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# Overview of the Integration of Communications, Sensing, Computing, and Storage as Enabling Technologies for the Metaverse over 6G Networks

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**Abstract:** The metaverse, as an envisioned paradigm of the future internet, aims to establish an immersive and multidimensional virtual space in which global users can interact with one another, as in the real world. With the rapid development of emerging technologies—such as digital twins (DT), blockchain, and artificial intelligence (AI)—the diverse potential application scenarios of the metaverse have attracted a great deal of research attention and have created a prosperous market. The demand for ubiquitous communications, pervasive sensing, ultra-low latency computing, and distributed storage has consequently surged, due to the massive heterogeneous devices and data in the metaverse. In order to achieve the metaverse, it is essential to establish an infrastructure system that integrates communications, sensing, computing, and storage technologies. Information about the physical world can be obtained by pervasive sensing, computing resources can be scheduled in a reasonable manner, quick data access can be achieved through the coordination of centralized and distributed storage, and, as the bridge, mobile communications systems connect communications, sensing, computing, and storage in a new system, which is the integration of communications, sensing, computing, and storage (I-CSCS). Following this trend, this paper discusses the requirements of the metaverse for spectrum resources, ultra-reliable transmission, seamless coverage, and security protection in wireless mobile communications systems, and analyzes the fundamental supporting role of the sixth-generation mobile communications system (6G) in the metaverse. Then, we explore the functions and roles of the integrated sensing and communications technologies (ISAC), as well as the integration of communications, computing, and storage technologies for the metaverse. Finally, we summarize the research directions and challenges of I-CSCS in the metaverse.

**Keywords:** the metaverse; integration of communications, sensing, computing and storage (I-CSCS); 6G

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## 1. Introduction

In recent years, the metaverse has attracted global attention in academia and industry, further expediting its rapid development. The concept of the metaverse originated from Neal Stephenson's science fiction novel Snow Crash, published in 1992 [1]. Since then, the concept of the metaverse has been continuously evolving, with advances in technology and new application scenarios. For example, virtual games and movies, such as Second Life [2], Mine craft, Ready Player One, and Free Guy, have enriched the content of the metaverse. Facebook, Microsoft, Tencent, ByteDance, and other industry giants soon joined the research of the metaverse, and rapidly expanded the capability of the metaverse by integrating mixed-reality (MR), virtual-reality (VR), and augmented-reality (AR) hardware facilities, content production platforms, etc. The metaverse is a virtual space that aims to overcome the limitations of reality. It exists and interacts in parallel with the real world. It empowers human society with abilities that overcome many limitations of the real world.

The metaverse exists within the internet, but not just the world seen from the screen: the metaverse can provide users with an immersive experience instead. The metaverse is considered to be an evolution paradigm of the next-generation internet, following the web internet and mobile internet revolutions, allowing users experiences within virtual spaces, in an immersive and hyper-spatio-temporal manner.

In order to provide a mobile and accessible immersive experience for a large number of users, the metaverse has strict requirements for data communications, especially wireless communications systems, with an emphasis on high capacity, ultra-reliability, seamless coverage, security, and trustworthiness. In addition, it also requires high-precision sensing functions that can provide timely feedback, as well as powerful computing and storage platforms. These indicate that, on top of the separate systems of communications, sensing, computing, and storage, the metaverse urgently needs their integration, to achieve real-world-like experiences. In response to these demands, researchers have started focusing on studying integrated communications, sensing, computing, and storage (I-CSCS) systems. However, although mobile communications systems have evolved from 1G to 5G, the importance of I-CSCS was not widely studied until recent years. As shown in Figure 1, communications systems need to evolve from a pipelined, overlay, and plug-in development paradigm to an integrated, endogenous, and highly intelligent regime. Following this trend, one of the main visions of 6G wireless communications system is to build an information system that integrates communications, sensing, computing, and storage, which will provide better services for the metaverse business.

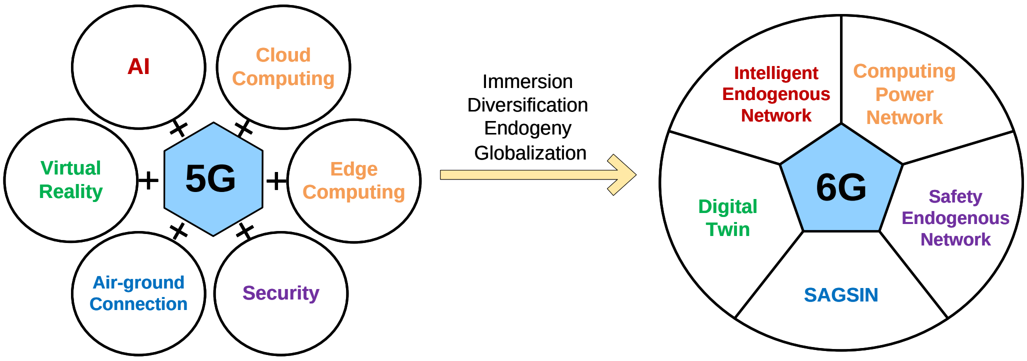


**Figure 1.** The evolution of mobile communications systems from 5G to 6G.

With the surge in demand for ultra-reliability, ultra-low latency, ultra-large bandwidth, and ubiquitous access in new industries, academia and industry began to search for network innovation in multi-system integration. Firstly, in integrated sensing and communications (ISAC), co-existence and mutual impact between communications and sensing functions were widely explored, so as to share not only the wireless spectrum, but also hardware devices, urging the deep integration of protocol interfaces and collaborative networking. Currently, the research on ISAC has developed from a phase concentrating on co-existence to cooperation and reciprocity, striving to form the sensing capability to observe the physical world in the 6G wireless communications network [3–18]. Secondly, in regard to the function of integrated communications and computing, diverse research has been conducted on distributed information processing, multiple-access edge computing (MEC) [19–27], resource allocation and coordination, data security and privacy protection, and chips and hardware equipment [28]. Multi-point networking technologies, such as the coordinated processing of computing tasks in macro and micro base stations, as well as the space–air–ground–sea integrated network (SAGSIN) [29], have received considerable attention. In addition, the integration of communications, sensing, and computing technologies also relies on storage functions. Users' high mobility, network reliability, and security requirements impose heavy demands on distributed access and storage. Therefore, incorporating new storage functions plays an important and irreplaceable role in devising robust networking systems for the metaverse. Following these principles, concepts such as mobile edge communications, computing and caching (MEC3) technologies, and the computing power network (CPN) have been researched, which have widely inspired intelligent evolution towards future networks [30–33]. Alongside these developing trends, this paper discusses I-CSCS technologies, and analyzes potential approaches to building a new system equipped with the capabilities of ultra-reliable low-latency communications, ubiquitous sensing, efficient computation, and powerful storage, in order to serve metaverse applications. For the I-CSCS-system-assisted metaverse, obtaining information about the physical world through sensing will establish a data basis in the virtual world. Scheduling the computational resources and processing tasks requires effectively minimizing the processing and end-to-end latency, as well as reducing redundant data transmission through joint design with storage systems. Finally, communications systems, as an integration bridge, are expected to fully cooperate with systems of sensing, computation, and storage, such that the metaverse can be stably served with satisfied experiences.

This paper has three main contributions, as follows:

- We initiate a discussion on the requirements of the metaverse for spectrum resources, ultra-reliable transmission, seamless coverage, and security protection in wireless communications systems, and we analyze the fundamental supporting role of 6G for the metaverse.
- We introduce the sensing function in the metaverse scenarios. In particular, we analyze the use of ISAC as a powerful support for the sensing function in the metaverse. Moreover, the requirements for distributed computing and storage in regard to the metaverse are presented, with an emphasis on CPN architecture. We discuss the computing and storage tasks and propose two implementation architectures for the metaverse, based on the CPN.
- We introduce developments and advantages of the integration of communications, sensing, computing, and storage (I-CSCS) systems, and we analyze the supports provided by I-CSCS for the metaverse. In addition, we discuss several challenges and future research directions in regard to the metaverse with I-CSCS.

The rest of the paper is organized as follows. We start with a brief review of the origin, development, definition, characteristics, architecture, and related technologies of the metaverse. In Section 3, we analyze the demand for wireless communications and the supporting role of the 6G system in the metaverse. Section 4 presents an overview of relevant research on ISAC technologies and serving functions for the metaverse. The requirements of the metaverse with regard to distributed computing and storage as well as CPN are introduced in Section 5. In Section 6, we discuss existing I-CSCS efforts and the role of I-CSCS in the metaverse. The challenges and research directions of the metaverse supported by I-CSCS are introduced in Section 7. The paper concludes with Section 8.

## 2. Introduction to the Metaverse

### *2.1. Origin and Development of the Metaverse*

The metaverse can be considered to have originated from Neil Stephenson's science fiction novel Snow Crash, published in 1992 [1]. The novel depicts a virtual world parallel to the real world. People can control things in the virtual world through digital identities, by wearing headphones and glasses. Subsequently, with the popularity of the internet, the metaverse gradually attracted more and more attention. Between 2000 and 2010, the metaverse was mainly presented in content mode, completing the evolution process from the initial establishment of a decentralized form to the formation of a preliminary intelligent form. In 2003, LindenLab launched Second Life, based on Open3D [2], which can be seen as the beginning of the decentralization of the metaverse. In 2009, MojangStudios developed Mine craft, which marked the emergence of intelligent features in the metaverse. With the fast development of mobile internet technologies, the network infrastructure has laid a solid foundation for the metaverse. In March 2021, the game company Roblox included the concept of the metaverse in the prospectus, which became a landmark event that attracted widespread attention to the metaverse [34]. The metaverse was then, therefore, regarded as a new area for the innovative digital economy [35]. In October 2021, Facebook was renamed Meta and announced a corporate transformation, no longer positioning itself as a single social media company, but rather as a metaverse company [36]. In November 2021, Satya Nadella, the CEO of Microsoft, announced that Microsoft would explore metaverse technology and join this digital world [37].

### *2.2. Definition of the Metaverse*

Unlike the early concept of the metaverse, the current metaverse is based on certain social values, to achieve synergy between virtual space and the physical world. However, there is no consensus on a definition of the metaverse in either academia or industry, and the definitions provided by different companies are not the same, due to their respective natures [38]. For example, Microsoft sees the metaverse as a persistent digital world, which is closely connected to people, things, and environments in the physical world, and which uses AI and MR technologies to support shared experiences across the real and digital worlds. Accompanied by the digital transformation of enterprises, the metaverse can support the holographic experiences of meetings and activities in virtual spaces, and it can facilitate creative collaborations among different departments within a company or different companies. Meta, on the other hand, focuses on surpassing 2D screens, and aims to bring users closer through immersive experiences on the internet, while maintaining social interaction and secure connection among people and communities. Roblox envisions the metaverse as a shared platform that provides users with immersive experiences, which allows them to create games online, transcend digital boundaries through diverse 3D experiences, and engage in learning, working, entertaining, designing, and socializing within the metaverse.

Matthew Ball provided a comprehensive definition of the metaverse in [39]. Specifically, the metaverse is a persistent, interconnected, and large-scale 3D virtual world network, which can provide immersive experiences for numerous users simultaneously, while supporting the mapping of physical worlds to virtual worlds, and can also change human life and the operational mode of the industry. In short, the metaverse is envisioned as a virtual 3D world that supports human socializing, entertainment, working, and living, while simultaneously interacting with the physical world in all these aspects. With the deepening of the metaverse concept and the continuous enrichment of its use cases, movies such as Ready Player One and Free Guy and virtual games such as Second Life and Mine craft initially described the digital world form in the metaverse. With the optimization of network environments and the development of technologies, the growth momentum of the metaverse has strengthened the confidence of investors, researchers, and engineers. It is expected that the global market size of the metaverse will reach USD 200 billion by 2025 [40].

### *2.3. Characteristics of the Metaverse*

Based on the requirements, objectives, and application scenarios of the metaverse, its characteristics can be summarized as follows:

- Immersive Experience: Immersive experience is the fundamental pursuit of the metaverse, which simulates and renders the 3D environment and user interactions in the virtual world. It enables various sensory experiences for users and provides them with satisfying services.
- Digital Identity: The digital identity of users in the metaverse is a unique identifier, which accurately distinguishes between different users. Users can personalize and manipulate their appearance and equipment according to their preferences and requirements, so as to enhance the subjective and objective feelings of existence in the metaverse, comparable to the real world.
- Digital Economy: The metaverse is a virtual space parallel to the real world, which reflects the attributes of the real world. Therefore, the metaverse also needs a dynamic and adaptive economic system that enables users to create, buy, and sell items

and services and to acquire their own digital assets, co-existing with the market in the metaverse.

- Social Function: The metaverse supports interactions between users and is supposed to be able to discover other users nearby, which provides users with a channel for effective communications and interaction experiences.
- Low Latency: In the metaverse, real-time interaction is required between users, and between users and their environment. Therefore, the metaverse has high requirements for transmission latency and computing latency.
- Access Anytime and Anywhere: The goal of the metaverse is to establish a unified interaction platform for global users, so that there are no time or place constraints on the arrival and departure of users. Meanwhile, in wireless access environments, the probability of conflicts should be kept at a low level, to ensure smooth access.
- Diversified Content: The metaverse is a virtual mapping of the real world, and various real-life scenarios need to be accommodated in the metaverse. In addition, users have different requirements, due to their individual preferences. Therefore, content in the metaverse is highly heterogeneous and needs to meet the diversified requirements of users.
- Civilized Norms: The metaverse requires mechanisms such as trust and identity authentication, to assure user security, data privacy, and social order. For example, text filtering and content auditing systems are needed, to monitor behaviors that violate laws and policies.

### *2.4. Architecture of the Metaverse*

As shown in Figure 2, the architecture of the metaverse can be divided into three layers, corresponding to three planes, which are termed the physical plane, the link plane, and the virtual plane. The physical plane functions by sensing, collecting, and transmitting real-world data through wireless sensing technologies (such as WiFi, Bluetooth, radar, etc.) and a large number of sensors (such as sound, light, humidity sensors) with the capability of advanced communications and sensing technologies; it then uploads data to the link plane. In the link plane, a collaborative communications, computing, and storage process is carried out through a cloud-edge architecture-based computing network, to complete the scheduling of resources and the computation of tasks, and to then transmit the results to the virtual plane. The virtual plane provides real-time feedback information, reconstructs the mirror of the real world through DT technology, conducts dynamic interaction and synchronous evolutions, and adopts technologies, such as MR, to visualize virtual 3D scenarios for users [36,41,42].

### *2.5. Key Technologies for the Metaverse*

The metaverse is a complex concept that encompasses heterogeneous contents. Its development is driven by the evolution of underlying technologies. From the perspective of information foundation, the metaverse relies on multiple technologies. Many researchers are currently conducting research and organization on the core technologies of the metaverse. Song, an analyst in Guosheng Securities, proposed the BAND technology system for the metaverse, which incorporates blockchain technologies, AI technologies, network technologies (5G, 6G, WiFi6, etc.), and display technologies (VR, holographic projection, etc.) [43]. In [44], Zhao et al. creatively proposed six core technologies of the metaverse, known as BIGANT, which integrates blockchain technologies, interaction technologies, game engines and spatial computing, AI technologies, network technologies, and Internet of Things (IoT) technologies. These technologies provide heterogeneous services and support massive data for the metaverse, resulting in high demands on communications networks, ubiquitous sensing, intelligent computing, and distributed storage. Therefore, I-CSCS plays a crucial role in the realization and application of the metaverse.

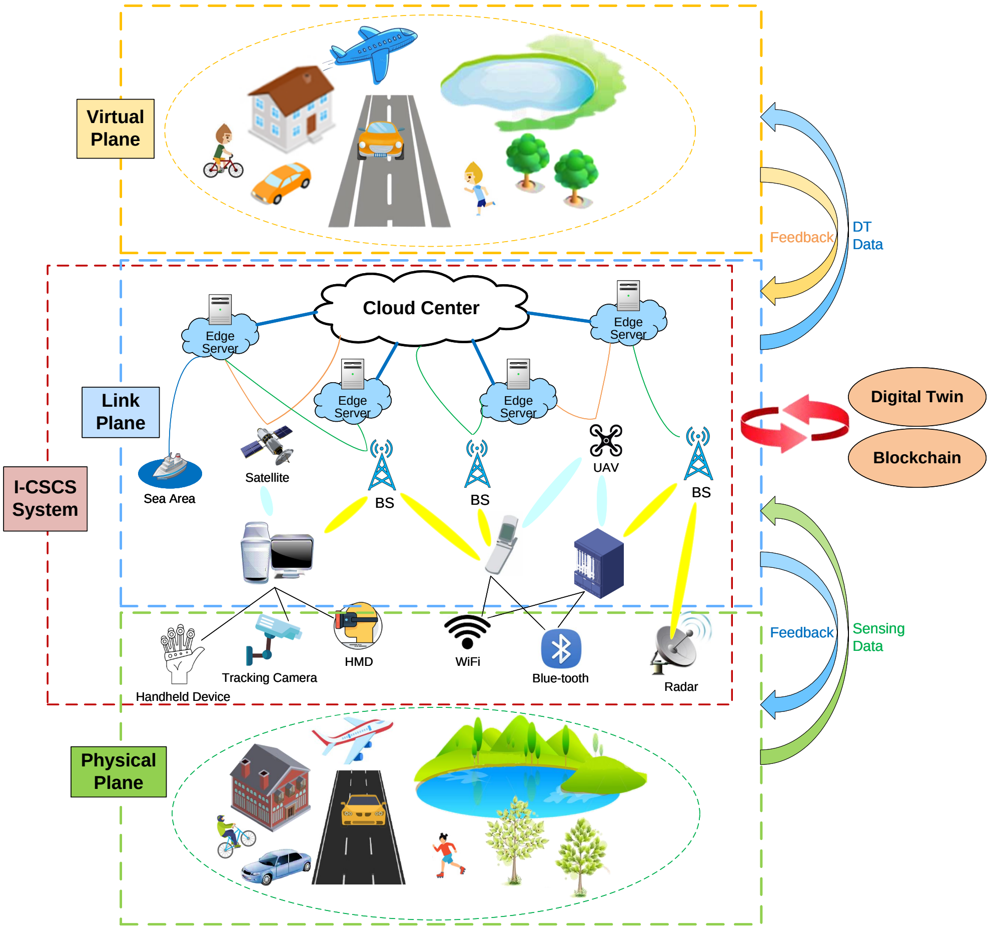


**Figure 2.** The architecture of the metaverse, which consists of physical, link, and virtual planes.

## 3. Wireless Communications Networks Infrastructure for the Metaverse

### *3.1. Metaverse and Wireless Communications Networks*

The metaverse is capable of simulating the real world and rendering it for users with virtual 3D scenes, offering immersive experiences that can break the limitations of time and space. The emergence of the metaverse expands the ways in which users can interact on the internet, from online chatting and video to virtual 3D spaces, which brings users closer to one another and interconnects devices and experiences as well. Furthermore, the metaverse has a wide range of applications and connects large-scale heterogeneous devices to serve diversified users' requirements. As a result, massive data loads and latency-sensitive tasks in the metaverse impose vast new challenges on real-time, secure, and reliable information exchanges in wireless networks. The core requirements of the metaverse for wireless networks are elaborated on, as follows.

Large Spectrum Resources Demand: Due to the deployment of the numerous heterogeneous wireless devices and sensors required by the metaverse, massive data loads place a heavy burden on the spectrum resources for gaining sufficient system capacity. In addition, the metaverse needs to assure various stringent QoS requirements for users. For example, future XR might require an aggregated data transmission rate within a cell coverage of no less than 100 Gbps, and it may need to guarantee milliseconds-level average latency. With persistently increasing communications demand, 6G aims to continuously improve spectrum efficiency and to dig new spectrum resources. On the basis of the efficient utilization of existing spectrum resources, it will explore higher frequency bands, such as terahertz (THz) and visible light. High-frequency communications have the potential to meet the extreme demands of the metaverse on ultra-large system capacity and ultra-high rate transmission [45]. Furthermore, non-orthogonal multiple access (NOMA) can further increase system capacity. For example, delta-orthogonal multiple access (D-OMA) is used for massive multi-access in 6G bursty networks, adopting the distributed large coordinated multi-point (CoMP) transmission-enabled NOMA method to allocate sub-bands to NOMA clusters in a partially overlapping manner. This technology can further improve the efficiency of spectrum resource utilization, thus being a promising method of accommodating more simultaneous access [46].

Ultra-Reliable Transmission: The metaverse needs a large volume of sensors and wireless-based sensing methods to collect the various types of physical information from the real world. It typically has strict requirements for reliability of transmission, as the completeness and accuracy of sensed information form the cornerstone of high-fidelity immersive experiences. However, due to the unstable channel qualities of wireless propagation environments, small-scale and large-scale channel fading can often severely degrade the signal-to-interference-plus-noise ratio. In response to these issues, as one of the key technologies in 6G, reconfigurable intelligent surface (RIS) can help to reshape wireless propagation environments, by adjusting the amplitude and phase of the reflection units. RIS can strengthen the desired signals and suppress the interfering signals, helping to provide a reliable transmission environment for metaverse services [47–49]. Moreover, to further enhance transmission reliability, the access network introduces many new advanced error correction coding technologies and flexible retransmission mechanisms, and, in the meantime, the core network adopts more robust redundant-based protection schemes [50]. Utilizing the various aforementioned technologies, the reliability of the 6G system is expected to reach a level of 99.99999%, in terms of successful delivery rates, offering a stable and reliable transmission service for the metaverse.

Ultra-Low Latency Transmission: A wearable device is one of the main stream ways for users to connect to virtual space. Due to the heterogenous and multi-timescale features of sensed signals from the physical plane, feedback information from the virtual plane, and processing data from the link plane, end-to-end latency may be significantly prolonged. In the meantime, it will cause asynchrony between the virtual world and the real world, severely degrading metaverse users' experiences. Correspondingly, transmission latency in communications networks needs to be controlled at a very low level [51]. Based on recent research results, the cloud-edge-end integrated network can effectively lower end-to-end delay. It will continue to serve as the fundamental architecture for 6G, and it remains a research hotspot. For example, reference [52] proposes a next-generation network architecture based on Cybertwin, which aims to optimize latency for cloud-to-end connections. In particular, this network architecture consists of four key components, which are core cloud, edge cloud, Cybertwin, and terminal. It can assist communications and make the control plane more efficient in determining the optimal configuration of resources, reducing the transmission latency of communications networks, and meeting the low-latency requirements of the metaverse.

Seamless Coverage: The metaverse is envisioned as an interactive environment for users worldwide, and is capable of providing users with a unified virtual world. Therefore, to provide users anytime and anywhere access/departure to/from the metaverse, wireless networks need to guarantee seamless coverage and ubiquitous connectivity. In response to this demand, 6G will support the space–air–ground–sea integrated network (SAGSIN), forming a comprehensive network architecture with wide coverage and high flexibility [29]. This will sufficiently connect the internet of humans and the IoT, wireless and wired networks, wide and local coverages, and aerial and terrestrial communications systems. In addition, as mentioned earlier, the introduction of RIS can overcome challenges imposed by propagation obstacles, channel fading, and environmental interference, which can fill coverage holes and blind spots [47,48]. Under the new 6G network, broadband high-speed communications and narrow-band communications for the IoT, as well as global positioning and real-time sensing capabilities, will be integrated together, to serve metaverse business with seamless coverage.

Security: The metaverse is a virtual mapping of the real world, which produces a large amount of private personal information. Digital assets and digital identity are the core elements of building metaverse society, and thus, the privacy and the security protection of this information are crucial. Security attacks, such as stealing and tampering, may occur in various aspects, including distributed computing, wireless transmission, and storage [53]. Many new technologies have been proposed, to enhance the security protection of private information. Among these technologies, federated learning (FL) allocates learning tasks to edge nodes, which avoids the step of uploading raw data, and therefore enhances the privacy protection of user data [54]. Blockchain technologies adopt a distributed ledger system with huge redundancy for recording transaction data, which greatly reduces the probability of data tampering. In addition, a unified authentication and authorization mechanism can be adopted, to maintain the security of the system, which defines and manages the identity and access processes of a security program [55,56]. In terms of transmission, underlying physical layer security and new anti-quantum cracking technologies can be integrated into traditional cryptography technologies, which will further enhance privacy and protect the integrity of user data [57–59].

### 3.2. Support from 6G for the Metaverse

The wireless systems from 1G to 4G were mainly designed for communication between people, the communications rates of which are increasing with evolution to the next generation. The 5G wireless system enables communications between people and people, people and machines, and machines and machines. The maturation of the metaverse is a long-term evolutionary process, along with the evolution of wireless communications technologies. Although mobile communications systems have evolved from 1G to 5G, the importance of I-CSCS was not widely studied until recent years, and the requirements of the metaverse have not been fully satisfied either. The Outlook White Paper of Architecture Vision and Key Technology of 6G Network, published in 2021, proposes that 6G will support the deep integration of the real physical world and the virtual digital world, where everything is intelligently connected. The 6G network mainly includes eight scenarios, which are immersive cloud XR, holographic communications, sensory interconnection, intelligent interaction, integrated sensing and communications, inclusive intelligence, digital twin, and global coverage. It can be seen that most of the scenarios satisfied by 6G are exactly the future scenarios planned by the metaverse, and these scenarios also put forward communications performance requirements that exceed 5G. As shown in Table 1, the peak data rate of 5G reaches 20 Gbit/s, which cannot satisfy the requirements of the metaverse, while 6G system can process the data in a better way [60]. In addition, the latency performance of 6G will match the metaverse scenarios, which can provide users with more immersive experiences [61,62]. What is more, the metaverse needs millimeter-level sensing accuracy, and 6G will support centimeter-level accuracy, which will be a significant improvement in sensing accuracy, compared to 5G. Therefore, 6G technologies can support metaverse scenarios better. The 6G wireless system aims at an overall improvement of the existing system, which expands the domains of communications, supports more application scenarios, meets diverse QoS requirements, and achieves seamless and ubiquitous communications. As mentioned above, the metaverse requires a large amount of spectrum resources, ultra-reliable low-latency communications, large-scale interconnection, and so on. To attain these goals, key 6G technologies, such as THz, RIS, and SAGSIN, have shown great potential and capability in supporting the metaverse and providing users with immersive experiences.

**Table 1.** The supports from 5G and 6G for the metaverse.

| | **5G** | **6G** | **Requirements of the Metaverse** |
|---|---|---|---|
| Peak data rate | 20 Gbit/s | 50, 100, 200 Gbit/s | >100 Gbit/s |
| Latency over the air interface | >1 ms | 0.1–1 ms | <1 ms |
| Sensing accuracy | Meter-level | Centimeter-level | Millimeter-level |

It is well recognized that the metaverse is also a user-generated content (UGC) platform, allowing users to customize their own personalized scenarios. Correspondingly, 6G will be designed with flexible and programmable software/hardware resources and unified interfaces, being capable of supporting various new applications, such as immersive cloud XR, holographic communications, sensory interconnection, intelligent interaction, DT, and global coverage [31]. In addition, there are numerous mobile data, different types of services, and various forms of sensing information in the metaverse. With the support of technologies such as cloud-edge-end networks and MEC3 towards 6G, each node of the network can share its computing and storage resources, such that the massive computing and storage requirements of the metaverse can be well balanced and effectively fulfilled.

In the future, 6G will be a secure endogenous network with the characteristics of active immunity, elastic autonomy, virtual symbiosis, and ubiquitous security. It can detect and learn multi-dimensional data such as network data, user data, security threats, and network attacks. Moreover, 6G can jointly make use of DT, AI, and cloud-edge-end intelligence, to reduce the costs of and improve the efficiently of security in communications networks.

## 4. Ubiquitous Sensing and ISAC

### *4.1. Sensing Devices*

There will be a wealth of interactive activities in the metaverse, generated by interactions between digital identities, between digital identity and environment, and between virtual environments. Due to the frequent actions of users, digital identity has higher dynamics than the environment. Therefore, the real-time collection, transmission, processing, and feedback of user information from the physical world to the virtual world are important. After the sensing device obtains physical information, the communications system needs to promptly request and upload data and to process tasks through the cloud-edge-end integrated networks, to provide users with smooth virtual experiences [63]. A lightweight sensing device is one of the important ways for users to embrace the metaverse. Users can obtain visual and auditory senses in the metaverse through head-mounted devices (HMDs). Through motion detection equipment, the actions and postures of the users can be mapped to the virtual world, which creates vivid interaction experience for users in the metaverse. Tactile feedback devices can generate virtual pressure and even the touching sensations of objects' textures, providing users with a tactile experience. Next, we briefly review the mainstream sensing devices, including HMDs, motion detection equipment and tactile feedback devices.

Head-Mounted Devices (HMDs): The metaverse presents a virtual world to users, based on XR technologies, functioning as a channel for users to access the metaverse, as in the real world. XR refers to technologies including VR, AR, and MR, which combine virtual and real scenes to achieve human–machine interactions. VR can provide experiences not bounded by physical limitations. HMD builds an enhanced version of display with sensing and operating functions. Users can wear HMD to cover the entire range of view over the virtual world, implementing real-time interactions. In AR, users can see virtual objects and the real world simultaneously, by wearing special AR glasses. By overlaying virtual objects onto views of the real scene, AR can enrich actions in the real world. The HMD for VR and the special-material glasses for AR both use technologies including gyroscopes, accelerometers, visual tracking, and displays, to present changes in virtual environments varying timely with users' movements. They are responsible for displaying corresponding virtual objects in appropriate positions, so that the synchronization of users' interactions and feedback can be achieved, avoiding generation of dizziness and imbalance for users.

Motion Detection Equipment: Motion detection devices can sense users' movements and rebuild them in the virtual world. For example, Meta's Reality Labs has invented an electromyography (EMG) wristband, which allows users to control the movement of digital identities by moving the fingers. Even when a user stops moving in the real world, he/she can still control the movements in the virtual world, in that the EMG wristband can detect minor muscle signals through the electromyography and convert these signals into motion commands in the virtual world. Currently, the accuracy of EMG wristbands is not sufficiently high. However, in the future, motion detection equipment been recognized as one of the most important input methods for VR HMDs, AR glasses, and so on.

Tactile Feedback Device: Tactile devices can provide users with tactile sensations, according to interactions in the metaverse. For example, Meta has invented a tactile glove that utilizes 15 airbag actuators, the complex control system of which adjusts the inflation level, to set different pressures on different positions of a user's hand. It should be noted that these tactile sensations need to work together with visual and audio prompts, in order to avoid a false sense of physical contact.

### *4.2. Wireless Sensing Functions*

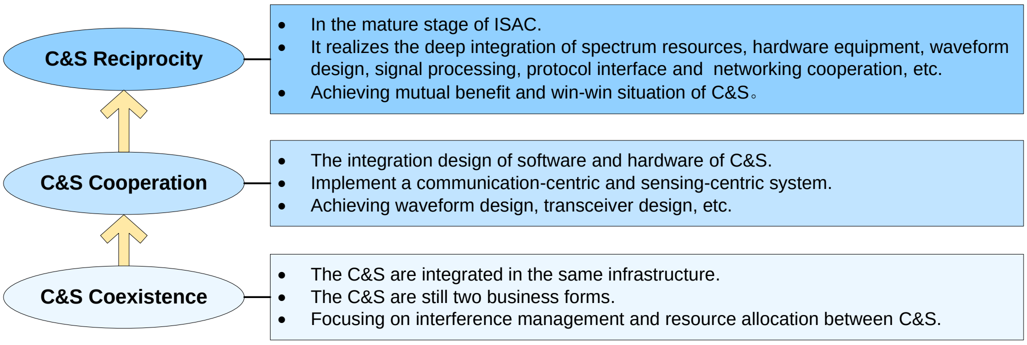
In order to accurately map the real world's status and information to the virtual world, it is necessary to sense not only the postures and movements of humans, but also information about environments in the real world. However, sensing devices themselves cannot achieve comprehensive perception of the real world. As a major approach, wireless-signal-based sensing is also needed. For example, typical wireless signals that can carry sensing functions include Bluetooth, WiFi, ZigBee, UWB, and radar signals. They can be used for sensing tasks, such as positioning, ranging, authentication, recognition targeting, monitoring, etc. However, since wireless signals are often reflected, diffracted, and faded by obstacles in environments, receiving devices need to first pre-process received signals, by filtering and removing noise, and then extract the features of the signals, such as signal strength, phase, and doppler frequency shift, etc., to perform diverse sensing functions.

When applying wireless-signal-based sensing approaches, sensing signals introduce extra costs at frequency band, extra consumption of power, and longer latency. Due to the separated designs of communications and sensing, great challenges are imposed on the scarce spectrum resources. To address these problems, recent studies have been undertaken, to integrate communications and sensing functions, so as to more efficiently use the spectrum, save power, and reduce the overall system latency. The proposal of ISAC can effectively relieve the problems above, and will be further discussed in the next section.

### *4.3. Integrated Sensing and Communications (ISAC)*

The metaverse is supposed to offer complicated services, which often include both communications and sensing functions via wireless signals. However, the sensing and communications links sometime overlap in the space and time domains. As a result, sensing and communications functions affect each other in a negative way. At the same time, the frequency band of communications is now developing towards higher-frequency bands, such as millimeter wave (mmWave), THz, and visible light, which unavoidably generate more overlaps with traditional sensing frequency bands, forcing the study of ISAC to accommodate more functions without the same band. Moreover, sharing the same set or parts of hardware for both communications and sensing functions can reduce the equipment cost and energy consumption of the system.

For the development of ISAC, the integration and evolution of communications and sensing functions will be phased and hierarchical. Specifically, the development process can be divided into three stages: the co-existence stage, the cooperation stage, and the reciprocity stage [7], as shown in Figure 3. In the phase of co-existence, the separated communications and sensing systems will be integrated into the same communications infrastructure, to improve the utilization of resources, such as spectrum, energy, and hardware. However, the communications and sensing services still co-exist in an independent fashion, with the focus on the interference management [4–6] and resource allocation [13–15] between them. In the cooperation stage, the software and hardware of communications and sensing are jointly designed to use one waveform carrying two functions [7–12]. In this stage, the sensing system can assist in enhancing the communications system, or the communications system can assist in enhancing the sensing system mutually. The reciprocity stage is the mature stage of ISAC development, which will achieve the comprehensive, multi-level, and deep integration of spectrum resources, hardware devices, waveform design, signal processing, protocol interfaces, networking cooperation, etc. At this stage, win–win results between communications and sensing will be achieved, which will greatly enhance the capabilities of both systems, and support diverse ISAC services.



- In the mature stage of ISAC.
- It realizes the deep integration of spectrum resources, hardware equipment, waveform design, signal processing, protocol interface and networking cooperation, etc.
- Achieving mutual benefit and win-win situation of C&S。

- The integration design of software and hardware of C&S.
- Implement a communication-centric and sensing-centric system.
- Achieving waveform design, transceiver design, etc.

- The C&S are integrated in the same infrastructure.
- The C&S are still two business forms.
- Focusing on interference management and resource allocation between C&S.

**Figure 3.** The integration and evolution of ISAC.

The application scenarios of ISAC are extensive. The IMT-2020 (5G) Promotion Group analyzed the demand of ISAC in four major scenarios, which are smart transportation, smart low altitude, smart life, and smart grid [16], as shown in Figure 4. In the smart transportation scenario, ISAC can fully sense the road, achieving high-precision map construction, road supervision, and perimeter intrusion detection, to ensure traffic safety, improve traffic efficiency, and further assist in autonomous driving applications. In the smart low altitude scenario, ISAC enables the global sensing of low altitude, and supports functions such as drone supervision, obstacle avoidance, flight intrusion detection, and flight path planning. In the smart life scenario, ISAC can achieve respiratory monitoring, intrusion detection, and so on, which improves the quality of personal health monitoring, and ensures the safety of areas of interests. Furthermore, ISAC can also support gesture and motion recognition and weather monitoring, to improve living convenience and ensure safe travel. In the smart grid scenario, ISAC can assist in beam management, channel estimation enhancement, energy conservation and resource scheduling, and optimization of base stations and terminals, to improve the performances of wireless communications systems.

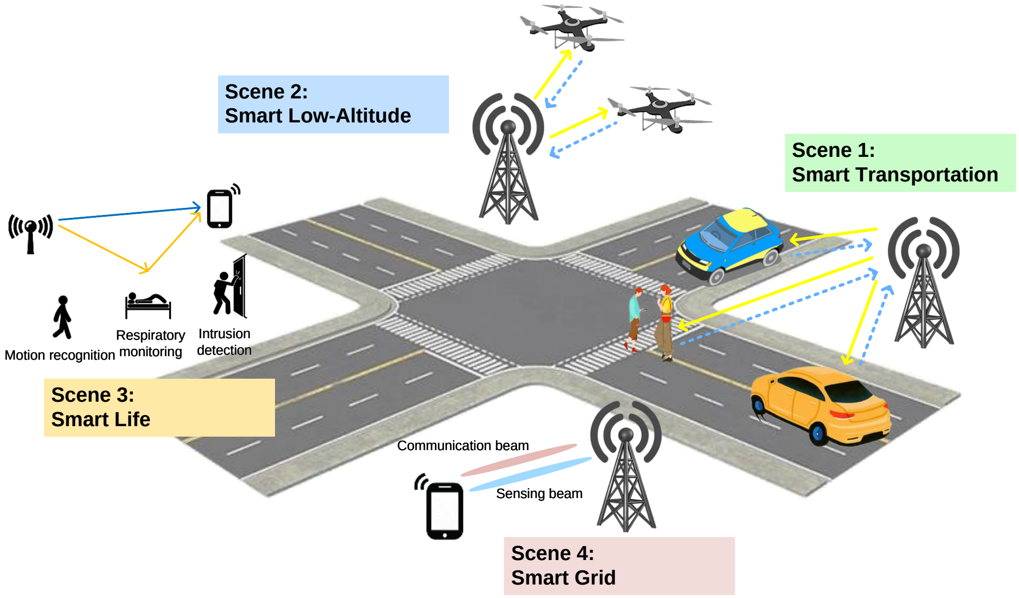


**Figure 4.** The major scenarios of ISAC.

In ISAC, simultaneous localization and mapping (SLAM) is one of the important technologies. SLAM, which was first proposed by Whyte and Leonard [64], attempts to attain the capability of real-time and high-precision recognition and 3D modeling, including construction of 3D point cloud images, positioning, and pose tracking. It can map surrounding environments to the virtual space, based on the sensing signals. SLAM can be divided into laser SLAM [65] and visual SLAM [66], according to different sensing approaches. Currently, 2D/3D SLAM based on LiDAR can provide accurate angle and distance sensing, which can achieve the accuracy of a 1° angle and a distance measurement accuracy at centimeter level. Visual SLAM, based on visual sensors, provides richer and more detailed information. In the metaverse, SLAM technology helps to restore relationships across users and surrounding environments, to perceive changes of environments in real time, and to track user's movements or eyeball behavior. After mapping the information to the virtual space, through DT technologies, it can support the user's real-time interactions. However, in SLAM, real-time processing of sensing signals, especially for complicated image processing tasks, requires large computing and storage resources, leading to high power consumption and high operating costs.

With the support of ISAC, ubiquitous sensing of the physical world can be achieved by wide deployment of ISAC wireless devices in the real world, collecting sufficient physical world information for realization of the metaverse. In invisible-to-visible (I2V) technology, the windshield of a vehicle is replaced by a huge screen made of special materials. When the vehicle moves in the physical world, the equipment starts high-precision positioning and maps the vehicle's movement and environment conditions to the virtual space. The screen displays the scene in the metaverse in real time, replacing the real vision with a completely virtual vision, but with more information for users. At the same time, through digital identities' interactions with environments, users can avoid road obstacles and ascertain the best driving route.

## 5. Integration of Communications, Computing, and Storage

### *5.1. Distributed Computing and Storage*

The metaverse is the virtualization and digitalization of the real world, including diversified applications and heterogeneous devices. It produces significant computing-intensive and delay-sensitive tasks, which presents new challenges for computing and storage abilities. The metaverse integrates a variety of technologies, among which DT and blockchain are the key underlying technologies. There are significant differences in computing and storage of DT and blockchain, resulting in different requirements on the system.

DT mainly processes and renders virtual scenes and virtual characters, digitally and dynamically mapping the real world to the virtual space in real time. It needs to meet the latency requirements of heterogeneous tasks and to minimize processing and transmission delays. Usually, the cloud center is far from terminal devices, and congestion typically occurs when multiple users upload data simultaneously. Therefore, an edge server is introduced, to reduce the transmission distance and queue delay [67]. In addition, computing-intensive tasks will place a heavy computing burden on terminals and servers, which requires reasonable scheduling of the computing/storage resources, thus placing high demands on computing power and hardware capability.

Blockchain mainly processes and stores digital assets in a decentralized manner. Notably, blockchain does not require high computing power for each single node, but it needs to ensure the security of digital assets and the digital identities of users. Blockchain uses the distributed ledger, hash algorithms, and timestamps to encrypt and store the user's personal information in many distributed nodes, each with a copy, which greatly reduces the possibility of data tampering, and thus improves the security, privacy, and integrity of users' assets and data. However, blockchain generates a huge amount of redundant data [68], which causes relatively high processing latency and requires a large amount of storage space.

Following the above discussions, the realization of the metaverse calls for the optimized scheduling of communications, computing, and storage resources, as well as the coordination of cloud servers, edge servers, and device terminals, in order to minimize overall delay and maximize resource utilization, according to different technologies.

### *5.2. Integration of Communications, Computing, and Storage*

#### 5.2.1. Introduction to CPN

Due to the growing demand for ubiquitous access and the increasing characteristics of intelligent terminals, some functions of the cloud center are gradually shifting to the network edge. MEC technologies are fast developing and maturing [27]. MEC can sufficiently make use of communications and computing. As an access technology close to end users, MEC can better support delay-sensitive tasks. The deployment of many edge devices could further improve the processing speed of the system. However, the redundant data transmission introduced by MEC increases the burden on communications systems. Reference [32] proposed MEC3 technology based on MEC. By caching data or programs in advance, it reduces repeated transmission of information. In the metaverse, real-time ability and large-scale connectivity are crucial for interactive applications. According to the characteristics of the MEC, it plays an important supporting role in the metaverse, which enables the improvement of the user experience, reduces the transmission latency, and supports richer application scenarios. However, with the deep integration of information technologies and vertical industries, it is crucial to jointly allocate communications, computing, and storage resources to clouds, edges, and terminals across cloud servers, edge servers, and device terminals, to meet the diverse needs of ubiquitous connectivity, distributed perception, and intelligent information processing in the future [69].

In order to meet the demand for lightweight and dynamic computing, industry has proposed the concept of the computing power network (CPN) [33]. Traditionally, the computing resources of terminals have been decentralized. By contrast, the introduction of cloud computing has initiated a shift in computing power from the distributed form to the centralized form, establishing a paradigm of cloud-connected networks. With the development of wireless communications and AI, 6G will no longer play a single role as the communications networks. The computing power distributed in cloud centers, edge servers, and terminals also needs to be connected and flexibly organized, forming a computing power network. In this case, 6G will jointly manage resources for communications, computing, and storage. Correspondingly, this will lead to higher requirements on the computing capability in cloud centers, faster responses from edge servers, and the sensing interactions of terminals. The CPN can efficiently connect and coordinate the diverse computing and storage resources of the cloud centers, edge servers, and terminals. The CPN supports the functions of computing power service, computing power routing, and computing network arrangement. It is expected to realize ubiquitous computing interconnections, improve the utilization efficiency of resources, and achieve consistency of user experiences [31]. Then, it might well meet the requirements of the layout of computing power for the metaverse in the future. The CPN is not a network with a single communications function, but also supports computing and storage functions. Next, we discuss computing and storage tasks built upon the CPN, with an emphasis on requirements, features, and principles.

Computing Tasks: Computing tasks can be divided into binary computation offloading tasks and partial computation offloading tasks, based on the offloading methods. In the binary computation offloading model [19,20,26], computing tasks cannot be split into subtasks and cannot be executed separately. They need to be executed locally by the terminal devices or offloaded to the server. In the partial computation offloading model [21–23], computing tasks can be divided into finer granularity, based on their characteristics. Considering the correlation between subtasks, some can be executed locally, while others are offloaded to the server for execution.

Computing tasks in the CPN are basically completed by collaboration among cloud servers, edge servers, and terminals. Appropriate task offloading decisions can improve resource utilization and reduce the processing latency of the system. Cloud centers are suitable for processing computation-intensive and latency-tolerant tasks, in light of their powerful computing resources. By contrast, although edge servers have limited computing resources, they are close to terminals that request services, which are suitable for processing latency-sensitive tasks. Generally, offloading all tasks does not result in optimal performances [23–26]. It is crucial to jointly consider factors such as delay sensitivity, computational density, the available resources of the server, queuing delay, and wireless channel qualities, to assign different priorities first, and then process some tasks locally while offloading others, which can achieve better performance.

Storage Tasks: Due to the essential characteristics of the metaverse, such as diversified applications, heterogeneous connectivity devices, anytime- and anywhere-access for users, and digital identities, a sustainable storage platform and efficient storage strategies are urgently needed, in addition to computing power [70–73]. Servers will store the information in a collaborative manner and share the contents with other servers. In this sense, it is possible to reduce the load of duplicate data processing and uploading, by dynamically obtaining the terminals' information, predicting their demands, and collaboratively storing data, thereby improving storage resource utilization efficiencies and reducing latencies of services over the entire system.

Storage functions typically include content storage and policy storage. In policy storage schemes [74–77], a set of popular policies are stored in servers in advance. When a server receives relevant requests, it processes the tasks based on the requests, and then returns to the selected policy device terminals. In content storage schemes [78–80], the popular content is stored in servers in advance. When the relevant requests arrive, the servers can directly return the data to the terminal. By contrast, the overall latency of content storage is lower. However, the policy storage scheme can better generalize and adapt to heterogeneous applications. It can well support different data requests from users, with the preset policies.

Unlike the stable resource scheduling in cloud centers, edge servers do not tend to share storage space and data, due to specific requirements, such as workload, latency, and privacy [81]. In case of emergency, the inconsistent availability information of storage resources on edge servers may lead to issues of high data loss rate. To solve this problem, Ref. [82] proposed an approach that increases the total number of edge devices, and Ref. [83] proposed a method of replicating data on all nodes. However, the methods cited above will increase the overall cost of the system and may degrade performance. Reference [70] proposed a resource incentive framework based on game theory, which allocates more network bandwidth to devices that contribute more storage spaces, thus gaining better QoS.

#### 5.2.2. Implementation Architecture of the CPN's Computing and Storage Functions for the Metaverse

The CPN flexibly schedules users and allocates network resources, computing resources, and storage resources, according to business needs and the associated requirements on cloud servers, edge servers, and terminals. The CPN thus can provide an efficient task offloading and storage scheme for the metaverse, making itself a cornerstone of the metaverse implementation. In particular, based on the CPN, some mainstream implementation architectures have been proposed for the metaverse [36,84–87], where computing functions and storage functions interplay in different ways. Two typical architectures are briefly presented, as follows.

Architecture 1: As shown in Figure 5, computing tasks in the metaverse, such as the processing and rendering of virtual scenes and characters, are conducted on edge servers or in cloud centers. Then, the processed interactive data will be transmitted back to the terminal side for displaying. To achieve decentralized management and information security, the processed data can be stored in and synchronized with blockchain technologies. There are two ways of incorporating blockchain as the CPN's storage functions. One way is to use private blockchain across the cloud servers and edge servers, thus freeing terminals from heavy computing burdens and also reducing communications costs. The other way is to employ public blockchain, such that the integrity of transaction information can be protected by storing numerous ledger copies over the entire network. However, the interaction delay and computing power requirements for a single node of this architecture are relatively high, and it is, therefore, not conducive to multi-person operations in the metaverse.

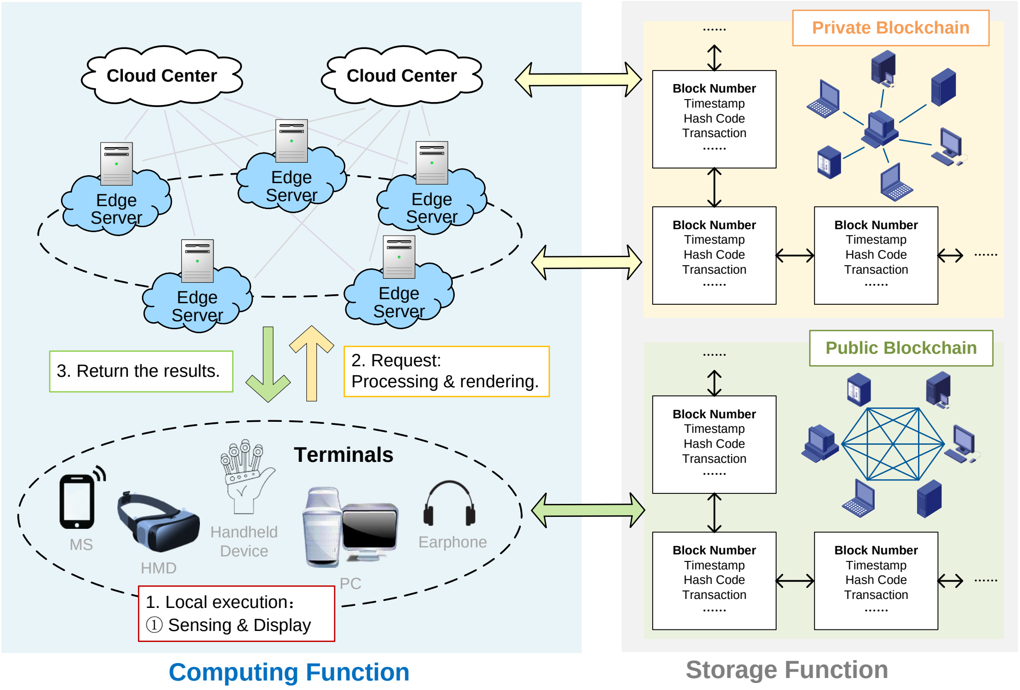


Figure 5. The implementation architecture 1 of the metaverse based on the CPN.

Architecture 2: As shown in Figure 6, this architecture adopts the hierarchical processing method. It offloads the virtual scenes, characters, and interactive tasks to the cloud centers or edge devices for processing. User terminals only need to receive and present virtual-world images and to perceive and upload physical-world information. When a terminal offloads a computing task, the terminal first sends a request to an edge server. If the edge server has sufficient computing resources, it directly processes the tasks, returns data results, and synchronizes the results with the consortium blockchain for storage. It is worth noting that consortium blockchain is recommended because it can better balance between the computing capability of terminals and the security of the stored information. Otherwise, the edge server sends a reinforcement request to the cloud center. After the cloud center processes the task, the result will be returned to the terminal and synchronized with the consortium blockchain. Furthermore, if the cloud center cannot meet the computing power demand, it will request computing power scheduling from other cloud centers in the network. This method can reduce the data transmission delay and task processing delay, so as to ensure the immersive experiences of users in the metaverse.

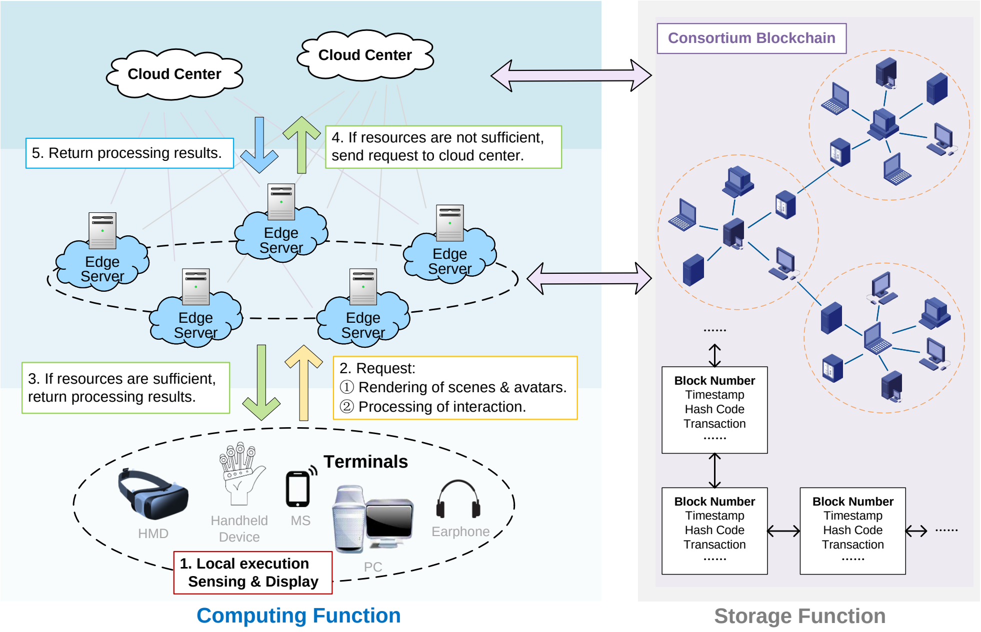


**Figure 6.** The implementation architecture 2 of the metaverse based on the CPN.

## 6. I-CSCS and the Metaverse

### 6.1. Integration of Communications, Sensing, Computing, and Storage (I-CSCS)

With the large-scale commercialization of 5G, human society is transforming faster towards digitization, networking, and intelligence, which has also initiated research for the 6G era. The newly emerging and persistently evolving application scenarios, such as smart city and the metaverse, have generated more and more diversified demands, which are increasing the heterogeneity of connection devices and network functions. The demands for ultra-low latency, ultra-high reliability, ultra-large bandwidth, and ubiquitous access are drastically surging. In response to these challenges, academic researchers and industry engineers have begun to study integration of communications, sensing, computing, and storage (I-CSCS), which is expected to play a crucial role in supporting visions of the 6G network. The IMT-2030 (6G) Promotion Group released a report on ISAC in 2021, which discusses the research status, development trends, application scenarios, and key technologies of ISAC [3]. The White Paper of Ten Fundamental Issues of Integrated Computing and Communications Network, published in 2022, discusses distributed information processing, source coding of fusion computing, computing architecture and chips, network architecture and fusion control mechanisms, resource substitution, and joint arrangement, which promotes the creation of a theory and technology of integrated computing and communications [28]. The China Institute of Communications released a report on the forefront of the integrated communications, sensing and computing network in January 2022. This report introduces the connotation, typical application scenarios, and performance evaluation index system of the network, and discusses the content, such as the air interface design, networked perception, and the intelligent CPN [30]. According to the latest ITU report on the vision of 6G, integrated sensing and communications (ISAC) has been determined as one of the main usage scenarios for IMT-2030. In the meantime, ubiquitous computing is also recognized as a non-negligible trend for new users and emerging applications [88]. In addition, storage has been widely accepted as an enabler, to enhance the efficiency of content delivery services. Consequently, the integration of communications, sensing, computing, and storage would attract fast-increasing research attention towards the 6G network.

Based on the above discussions, I-CSCS will deeply integrate communications, sensing, computing, and storage technologies, which may break the boundaries between different systems, and thereby would form a new system with collaborative functions of communications, intelligent sensing, ubiquitous computing, and storage. In this sense, I-CSCS could facilitate the construction of full connections between the digital and physical worlds, and meet the demands of industry digitization and comprehensive development of new business. In order to support the implementation and innovation of I-CSCS, it is necessary to enhance the capabilities of communications, sensing, computing, and storage in a compatible way, within a single system involving technologies, architectures, and other aspects. For example, the evolution of network architecture to air–ground–space integration will evidently and effectively enhance coverage and QoS, compared to the traditional architecture that relies solely on terrestrial or satellite communications systems. In addition, any single system could further enrich its functionality and improve performance, by collaborating with other systems. For example, the performances of communications systems could be improved, through help from technologies such as wireless sensing, federated learning, and distributed caching. Finally, through the cooperation and deep integration of communications, sensing, computing, and storage, it will be much easier to co-ordinate system functions and resources in an intelligent way. Specifically, integrated systems can autonomously perceive service requirements, intelligently match users’ behavior patterns, arrange schedules, and allocate resources.

It is clear from the above description that the I-CSCS system has advantages in many areas. However, it also has some limitations that need to be considered. Firstly, the real-time ability requires a fast response, but may consume more computing and communication resources. Therefore, a trade-off between real-time processing and resource consumption is necessary, to meet the requirements within the available resources of the system. Secondly, the integrated systems may require data processing on the edge devices, which may violate the privacy of the users. Accordingly, there should be a consideration between data privacy protection and providing valuable information during data processing. Thirdly, the unstable network connections may result in increased transmission latency, affecting real time and performance, so the conditions of the networks cannot be ignored. In addition, the inconsistencies in standards between different vendors and technologies can lead to interoperability problems in integrated systems. The standardization effort needs to ensure seamless connectivity and interaction between different components. It can be seen that the operation of the I-CSCS networks requires more discussions and research, and that improvement in the performance of the networks also needs to take into account a variety of factors, to make further trade-offs.

### *6.2. The Support from I-CSCS for the Metaverse*

The metaverse is parallel to and interacts with the real world, so diversified applications and massive interactive data in the real world will also be reflected in the metaverse. The metaverse incorporates technologies in many fields, such as DT, blockchain, and so on. Clearly, the realization of the metaverse is impossible without support from communications, sensing, computing, and storage functions. The coupled relationships of key performance indicators (KPIs)—which are the age of information (AoI) latency and reliability, ultra-reliable, and low-latency communication (URLLC)—were researched in [89], especially the potential of short-packet structure optimization for improving the KPIs. In addition, it also presented the co-design of sensing, communication, and computing, to realize the real-time requirements. The authors in [90] introduced the technical framework of the metaverse, from the aspects of the generation of virtual worlds, the connection of virtual and real objects, and the transmission of data. They also investigated the XR, motion capture, and brain–computer interface technologies, which evaluated the potential of the sensing functions for the metaverse. Reference [91] investigated an edge-computing-assisted metaverse system, in which the virtual service provider (VSP) partially offloaded sensing data collected from UAVs to an edge computing platform. It formulated the VSP’s offloading problem as a stochastic problem and utilized deep reinforcement learning (DRL) algorithms, so as to ensure the promptness of the metaverse services and to satisfy the latency requirements of the metaverse users. Furthermore, it also required a powerful platform that was able to integrate the above four functions to work together, rather than interacting with each individually.

On the other hand, massive data generated by the metaverse needs many spectrum resources and large-scale interconnections to be timeously fed back to users' devices. This implies that wireless communications with low latency, parallel co-existence of many links, large bandwidth, and stringent synchronization requirements are urgently needed. Fortunately, with the continuous evolution and development of communications systems, the 6G network is expected to explore THz-band communications, to fully utilize low-band, medium-band, and high-band spectrum resources, so as to fill the huge gap between capabilities and requirements in communications. In addition, 6G aims to reduce the communications latency to 0.1 ms, and to achieve the global coverage and seamless connection that could efficiently tie numerous connections all over the world.

There is a large amount of user interaction and environment variation in the metaverse. Therefore, ubiquitous sensing of the status of users and environments becomes critically important. Via sensing functions, physical information and users' feelings in the real world can be connected to the virtual space, with low latency and high-fidelity. It is also worth noting that comprehensive sensing functions will not only work in just one way from the real world to virtual space, but will also extend the other way, i.e., from the virtual space to users in the real world, with associated supporting devices, such as wearable devices. These devices can feed users with visual, auditory, and tactile information in the metaverse, while tracking/sensing the users' physical actions and environmental information in the real world, so as to offer the users truly immersive experiences.

The metaverse is a platform with a wide spectrum of applications. Reasonable scheduling and coordination of computing and storage resources can support diverse applications, heterogeneous devices, and massive programs and data. According to the business requirements, flexibly allocating the resources on demand in cloud centers, edge servers, and device terminals enables efficient processing of offloading tasks, and reduces the latency of the system. In addition, a sustainable storage platform and efficient storage strategies also play an essentially fundamental role in the metaverse. Storing popular content in advance and optimizing task queuing latency can effectively reduce the time cost of serving intensive tasks.

To sum up, the success of the metaverse is inseparable from excellent communications, sensing, computing, and storage functions bound tightly as an integrated entity. This principle suggests that I-CSCS should be a fundamental function block of the metaverse. The sensing function obtains physical-world information through ubiquitous and comprehensive sensing, and provides a data foundation for rendering capability in the virtual world. The computing function processes tasks, by scheduling the computing resources, so as to minimize the processing latency. With the assistance of storage functions, the redundant data transmissions load and queuing delay can effectively be reduced. Finally, the communications system serves as a bridge to integrate the above three technologies, and then constructs a new supporting system as a whole for the metaverse. With evolving and deeper integration among cooperative communications, multi-dimensional sensing, intelligent computing, and storage, I-CSCS can further improve the overall performances of the metaverse, thus more efficiently tunneling between the real world and the metaverse.

## 7. Challenges and Future Research Directions

In this section, we discuss several challenges and future research regarding the metaverse with I-CSCS, from the following aspects, as shown in Figure 7.

### *7.1. Protocol Evolution*

The network protocol is a set of agreements that must be followed by both communications parties. A communications protocols stack typically includes the protocols of the physical layer, data-link layer, network layer, transmission layer, and application layer. Only by following the protocols can different devices collaborate with one another and efficiently complete various tasks. As mentioned above, diversified applications and massive data in the metaverse need the support of I-CSCS. Yet, the I-CSCS system is a new paradigm deployed on the basis of communications networks. Thus, it can be foreseen that the metaverse will make multiple architectures and protocols compatible with one another. In this situation, communications protocols, such as MAC, routing, and transmission congestion control protocols unavoidably face an urgent need to evolve or be redesigned, in order to meet business demands and users' requirements. Just recently, ITU's report on 6G vision [88] listed integrated sensing and communications and integrated AI and communications as major application scenarios for 6G, which implies the start of standard evolution to absorb diverse functions, such as sensing and computing outside communications.

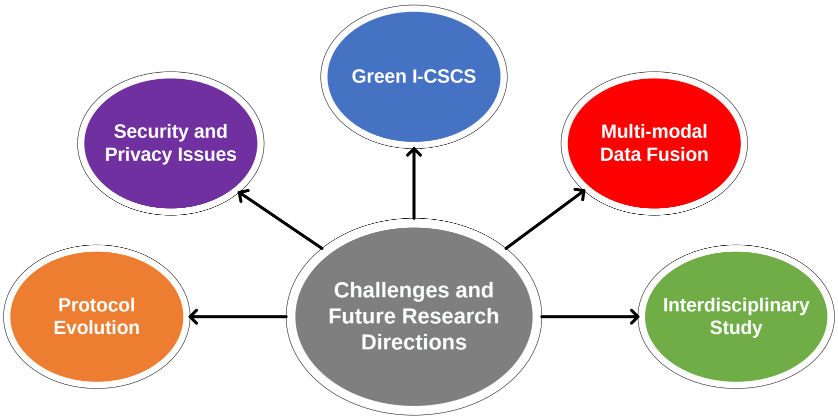


**Figure 7.** The challenges and future research directions regarding the metaverse with I-CSCS.

### *7.2. Security and Privacy Issues*

Security protocols and mechanisms for communications, sensing, computing, and storage domains typically function separately. However, trust and authentication mechanisms for multiple domains may not necessarily enhance the overall security performance when working together: on the contrary, this may lead to severe inconsistency and/or inefficient execution. Targeting this potential issue, reference [92] proposed the concepts of attribute-based authenticated key exchange (AB-AKE) and the attribute-based key encapsulation mechanism (EP-AB-KEM) for exchanging session keys among different sessions, to avoid inconsistency. Reference [93] proposed a security mechanism for secure signaling communications, based on federated content distribution networks (FCDNs), which describes protocols and analyzes security performance for the collaboration between different domains, thus effectively answering the challenge of the trust certificate distribution across multiple domains. These results and subsequent research topics should be very useful in regard to future I-CSCS.

Massive data generated by heterogeneous devices in the metaverse contain numerous items of private information—digital identity and digital assets being the essentially important ones. Users' privacy information and data security is the first priority for the metaverse to protect. Recently, blockchain technologies have adopted the distributed ledger system for data storage and management, which provides a potential solution to ensuring data trustworthiness. Specifically, in a distributed ledger system, information is open and is shared among all user nodes; each user keeps a copy of the ledger's data and updates the ledger when new transactions happen. If a malicious node attempts to tamper with the ledger, it is almost impossible for it to tamper with the data in all nodes. Therefore, blockchain can prevent unauthorized users and systems from tampering with the ledger data and can thus assure the integrity of the data. Moreover, blockchain can also absorb the capability of cutting-edge cryptographic technologies, such as the newest asymmetric/symmetric encryption algorithms and hash algorithms, to prevent privacy information being leaked. Having the above merits, blockchain has been widely accepted as the most promising storage approach for the metaverse. However, there are still significant issues in applying blockchain. For example, the metaverse is composed of multiple applications and subsystems, which have different protocols and technologies, thereby hindering identification and interaction across different subsystems. Consequently, unified authentication, authorization, and encryption mechanisms need to integrate different subsystems in the metaverse, gaining interoperability in the sharing-oriented networking environments. In addition, the blockchain-based methods are known for energy-consuming and computing-consuming issues and long processing/synchronization latency issues [55,56]. How to fit blockchain with lightweight designs for resource-constrained devices will be a lasting challenge.

### 7.3. Green I-CSCS for the Metaverse

I-CSCS systems integrate massive heterogeneous devices and various infrastructures for communications, sensing, computing, and storage, as well as the intensive deployment of sensing devices and edge servers, which causes significant energy consumption problems. Therefore, the design of a green I-CSCS system is very important.

Dynamically and optimally suspend servers and lower the processing speed: Generally, a lot of energy consumption may be caused by maintaining an all-the-time online working status, regardless of the service load. Devices are not always in working condition, often wasting considerable energy and resources to maintain the available service capacity, even during periods of low load. Therefore, it would be very useful to suspend servers and to lower the processing speed when the load of service requests is light [94].

Utilize renewable energy sources: It has been recognized that traditional energy sources face significant challenges to meeting the ever-expanding requirements on computing-based services and the associated communications, sensing, and storage. At the same time, carbon emissions caused by traditional energy have a huge impact on ecological environments, which goes against the goal of green development. Alternatively, renewable energy can be used to overcome these challenges. Renewable energy sources, such as wind, solar, hydro, vibration, and tidal power, are the low-carbon and clean-energy options for maintaining green environments. Some renewable energy can be harvested by lightweight devices and used to support running devices, such as solar energy and vibration, which can then be designed to work collaboratively with I-CSCS functions. Moreover, renewable energy typically has evident peak and off-peak features/patterns of power generation in time domain and/or geographic locations. Based on these features, optimized coordination and resource allocation for computing services in the metaverse is no doubt an effective approach to saving power. In addition, massive users spanned over the metaverse themselves can serve as energy storage nodes. Taking advantage of this potentially offers new ways to balance requests and consumption of power with high utilization efficiency.

### 7.4. Multi-Modal Data Fusion for the Metaverse

Multiple perceptual modalities may be involved in the metaverse, such as visual, auditory, and tactile. The effective fusion and synchronization of data from these different modalities are complex and important tasks, which need to solve the problems of temporal synchronization, calibration, and integration of these multimodal data. Therefore, accurate sensing function and efficient computing and storage functions are essential to achieving low sensing bias and latency. For example, if the visuals and motions of the user are not synchronized, the brain will receive abnormal information, which may cause confusion and vertigo for the user.

### 7.5. Interdisciplinary Study towards the Metaverse

The metaverse is a complex system built upon the internet, covering varieties of technologies, including communications, ubiquitous access, XR, cloud computing, decentralization management, and software-related technologies. Moreover, the realization of the metaverse needs the support of multiple disciplines, including computer science, communications engineering, economics, social science, psychology, and other technologies. All these will be tied tightly to information sciences, which impose new requirements on

I-CSCS to adapt to offering wider and stronger functions with regard to more immersive experiences, rather than staying unchanged as a separate technology.

## 8. Conclusions

There are strict requirements on communications as well as on sensing, computing, and storage functions, working together as a whole to support the metaverse. In this paper, we overviewed I-CSCS as enabling technologies for the metaverse. We first discussed the requirements of the metaverse on spectrum resources and QoS, such as ultra-reliable low-delay communications, seamless coverage, and security, followed by analyzing the support role of 6G in regard to the metaverse, which has commenced integration of communications, sensing, and computing. Then, we discussed information in the physical world that is collected by sensing devices and signals, and we analyzed the role of ISAC in serving the metaverse. Moreover, the requirements of distributed computing and storage in regard to the metaverse were presented, with an emphasis on CPN architecture. Next, we discussed the necessity and tendency of I-CSCS and its incorporation into the metaverse. Finally, we summarized the challenges and future research directions of I-CSCS in supporting the metaverse.

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