, vol. 32, no. 2, pp. 281–294, Feb. 2021.
[106] Z. Su, Y. Wang, Q. Xu, and N. Zhang, ''LVBS: Lightweight vehicular blockchain for secure data sharing in disaster rescue,'' *IEEE Trans. Depend. Sec. Comput.*, vol. 19, no. 1, pp. 19–32, Jan. 2022.
[107] G. Amaizu, J. Njoku, J. M. Lee, and D.-S. Kim, ''Security in metaverse: A closer look,'' in *Proc. Korean Telecommun. Soc. Conf.*, Feb. 2022, pp. 9–11.
[108] D. W. Chadwick, ''Federated identity management,'' in *Foundations of Security Analysis and Design V*. Springer, 2009, pp. 96–120.

[109] E. Samir, H. Wu, M. Azab, C. Xin, and Q. Zhang, "DT-SSIM: A decentralized trustworthy self-sovereign identity management framework," *IEEE Internet Things J.*, vol. 9, no. 11, pp. 7972–7988, Jun. 2022.
[110] T.-T. Kuo, H.-E. Kim, and L. Ohno-Machado, "Blockchain distributed ledger technologies for biomedical and health care applications," *J. Amer. Med. Inform. Assoc.*, vol. 24, no. 6, pp. 1211–1220, 2017.
[111] Z. Xiong, Y. Zhang, D. Niyato, P. Wang, and Z. Han, "When mobile blockchain meets edge computing," *IEEE Commun. Mag.*, vol. 56, no. 8, pp. 33–39, Aug. 2018.
[112] E. Fazeldehkordi and T.-M. Grønli, "A survey of security architectures for edge computing-based IoT," *IoT*, vol. 3, no. 3, pp. 332–365, Jun. 2022.
[113] S. Guo, X. Hu, S. Guo, X. Qiu, and F. Qi, "Blockchain meets edge computing: A distributed and trusted authentication system," *IEEE Trans. Ind. Informat.*, vol. 16, no. 3, pp. 1972–1983, Mar. 2020.
[114] L. U. Khan, Z. Han, D. Niyato, E. Hossain, and C. S. Hong, "Metaverse for wireless systems: Vision, enablers, architecture, and future directions," 2022, *arXiv:2207.00413*.
[115] J. D. N. Dionisio, W. G. Burns III, and R. Gilbert, "3D virtual worlds and the metaverse: Current status and future possibilities," *ACM Comput. Surv.*, vol. 45, no. 3, pp. 1–38, Jun. 2013.
[116] H. Liu, M. Bowman, R. Adams, J. Hurliman, and D. Lake, "Scaling virtual worlds: Simulation requirements and challenges," in *Proc. Winter Simulation Conf.*, Dec. 2010, pp. 778–790.
[117] D. Lake, M. Bowman, and H. Liu, "Distributed scene graph to enable thousands of interacting users in a virtual environment," in *Proc. 9th Annu. Workshop Netw. Syst. Support Games*, Nov. 2010, pp. 1–6.
[118] R. Bruschi, F. Davoli, P. Lago, and J. F. Pajo, "A scalable SDN slicing scheme for multi-domain fog/cloud services," in *Proc. IEEE Conf. Netw. Softw. (NetSoft)*, Jul. 2017, pp. 1–6.
[119] M. P. Wylie-Green and T. Svensson, "Throughput, capacity, handover and latency performance in a 3GPP LTE FDD field trial," in *Proc. IEEE Global Telecommun. Conf. GLOBECOM*, Dec. 2010, pp. 1–6.
[120] T. Ouyang, Z. Zhou, and X. Chen, "Follow me at the edge: Mobility-aware dynamic service placement for mobile edge computing," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 10, pp. 2333–2345, Oct. 2018.
[121] H. Zhang, N. Liu, X. Chu, K. Long, A. Aghvami, and V. C. M. Leung, "Network slicing based 5G and future mobile networks: Mobility, resource management, and challenges," *IEEE Commun. Mag.*, vol. 55, no. 8, pp. 138–145, Aug. 2017.
[122] R. Di Pietro and S. Cresci, "Metaverse: Security and privacy issues," in *Proc. 3rd IEEE Int. Conf. Trust, Privacy Secur. Intell. Syst. Appl. (TPS-ISA)*, Dec. 2021, pp. 281–288.
[123] D. C. Nguyen, M. Ding, Q.-V. Pham, P. N. Pathirana, L. B. Le, A. Seneviratne, J. Li, D. Niyato, and H. V. Poor, "Federated learning meets blockchain in edge computing: Opportunities and challenges," *IEEE Internet Things J.*, vol. 8, no. 16, pp. 12806–12825, Aug. 2021.
[124] S. Wijethilaka and M. Liyanage, "The role of security orchestrator in network slicing for future networks," *IEEE J. Commun. Netw.*, 2022.
[125] R. F. Olimid and G. Nencioni, "5G network slicing: A security overview," *IEEE Access*, vol. 8, pp. 99999–100009, 2020.
[126] J. Smed, T. Kaukoranta, and H. Hakonen, "Aspects of networking in multiplayer computer games," *Electron. Library*, vol. 20, no. 2, pp. 87–97, Apr. 2002.
[127] Y. Sun, Z. Chen, M. Tao, and H. Liu, "Communications, caching, and computing for mobile virtual reality: Modeling and tradeoff," *IEEE Trans. Commun.*, vol. 67, no. 11, pp. 7573–7586, Nov. 2019.
[128] J. Pilz, M. Mehlhose, T. Wirth, D. Wieruch, B. Holfeld, and T. Haustein, "A tactile internet demonstration: 1 ms ultra low delay for wireless communications towards 5G," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2016, pp. 862–863.
[129] Y. Cai, J. Llorca, A. M. Tulino, and A. F. Molisch, "Compute- and data-intensive networks: The key to the metaverse," 2022, *arXiv:2204.02001*.
[130] T. Braud, P. Zhou, J. Kangasharju, and P. Hui, "Multipath computation offloading for mobile augmented reality," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. (PerCom)*, Mar. 2020, pp. 1–10.
[131] Z. Chen, W. Hu, J. Wang, S. Zhao, B. Amos, G. Wu, K. Ha, K. Elgazzar, P. Pillai, R. Klatzky, D. Siewiorek, and M. Satyanarayanan, "An empirical study of latency in an emerging class of edge computing applications for wearable cognitive assistance," in *Proc. 2nd ACM/IEEE Symp. Edge Comput.*, Oct. 2017, pp. 1–14.
[132] L. Zanzi, V. Sciancalepore, A. Garcia-Saavedra, H. D. Schotten, and X. Costa-Pérez, "LACO: A latency-driven network slicing orchestration in beyond-5G networks," *IEEE Trans. Wireless Commun.*, vol. 20, no. 1, pp. 667–682, Jan. 2021.
[133] S. O. Oladejo and O. E. Falowo, "Latency-aware dynamic resource allocation scheme for multi-tier 5G network: A network slicing-multitenancy scenario," *IEEE Access*, vol. 8, pp. 74834–74852, 2020.
[134] X. Foukas, G. Patounas, A. Elmokashfi, and M. K. Marina, "Network slicing in 5G: Survey and challenges," *IEEE Commun. Mag.*, vol. 55, no. 5, pp. 94–100, May 2017.
[135] P. Rost, A. Banchs, I. Berberana, M. Breitbach, M. Doll, H. Droste, C. Mannweiler, M. A. Puente, K. Samdanis, and B. Sayadi, "Mobile network architecture evolution toward 5G," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 84–91, May 2016.
[136] L. Suárez, D. Espes, F. Cuppens, C.-T. Phan, P. Bertin, and P. L. Parc, "Managing secure inter-slice communication in 5G network slice chains," in *Proc. IFIP Annu. Conf. Data Appl. Secur. Privacy*. Springer, 2020, pp. 24–41.
[137] B. Bordel, R. Alcarria, D. Sánchez-de Rivera, and A. Sánchez, "An inter-slice management solution for future virtualization-based 5G systems," in *Proc. Int. Conf. Adv. Inf. Netw. Appl.* Springer, 2019, pp. 1059–1070.
[138] *The Evolution of Security in 5G, a Slice of Mobile Threats*, 5G Americas, Bellevue, WA, USA, 2019.
[139] M. Schneider, J. Rambach, and D. Stricker, "Augmented reality based on edge computing using the example of remote live support," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Mar. 2017, pp. 1277–1282.
[140] S. Troia, G. Sheng, R. Alvizu, G. A. Maier, and A. Pattavina, "Identification of tidal-traffic patterns in metro-area mobile networks via matrix factorization based model," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. Workshops (PerCom Workshops)*, Mar. 2017, pp. 297–301.
[141] J. Kikuchi, C. Wu, Y. Ji, and T. Murase, "Mobile edge computing based VM migration for QoS improvement," in *Proc. IEEE 6th Global Conf. Consum. Electron. (GCCE)*, Oct. 2017, pp. 1–5.
[142] T. M. King. *Testing the Metaverse and Beyond*. Accessed: Jun. 26, 2022. [Online]. Available: https://medium.com/@tariq_king/testing-the-metaverse-and-beyond-5171ef934f0c
[143] D. Gunning and D. Aha, "DARPA's explainable artificial intelligence (XAI) program," *AI Mag.*, vol. 40, no. 2, pp. 44–58, 2019.
[144] D. Gunning, M. Stefik, J. Choi, T. Miller, S. Stumpf, and G.-Z. Yang, "XAI—Explainable artificial intelligence," *Sci. Robot.*, vol. 4, no. 37, 2019, Art. no. eaay7120.
[145] IEEE. *Standard for XAI—Explainable Artificial Intelligence—For Achieving Clarity and Interoperability of AI Systems Design*. Accessed: Jul. 2, 2022. [Online]. Available: https://standards.ieee.org/ieee/2976/10522/
[146] P. Porambage, G. Gür, D. P. M. Osorio, M. Liyanage, A. Gurtov, and M. Ylianttila, "The roadmap to 6G security and privacy," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 1094–1122, 2021.
[147] C. de Alwis, Q.-V. Pham, and M. Liyanage, *6G Frontiers: Towards Future Wireless Systems*. Hoboken, NJ, USA: Wiley, 2022.
[148] C. D. Alwis, A. Kalla, Q.-V. Pham, P. Kumar, K. Dev, W.-J. Hwang, and M. Liyanage, "Survey on 6G frontiers: Trends, applications, requirements, technologies and future research," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 836–886, 2021.
[149] C. De Alwis, P. Kumar, Q.-V. Pham, K. Dev, A. Kalla, M. Liyanage, and W.-J. Hwang, "Towards 6G: Key technological directions," *ICT Exp.*, Oct. 2022.
[150] C. Sandeepa, B. Siniarski, N. Kourtellis, S. Wang, and M. Liyanage, "A survey on privacy for B5G/6G: New privacy challenges, and research directions," *J. Ind. Inf. Integr.*, vol. 30, Nov. 2022, Art. no. 100405.

SUPUN KARUNARATHNA received the bachelor's degree in electrical and electronic engineering from the University of Peradeniya, Sri Lanka, in 2019. He is currently pursuing the M.Sc. degree with the University of Moratuwa, Sri Lanka. He was a Core Network Engineer with Dialog Axiata PLC, from 2019 to 2021. He is also a Senior Packet Core Engineer with Hutchison Telecommunications Lanka Pvt., Ltd. His main research interests include 5G, edge computing, network slicing, and network security.

SHALITHA WIJETHILAKA (Student Member, IEEE) received the bachelor's degree (Hons.) in electronics and telecommunication engineering from the University of Moratuwa, Sri Lanka, in 2017. He is currently pursuing the Ph.D. degree with the School of Computer Science, University College Dublin (UCD), Ireland. He is a Teaching Assistant with UCD. He has industrial experience in the Internet of Things (IoT) and telecommunication networks, from 2017 to 2020. His research mainly focuses on improving network slicing security in telecommunication networks. In addition, he is interested in blockchain and federated learning in telecommunication, metaverse realization, and the IoT security. He is a Reviewer of IEEE Access, Springer Nature, and IEEE ICC. For more info: https://ucdcs-research.ucd.ie/phd-student/shalitha-wijethilaka

PASIKA RANAWEERA (Member, IEEE) received the degree (Hons.) from the University of Ruhuna, Sri Lanka, in 2010, the master's degree in information and communication technology (ICT) from the University of Agder, Norway, in 2013, and the Ph.D. degree in improving the security of service migrations of multi-access edge computing (MEC) from University College Dublin (UCD), Ireland, in 2023. Prior to his Ph.D. studies, he was a Lecturer with the Department of Electrical and Information Engineering, Faculty of Engineering, University of Ruhuna, from 2014 to 2018. He has been a Postdoctoral Researcher with the School of Computer Science, UCD, since January 2023. He received the Lanekassen Scholarship for pursuing the master's degree. He has experience in conducting teaching/instructing/demonstration work at international universities (UCD and Beijing-Dublin International College (BDIC), China). He is currently conducting collaborative research with researchers at IIT, India; the University of Oulu, Finland; and the University of Ruhuna. He is a member of the Netslab and the PEL Research Group, UCD. He has authored/coauthored various book chapters, international journals, magazine articles, and conference papers. He is focused on enhancing the security measures in 5G and beyond 5G mobile networks, while his main research focus is directed at federated learning-based security issues and how to overcome them utilizing blockchain. His additional research directives extend to lightweight security protocols, formal verification, security, service quality optimization, 5G and MEC integration technologies (SDN, NFV, and blockchain), privacy preservation techniques, and the Internet of Things (IoT) security. He is a member of IEEE ComSoc. He serves as a Reviewer for IEEE Internet of Things Journal, IEEE Access, *IEEE Communication Magazine*, *IEEE Internet of Things Magazine*, *SN Computer Science*, and various IEEE-hosted conferences and workshops under the IEEE Communication Society. For more information: https://netslab.ucd.ie/netslab_team/pasika-ranaweera/

KASUN T. HEMACHANDRA (Member, IEEE) received the B.Sc. degree (Hons.) in electronic and telecommunication engineering from the University of Moratuwa, Sri Lanka, in 2008, and the M.Sc. and Ph.D. degrees in electrical and computer engineering from the University of Alberta, Canada, in 2010 and 2015, respectively. From 2015 to 2017, he was an Alberta Innovates Eyes-High Postdoctoral Fellow with the Department of Electrical and Computer Engineering, University of Calgary, AB, Canada. Currently, he is a Senior Lecturer with the Department of Electronic and Telecommunication Engineering, University of Moratuwa. He also serves as the Director for the University of Moratuwa and the Dialog Axiata 5G Innovation Centre. His current research interests include in-band full duplex systems, device-to-device communications, open radio access networks (O-RANs), vehicular networks, and the application of machine learning techniques in wireless communications.

THARAKA SAMARASINGHE (Senior Member, IEEE) was born in Colombo, Sri Lanka, in 1984. He received the B.Sc. degree in engineering from the Department of Electronic and Telecommunication Engineering, University of Moratuwa, Sri Lanka, in 2008, and the Ph.D. degree from the Department of Electrical and Electronic Engineering, University of Melbourne, Australia, in 2012. He was a Research Fellow with the Department of Electrical and Computer Systems Engineering, Monash University, Australia, from 2012 to 2014. He has been with the Department of Electronic and Telecommunication Engineering, University of Moratuwa, since January 2015, where he is a Senior Lecturer. He is also an Honorary Fellow with the Department of Electrical and Electronic Engineering, University of Melbourne. His research interests include communications theory, information theory, and wireless networks. He received the award for the Most Outstanding Undergraduate Upon Graduation from the University of Moratuwa.

MADHUSANKA LIYANAGE (Senior Member, IEEE) received the D.Tech. degree in communication engineering from the University of Oulu, Oulu, Finland, in 2016. He is an Assistant Professor/Ad Astra Fellow and the Director of the Graduate Research with the School of Computer Science, University College Dublin (UCD), Ireland. He is also acting as an Honorary Adjunct Professor with the University of Ruhuna, Sri Lanka, and the University of Sri Jayawardhanepura, Sri Lanka. His research interests include 5G/6G, blockchain, network security, artificial intelligence (AI), explainable AI, federated learning (FL), network slicing, the Internet of Things (IoT), and multi-access edge computing (MEC). He was a recipient of the prestigious Marie Skłodowska-Curie Actions Individual Fellowship and the Government of Ireland Postdoctoral Fellowship from 2018 to 2020. In 2020, he received the 2020 IEEE ComSoc Outstanding Young Researcher Award by IEEE ComSoc EMEA. Also, he was awarded an Irish Research Council (IRC) Research Ally Prize as a part of the IRC Researcher of the Year 2021 awards for the positive impact he has made as a supervisor. In 2022, he received the 2022 The Tom Brazil Excellence in Research Award by the SFI CONNECT Center. In 2021 and 2022, he was ranked among the World's Top 2% Scientists (2020 and 2021) in the list prepared by Elsevier BV, Stanford University, USA. For more information: www.madhusanka.com