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The Dual Iconic Features and Key Enabling Technologies of 6G

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1. Introduction

Since the 1980s, when the first generation (1G) of mobile networks came into being, mobile communications have been developing with the trend of a generational upgrade occurring every decade. At present, the fifth generation (5G) is in the commercial stage and the sixth generation (6G) is in the research stage. It is expected that the standardization for 6G will debut in the year 2025, and the first version for commercialization will be launched in 2030. For the purpose of better understanding 6G, this paper proposes two iconic features and enabling technologies for 6G based on an analysis of the 6G vision.

2. The dual iconic features of 6G

For mobile communications, it is common for an even generation to have a longer life cycle than the odd generation that came before it. This is because odd generations only initiate new applications, while even generations develop these applications in order to solve existing problems and defects. There is a saying in the industry, "4G changes life and 5G changes society," which refers to the fact that 1G to 4G mainly served people, whereas 5G serves both people and things, enabling industrial upgrading and digital transformation. For 1G to 4G, the 20%/80% rule held true, only 20% of the land area has mobile communication coverage, and 80% of the traffic was generated indoors. However, it is unclear whether today's vertical industry applications will still obey this rule. At present, 5G is encountering growing problems as mobile communications enter vertical industries for the first time; these problems include wide-area sparse access, flexible customization, cross-border application integration, and other challenges.

Therefore, the study of 6G should simultaneously consider how to solve the problems presented by 5G and embrace new requirements after 2030. Following the commercialization process of 5G, 6G has been widely studied by academic institutes and industries as a hot topic. Thus far, numerous publications [1] and white papers [2–6] have explained the vision and technologies for 6G. Among these, China Information Communication Technology Group (CICT) and the National Key Laboratory of Wireless Mobile Communications jointly issued three white papers on 6G, presenting the vision of global coverage and context–aware connection [6].

Within this vision [1–6], we believe that the key applications of 6G will include at least two categories. The first category is for the Internet of Things (IoT), as 6G will achieve a virtualized world with digital twins for the perception of everything in the physical world. The second category is for people, as 6G will enable people's five senses to connect with the tactile Internet and even to connect with the meta-universe of immersive social networking and games, as shown in Fig. 1.

Therefore, 6G presents two major challenges. The first challenge involves connected wide-area and spatial coverage. For technical and economic reasons, the current 4G/5G terrestrial cellular communication mainly covers economically developed and densely populated zones, only accounting for about 20% of the land area or 6% of the earth's surface. The second challenge relates to access point (AP) local coverage, since the meta-universe AP must provide critical personal experience with a high data rate, low latency, and huge system capacity. There is also a high-speed Internet access requirement for numerous customers onboard passenger aircraft and cruise ship.

To address the challenges mentioned above, 6G will change how people think about mobile networks. 6G will have two new iconic features: integrated terrestrial-satellite communication (ITSC) [7], which will solve the problem of wide-area coverage; and a user-centric access network (UCAN), which will address the problem of local coverage, as shown in Fig. 2. These iconic features will subvert the conventional iconic features of mobile communications from 1G to 5G, such as terrestrial/land mobile communications and a base-station-centric cellular network, as shown in Fig. 3.

2.1. The first iconic feature of 6G: ITSC

Being requirement driven, the existing 3G/4G/5G terrestrial mobile communication networks currently cover 70% of the population; however, it is difficult to achieve cost-effective coverage in space, on oceans, and in forests, deserts, and other remote areas. With the expansion of human activities, it is necessary for digital twins and the Internet of Everything to be supported by 6G over a wider extent of the globe. As a result, the problem of wide-area 6G coverage must be solved using a global and cost-effective approach. Satellite communications provide a good solution to this problem.

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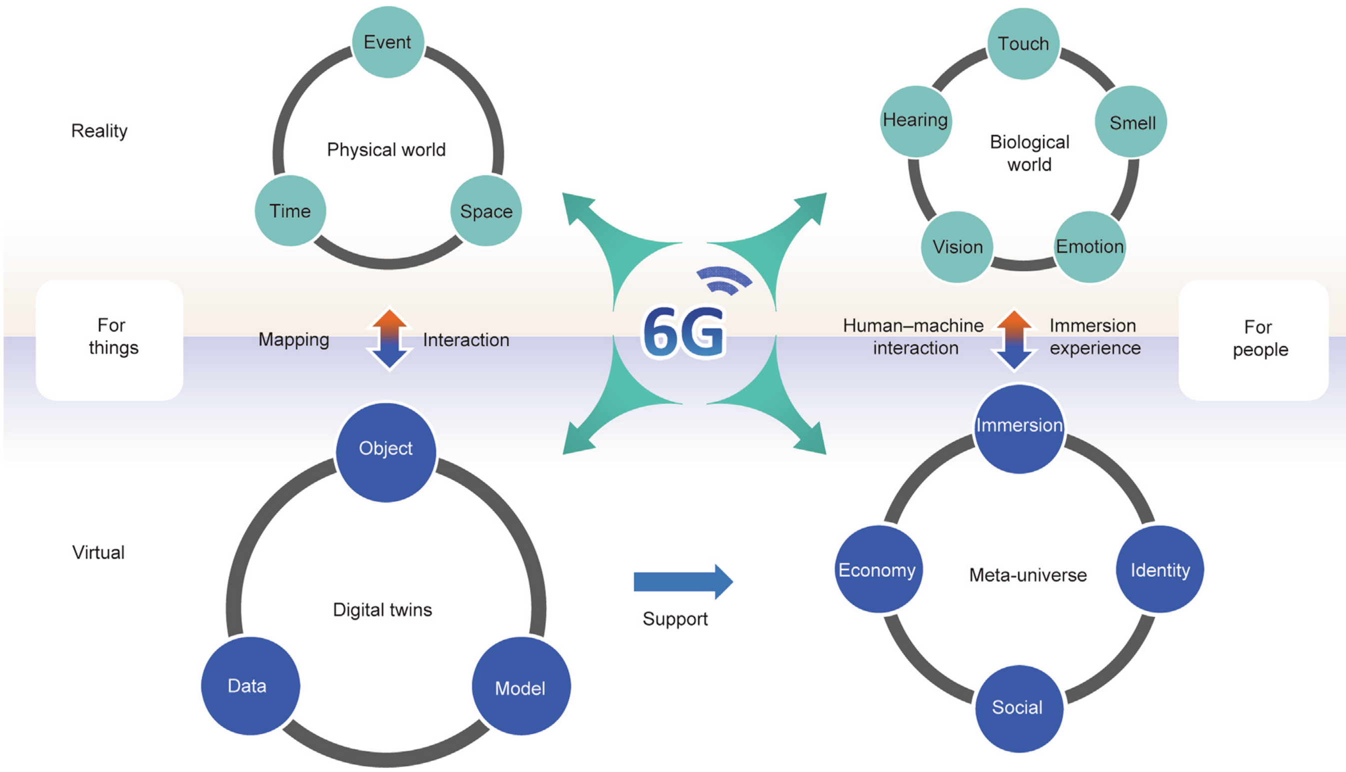

Fig. 1. The 6G vision and two categories of applications: digital twins and the meta-universe.

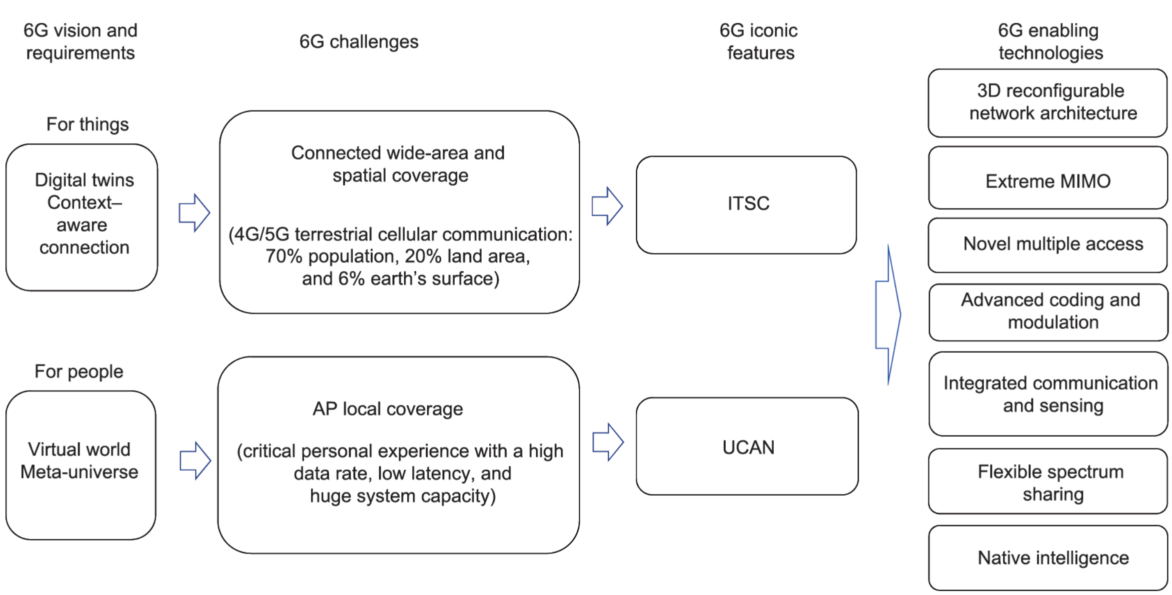

Fig. 2. From the vision of 6G to the dual iconic features and key enabling technologies of 6G. 3D: three-dimensional.

Due to their development being driven by industry, many different conventional satellite communication systems exist, which are incompatible, small in scale, and high in cost. Moreover, existing terrestrial networks and satellite networks are developing independently, resulting in different standard systems and fragmented industrial chains, which lack economies of scale. Based on the excellent progress that has been achieved in communications, semiconductors, and satellite technologies in recent years, it is possible to integrate terrestrial-satellite communication around a single standard in 6G; this will result in a unified air interface, unified access authentication, and a unified core network to achieve global coverage [7]. In this way, individual users with their mobile phones in cities, remote areas, deserts, and forests, while adopting any kind of terminal (e.g., airborne, vehicle-mounted, or ship-mounted terminals) can receive integrated communication service, undergo seamless handovers, and roam freely between terrestrial and satellite communications. This is the first iconic feature of 6G.

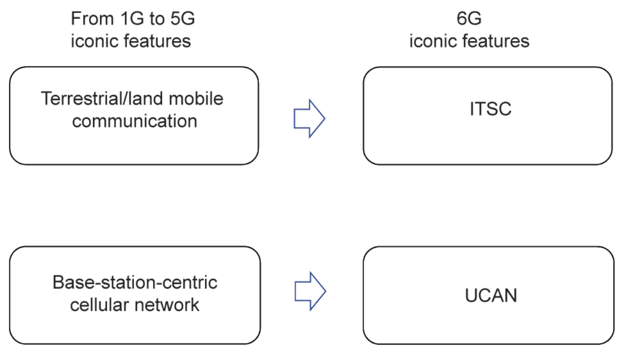

Fig. 3. Changes in the iconic features of conventional mobile communications to those of 6G.

2.2. The second iconic feature of 6G: UCAN

Cellular networks have been regarded as the foundation of mobile communications since Bell Labs first invented this concept in the 1960s [8], as shown in Fig. 4. This is why mobile communications are often referred to as cellular communications. The innovation of cellular technology enables wireless communication to address the two major challenges of frequency reuse and interference resistance. With generated handover technology between adjacent cells, communication can be continued while a user crosses the boundary between two cells.

With the advancement of massive multiple input and multiple output (MIMO) and beamforming technology in recent years, beams have been focused and narrowed, allowing the frequency to be reused and reducing related interference. In addition, artificial intelligence (AI) technology has been widely applied in communication networks, which can help to solve interference via spectrum perception and scheduling. Therefore, the original design goals of a cellular network with frequency reuse and interference resistance can be achieved by means of beam-space multiplexing [9] and AI, making a "de-cellular" [10] technology trend possible—that is, a shift toward non-cell-based communication networks. One typical "de-cellular" solution is a UCAN, where multiple APs (e.g., ground base stations or satellites) are dynamically grouped together to simultaneously serve a single user, thereby achieving the dynamic multiplexing of wireless resources. Another typical solution is the joint networking of satellites and unmanned aerial vehicles (UAVs) serving the wide-area IoT in order to solve the problem of a sparse and uneven distribution of IoT devices over a wide area. For new 6G services with a high data rate, such as extended reality (XR) or holographic type communication (HTC), the traditional cellular architecture will be unable to meet users' needs at the edge of a cell in the network, and the system capacity will be extremely restricted, even if there are resources available. In comparison, a UCAN can greatly improve the performance near the edge of a cell, allowing more users to be supported; the total system capacity can then be improved as well.

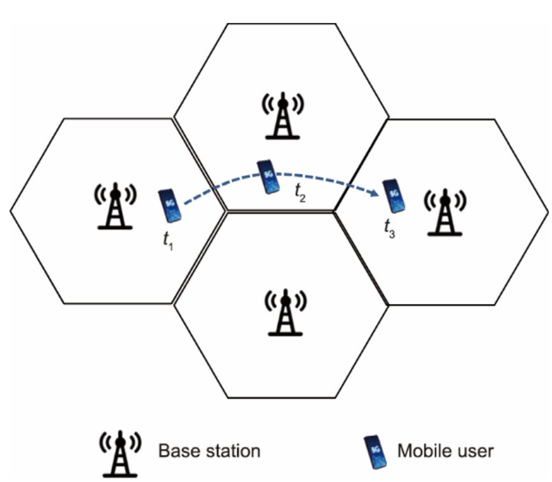

Fig. 4. A general view of cellular communications. t_1, t_2, and t_3: different time slots.

6G will support a virtual world and immersive meta-universe experiences, which will present new challenges regarding the data rate per user and the total system capacity of local coverage. Therefore, 6G will utilize a UCAN architecture to manage local coverage. This is another iconic feature of 6G.

3. Key enabling technologies for 6G

Compared with 1G to 5G, the innovation of 6G with its dual iconic features requires the support of key technologies. Potential key enabling technologies include a three-dimensional (3D) reconfigurable network architecture, extreme MIMO (E-MIMO) [11], advanced coding and modulation, novel multiple access, integrated communication and sensing, flexible spectrum sharing, and native intelligence.

3.1. 3D reconfigurable computing and communication integration network architecture: Supporting ITSC, UCAN architecture reformation, and flexible customization in vertical applications

Conventional mobile communication networks only have two-dimensional (2D) architectures. However, the ITSCs will comprise a 3D network. Since there is an evident difference between satellite nodes and terrestrial nodes in terms of capabilities such as computation and storage, it is preferable to create a specific design for each node's network function according to its capabilities. Moreover, in order to support the user-centric radio access network, an architecture with characters of flexible, reconfigurable computing and communication integration must be introduced. Each elementary function of the network will be flexibly divided and deployed on demand between satellite nodes and terrestrial nodes, and the computing power will be organically shared within the cloud edge network. This architecture has the important characteristics of being distributed and service oriented in order to solve the problem of low-cost wide-area coverage, local dynamic high-data-rate coverage, and the poor flexibility of current 5G industry-oriented applications.

3.2. E-MIMO technology: Enhancing the 6G user data rate and system spectral efficiency

In addition to expanding the bandwidth to a high-frequency band, such as millimeter waves or even terahertz waves, it is necessary to use E-MIMO technology to obtain higher peak data rates and larger system capacity. Typical solutions include massive MIMO with a centralized or distributed application method, reconfigurable intelligent surfaces, and holographic MIMO. With its ability to expand channel resources, E-MIMO technology has the capability to expand coverage, suppress interference, and improve the utilization of wireless resources.

3.3. Novel multiple access: Meeting the challenges of ITSC and massive access

For 6G ITSC, the Internet of Everything or context–aware connection presents great challenges in achieving multiple access, since it is necessary to support variable scenarios. Examples of scenarios include a huge number of ubiquitous connections with more than ten terminals per square meter and integrated terrestrial-satellite coverage. At present, orthogonal multiple access technologies have no capability to process massive connection. Thus, 6G must adopt a more flexible and efficient resources multiplexing method to accommodate increased user access. Pattern division multiple access (PDMA) [12] is a typical technical solution for non-orthogonal multiple access proposed by the authors of this paper, and it is currently evolving to 6G in order to achieve uncoordinated random access and transmission (URAT).

3.4. Advanced coding and modulation: Providing flexible and efficient support for ultra-high throughput, ultra-low latency, and other scenarios

Coding and modulation are regarded as the basic technologies of mobile communications, and their design will directly impact key areas of performance in 6G, such as ultra-high throughput, ultra-high reliability, extremely low latency, and high mobility. Under different application scenarios, 6G requires the support of diversified coding and modulation technologies. For example, coding and modulation solutions can be created to satisfy ultra-low latency and/or ultra-high reliability, while other solutions can be created to support an extremely high throughput with low computation complexity. Additional solutions such as AI-assisted coding and modulation technology, joint coding and modulation technology, and so forth, can also be developed.

3.5. Integrated communication and sensing: Realizing the intelligent connection of all things and achieving intelligent perception

6G will use wireless perception technologies to obtain the position and attitude of non-target objects, as well as related environmental information. This multidimensional and multilevel perception data will extend the mobile communication system from unique target terminals to non-target objects and the related environment, thereby realizing the intelligent connection of all things and achieving intelligent perception. This advance requires further research on application scenarios, advanced architectures, environment perception and auxiliary communication technologies, and air interface technologies such as waveforms and interference resisting, among other topics.

3.6. Flexible spectrum sharing: Solving the challenges of contradictions between spectrum resource scarcity and under-utilization within ITSC

More diversified scenarios and the continuous growth of services have led to increasing spectrum requirements. However, there exists an evident contradiction in managing spectrum resources. Despite scarce spectrum resources, the spectrum is under-utilized due to the conventional static spectrum allocation policy and management method. Furthermore, some of the allocated spectrum has a lower usage. Therefore, flexible spectrum-sharing technology is required to improve the utilization efficiency of limited spectrum resources. In the processes of spectrum sensing and spectrum scheduling, AI can be used to improve accuracy. For example, AI-based spectrum sensing can help multiple operators to dynamically share the same wideband resources according to the available frequency usage while supporting a high data rate. AI-based spectrum scheduling can help users to effectively distinguish signals from a satellite link or terrestrial link, thereby realizing co-frequency spatial multiplexing and interference avoidance. Of course, in addition to technological breakthroughs, policies and regulations must be coordinated and innovated to develop flexible spectrum-sharing technologies from theory to practice.

3.7. Native intelligence: From 5G AI application to 6G wireless intelligence and network intelligence

Wireless intelligence and other technologies are evolving from AI-enabled 5G channel estimation, signal detection, wireless network optimization, and other decentralized applications to a 6G AI-based end-to-end wireless communication system for the purpose of improving transmission performance. 6G will use AI to perform network self-optimization and self-evolution, improve network security and reliability, reduce the costs of network operation and maintenance, and reduce network energy consumption. 6G network intelligence will be changed from centralized cloud intelligence to distributed network intelligence, while data processing will be transferred from the center to the edge. Edge intelligence will introduce the challenge of increased data interactions between base stations and terminals, requiring more research on network intelligence management and orchestration.

Acknowledgments

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