White Paper on 6G Vision and Candidate Technologies

IMT-2030 (6G) Promotion Group

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Contents

The IMT-2030 (6G) Promotion Group was established in June 2019 by the Ministry of Industry and Information Technology (MIIT) of China. The organizational structure is based on the original IMT-2020 (5G) Promotion Group. The members include major Chinese operators, vendors, universities and research institutions. The promotion group is the main platform for gathering China's industry-university-research forces, promoting China's sixth-generation mobile communication technology research and developing international views exchanges and cooperation.

1 6G Vision

Following the scaled commercial rollout of 5G networks, the global industry has begun researching and exploring the next-generation mobile communications technologies — 6G. In 2030 and beyond, society will enter an era of intelligence. Balanced, high-quality social services, scientific, precise social governance, and green, energy-saving social development will become the trend of society in the future. From mobile internet, to the internet of everything, and then to the intelligent connection of all things, 6G will realize the transition from serving people, people and things to supporting the efficient connection of intelligent agents. Through the intelligent interconnection of people, machines and things, and collaborative integration, it will meet the needs of high-quality economic and social development, serve smart production and life, and promote the construction of an inclusive and intelligent human society.

Fueled by breakthroughs in mathematics, physics, materials, biotechnology, and other fields, 6G will integrate with information technologies, such as advanced computing, big data, artificial intelligence (AI), and blockchain. This integration will further accelerate the fusion of communications with sensing, computing, and control, solidifying 6G as the foundation of our daily lives, industrial production, and green development. 6G will also maximize the potential of low-, medium-, and high-band spectrums to achieve seamless global coverage, meeting the requirements

Figure 1 Overall vision of 6G

for unlimited secure and reliable connections among people, machines, and things anytime, anywhere.

6G will provide fully immersive interaction scenarios and support precise spatial interaction to meet the requirements for multiple senses, feeling, and mind communications. Communication for sensing and inclusive intelligence will not only improve communications, but also supercharge the digitalization and intelligence of physical objects, greatly enhancing the quality of information and communication services.

6G will build innovative networks with both ubiquitous connections among people, machines, and things and efficient interconnection of intelligent agents. On the basis of greatly improving network capabilities, 6G will incorporate a plethora of new capabilities, including native intelligence, communication for sensing, digital twins, and native security. 6G will enable efficient and intelligent interconnection between people, people and things, and things in the physical world to build real-time, reliable, integrated, and ubiquitous virtual worlds that accurately reflect and predicts the real state of the physical world in real time, helping mankind advance to a new era where people, machines, and things are fully connected and the virtual and real worlds are deeply integrated. This will be essential to ultimately realize the vision of an “intelligent connection of everything, digital twin” society.

Realizing inclusive, personalized, and high-quality social services and precise governance by 2030 will require 6G to enable ubiquitous coverage and integrate the physical world with the virtual world. Technological breakthroughs and transformative production will require 6G to empower collaboration across industries and advanced intelligence and drive it to become a new engine of economic growth. Sustained development and emergency response will also require 6G to build networks reaching all terrestrial and aerial spaces, expanding connections from densely populated areas to fully geographical areas all over the world.

2.1 Changes in Social Structure

Digital technologies are required to increase inclusiveness across unbalanced income levels. Today, the wealth gap is continuously widening, posing huge economic and social risks. The International Telecommunication Union (ITU) proposed using information and communication technologies to help realize the UN Sustainable Development Goals. Technologies such as big data, AI, and holographic sensing will facilitate inclusive poverty alleviation in education, healthcare, and finance. They are powerful tools to help narrow income level gaps across the world, facilitate coordinated development of various groups, and comprehensively improve people's well-being. By 2030, the number of people in the middle class will increase from nearly 1.8 billion in 2009 to 5 billion globally [1]. The expansion of the middle class will accelerate the adoption of high-quality smart services. Applications such as holographic videos, 3D videos, and sensory interconnection alleviate the restrictions on time and location in our daily lives, which will significantly improve people's self-oriented smart life and immersive holographic experience. The new generation of digital technology will fully meet people's personalized and high-end needs in their lives.

Demographic imbalance calls for digital technology to improve human capital and allocative efficiency. Currently, the aging population is increasing across the world. Emerging economies that have benefited from the demographic dividend are also mired in the imbalance between slow growing population and stable economic growth. According to statistics from the UN, the proportion of world's population aged 65 and over has increased from 5.1% to 9.1%, and the world's total fertility rate has fallen from 5.05% to 2.45% over the past seven decades. The global population is predicted to reach 8.5 billion by 2030, one billion of which will be over 65 years of age [2], directly leading to a decrease in labor supply.

Driven by the new industrial and technological revolution, economic development will depend more on human capital than on the quantity of labor. Intelligent tools and technologies will be ideal for industries to make up for the labor shortage and increase production efficiency while also promoting unmanned production lines, factories, and other applications. 6G will be essential to innovation in fields such as education, healthcare, and entertainment to serve the differentiated requirements of different groups, while improving global human capital.

Change in the social governance structure necessitates modern governance. In the future, the entities of social governance will be further diversified. As social governance is gradually innovated, enterprises and individuals will engage through open data resources and ecosystems. As a result, the government will no longer be the sole leader and executor of social governance, significantly improving the capacity of social governance. In addition, the structure and process of governance will become more flattened, the social governance system will integrate and adapt to information technology, and the social management service system will develop in a grid incorporating all elements. This will shift the original information transmission from single-center to multi-center. The dynamics, complexity, and unpredictability of social governance scenarios will be also improved considerably. Under a more diversified, flattened governance structure, the demand for precise, scientific governance will enable digital twins to break down the barriers between social segments. As such, a new governance model that can restore the physical world through virtual mirroring, simulate complex social events and dynamic changes through AI and other technologies, and make accurate, scientific decisions and respond to real-time events will be developed.

2.2 High-Quality Economic Growth

Sustainable economic growth is fueled by the impetus brought by new technologies. The 2008 global financial crisis caused the growth rate of total factor productivity in major economies to drop for several successive years and slowed down global economic growth. In this context, it is urgent to inject new impetus into the global economy by developing new technology industries to drive sustainable economic development. Breaking the current economic growth pattern and embracing the high-quality and intelligent production mode are the only ways to ensure high-quality global economic growth. By 2030, people, machines, and things will work together, highlighting the importance of synergy across domains. Accurate, reliable, and quasi-real-time seamless transmission on various software and hardware will break the time and space limitations of traditional offices.

The new production mode will further involve machines and things that can sense human emotions, thoughts, and mental states to enable cross-space labor collaboration. Unmanned production or collaborative production among people, machines, and things, integrated with technologies such as big data, cloud computing, and digital twins, will drive the fully intelligent transformation of the industry and further improve production innovation abilities.

The globalization of services requires lower cost in all-round information communications. Globalization boosts economic development, and global collaboration based on division of labor lowers costs and improves efficiency. Since the industrial revolution, the efficiency of manufacturing, transportation, and logistics has been greatly improved, and the international division of labor has shifted from the production of final products to the intermediate links of production. Trade in intermediate products and large multinational companies emerged all over the world. In recent years, the cost of information and knowledge dissemination is continuously decreasing with the rapid development of next-generation information technologies. The field of data communications has obtained a lion share of material, technology, capital, and talent. In addition, communication platforms have become pools of resources and an important tool for promoting collaboration, improving efficiency, and building ecosystems. The international division of labor extends from the physical world to the digital world. In the future, the rapid development of next-generation digital technologies such as digital twins, holographic perception, and immersive interaction will further reduce the costs of communications between humans, humans and machines, and humans and things. Global trade will also shift from physical products to digital services. This will result in more coordinated and effective international division of labor, more reasonable industry distribution, and higher production efficiency.

2.3 Environmental Sustainability

Lower carbon emissions and carbon neutrality call for improved energy efficiency and green development. New development requirements have been raised for green and energy-saving 6G networks. In September 2020, China announced that it aims to have carbon dioxide emissions peak before 2030, and achieve carbon neutrality by 2060. Until now, more than 120 countries and regions have set goals for carbon neutrality, posing high requirements on the energy efficiency of future 6G mobile communications facilities and promoting energy conservation and environmental-friendly reconstruction in the industry. 6G needs to provide more accurate and efficient digital management capabilities to help energy-consuming industries reduce their carbon emissions. For example, in the electric power industry, situation monitoring and emergency response in the smart grid require 6G to provide more secure, reliable, and efficient sensing and analysis capabilities to achieve higher efficiency. In the construction industry, factories with assembled buildings and the quality control and safety supervision in smart manufacturing require a more complete digital design system and interactions between people and machines. In addition, as the advantages of 6G lie in its high speed and massive connectivity, dynamic optimization and precise decision-making throughout the entire industrial production process can be achieved to save energy and reduce emissions in the industrial field.

Extreme weather conditions and global emergencies require wider sensing and closer intelligent collaboration. Frequent extreme climate events call for a real-time accurate environment monitoring system and a highly intelligent collaboration system. According to the State of the Global Climate 2020 released by the WMO, 2020 was one of the three warmest years on record. Floods, hurricanes, and fires have caused losses of tens of billions of dollars to affected countries. To comprehensively protect global ecosystems and environments, networks must expand connections to sensors widely distributed in oceans, mountains, rainforests, and grasslands to enable closed-loop management for monitoring, protection, prevention, and rescue. Stronger 6G regional collaboration and better resource allocating are required to tackle global emergencies and improve resource utilization. However, none of these goals can be achieved without powerful ubiquitous 6G communications in the land, sea, sky, and space. Moreover, close partnership and flexible dispatching of resources are implemented to facilitate a wide-area intensive mobilization through more inclusive, intelligent, and efficient collaborations across regions.

Towards 2030 and beyond, 6G network will realize the deep integration of real physical world and virtual digital world, and build a new world of intelligent connection of everything and digital twin. The extensive and in-depth application of immersive cloud XR, holographic communications, sensory interconnection, intelligent interaction, communication for sensing, proliferation of intelligence, digital twins, global seamless coverage in people's life, social production, public services will better support the demand for high-quality economic development, further realize the accuracy of social governance, the efficiency of public services, and the diversification of people's lives. New services and applications will promote the practice of people-centered development concept at a higher level, meet all-round spiritual and material needs of people, and continuously improve people's sense of gain, happiness and security.

3.1 Immersive Cloud XR — A Broad Virtual Space

Extended reality (XR) is an umbrella term encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). In cloud-based XR, content will be stored and all rendering and computing operations will be implemented on the cloud. This will greatly reduce the computing load and energy consumption of XR devices while freeing users from the constraints of cables. As such, lightweight XR devices will become the mainstream to guarantee more immersive and intelligent experiences, facilitating commercial adoption.

In 2030 and beyond, the immense improvement of networks and XR terminals

Figure 2 Immersive cloud XR — a broad virtual space

will drive XR technology to enter an era of full immersion. Cloud-based XR will be integrated with networks, cloud computing, big data, and AI to enable digital transformation in various fields, such as business and trade, industrial production, culture and entertainment, education and training, and healthcare.

Cloud-based XR will enable users to interact with environments by using audio and motion, including eye, head, and hand movements. This premium experience can be delivered only when ultra-low latency and ultra-high bandwidth are provided in relatively defined environments. Currently, cloud VR supports a motion-to-photon (MTP[1]) latency of less than 20 ms and end-to-end latency of as high as 70 ms. Towards 2030 and beyond, the total latency of cloud XR will be further reduced to below 10 ms. According to the Virtual Reality Promotion Committee, a fully immersive VR experience requires an angular resolution of up to 60 pixels per degree (PPD), a frame rate of at least 120 Hz, and a field of view (FoV) of at least 130°, resulting in each pixel having 12 bits. To reduce motion sickness, the required throughput will approximate 3.8 Gbps, given a 100:1 compression ratio.

3.2 Holographic Communications — Extremely Immersive Experience

With the continuous development of wireless networks, high-resolution rendering, and terminal displays, holographic technology will enable 3D dynamic interaction among people, things, and surrounding environments through natural and lifelike visual restoration, greatly empowering future-oriented communications.

Figure 3 Holographic communications — immersive premium experience

[1] The motion-to-photon (MTP) latency denotes the duration between when a motion occurs and when the resulting image becomes visible to the user.

Holographic communications will be widely used in culture and entertainment, healthcare, education, and production to bring a fully immersive experience to users without the restrictions of time, space, and the boundary between the real and virtual worlds. However, this will not be possible if future communications networks cannot meet the requirements for real-time 3D display and fast transfer of holographic images. To send 1920 x 1080 x 50 3D target data [3] with a 24-bit RGB and refresh rates of 60 frames per second (FPS), networks must support a peak throughput of approximately 149.3 Gbps, or an average throughput of 1.5 Gbps given a compression ratio of 100:1. Since immersive multidimensional interactions will involve thousands of concurrent data streams, the networks must be able to provide Tbps-level perceived throughput. For holographic targeted therapy and remote microsurgical operations, loss of information will lead to retransmission, which, in turn, will fail to meet requirements on reliability and latency. This will further raise the standards for networks in transmission security and reliability.

3.3 Sensory Interconnection — Fusion of All Senses

Sight and hearing as well as touch, smell, and taste are essential for us to understand our world. In 2030 and beyond, the signal transmission of not only hearing and sight but also the other main senses — touch, smell, and taste — will become a major part of communications and soon be used in various fields, from healthcare to education, entertainment, traffic control, production, and social interaction. In the future, people will be able to feel the warmth of a hug from a family

Figure 4 Sensory interconnection — fusion of all senses

member with just their mobile devices when living far apart. Even in their own homes, users may be able to enjoy experiences, such as a beautiful scenery and even a walk on the sandy beach while feeling the sea breeze in Maldives.

Fused interaction of all the major senses requires coordinated and synchronized transmission of data related to the different senses. To maintain high-quality experience, millisecond-level latency will become mandatory. The feedback of the touch sense is strongly related to body movement and locations, raising the requirements for high-precision positioning. The in-step transfer of all-sense information will not be possible if networks do not multiply their maximum throughput. With more senses interlinked during communications, robust data security must be assured to protect privacy and avoid infringement. In addition, each sense will have a unique digital representation, calling for new joint and independent encoding and decoding modes to facilitate data transmission.

3.4 Intelligent Interaction —Interactions of Feelings and Thoughts

6G mobile communications will provide a new opportunity to make breakthroughs in many areas of research, such as emotional and brain-computer interactions. Intelligent agents will be able to perceive, recognize, and think, evolving into a complete alternative to traditional intelligent devices. The user-tool relationship between people and intelligent agents will evolve to equal human-like interactions with emotions and mutual understanding. Such intelligent agents will be able to sense the psychological and emotional states of users through dialogue and facial

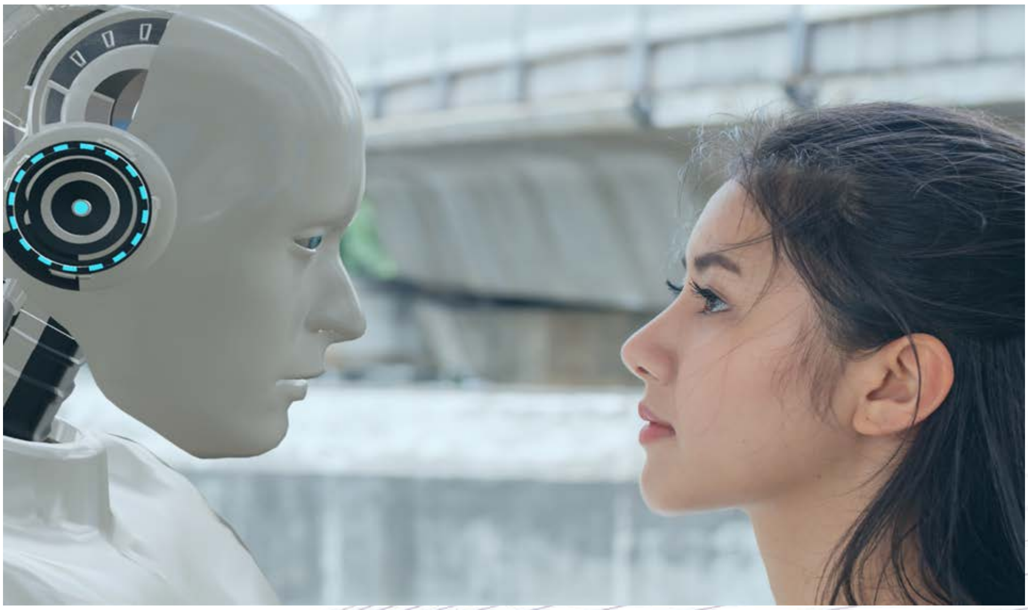

Figure 5 Intelligent interaction — interactions of feelings and thoughts

expressions to help the users mitigate health risks. Supporting lossless transmission of brain information, mind-controllable machines will be available to help the disabled overcome their physiological difficulties in their daily lives and work while quickly accumulating knowledge and skills.

Intelligent agents will enable proactive intelligent interactions and realize emotional judgment and intelligent feedback. This will lead to a tremendous upsurge in data to be processed. Such real-time interactions with humans will require networks to support a latency of less than 1 ms [4] and a user-perceived data rate of over 10 Gbps [5]. Intelligent interactions powered by 6G will involve a rich variety of information, including audible, facial, gestural, and physiological signals, with an extra major improvement in comprehending human's thinking and emotional situations. This will require networks to ensure 99.99999% reliability [6].

3.5 Communication for Sensing — Extending the Functions of Converged Communications

6G networks will utilize communications signals to sense, detect, locate, identify, and image targets. This will help wireless communications systems obtain information about the environment to further improve resource allocation and user experience. Leveraging higher-band spectrum such as mmWave or terahertz will facilitate the acquisition of environment information, which, in turn, will further enhance the performance of wireless systems. It will also facilitate the digitalization of physical entities in the environment and create more applications.

With real-time wireless sensing, advanced signal

Figure 6 Communication for sensing — extending the functions of converged communications

processing algorithms, and the exploration of edge computing and AI technologies, 6G will help sense the environment information and reconstruct the target environment with ultra-high-resolution (UHD) RF images, and enable centimeter-level positioning. This significantly accelerates the realization of the vision for virtual and smart cities. The sensor networks built based on wireless signals can supplement or even replace laser radars and cameras, which are easily affected by light, to improve sensing resolution and detection precision in all weather conditions. With these networks, surrounding objects such as pedestrians, bicycles, and baby strollers can be categorized through sensing. In addition, to implement applications such as collaboration between robots, contactless motion control, and action recognition, millimeter-level resolution will be required to provide high-precision real-time sensing services to users. Besides, with higher frequency bands such as THz, environmental pollution source detection and air composition monitoring such as PM2.5 analysis can also be implemented with sensing.

3.6 Proliferation of Intelligence — Ubiquitous Smart Core

By 2030, we will see more smart terminals, including smart personal and household devices, sensors in cities, unmanned vehicles, and smart robots. Unlike current smartphones, these new terminals will not only transmit data at high speeds, but also work with and learn from various smart devices. The number of devices connected through the 6G network is expected to reach trillions in the future. Through continuous learning, communication, cooperation, and competition, these devices can efficiently simulate and predict physical world

Figure 7 Proliferation of intelligence — ubiquitous smart core

scenarios and provide the optimal decisions.

In terms of network O&M, intelligent AI agents can provide data analysis and help decision-making by using knowledge and experience accumulated from practices. They will also support massive data processing and zero-latency control. In addition, they can coordinate the load of the network center and edges when the network changes and processes burst requests on access and transmission. In smart factories, a large number of collaborative production robots will enable information interaction and learning through intelligent agents and continuously update their models, which, in turn, optimizes manufacturing. In addition, 6G's intelligent design can utilize resources on demand to provide action policies for unmanned systems such as UAV clusters and smart robots in real time, achieving efficient control and high-precision positioning. Moreover, AI can interlink data such as image, voice, and temperature data to enable reliable and low-latency communications and collaboration between smart terminals in specific environments and continuously improve efficiency and accuracy of operations through learning based on big data.

Applying AI is essentially to fully explore and continuously learn from big data with enhanced computing power. In the era of 6G, network self-learning, self-operation, and self-maintenance will be developed based on AI and machine learning. By then, networks will be robust enough to adapt to various real-time changes. Through self-learning and collaboration between devices, 6G networks will empower society to achieve ubiquitous learning and continuous updates. AI services and applications will be brought to end users, making real-time and reliable AI intelligence accessible to each individual, home, and industry. This can finally make real inclusive intelligence a reality.

3.7 Digital Twins — Digital Mirror of the Physical World

With advancing sensing, communications, and AI technologies, objects or processes will be digitally replicated. Interactions such as people-to-people, people-to-thing, and thing-to-thing will be intelligently mapped into the digital world. Leveraging data mining and advanced algorithm models, the digital world can utilize abundant historical and real-time data to simulate, verify, predict, and control physical objects or processes, delivering the optimal solution for issues in the physical world.

The 6G era will usher in a world of digital twins. In healthcare, medical systems can use digital twin information for diagnosis and provision of the optimal treatment. In the industrial field, product design can be digitally optimized to reduce costs and improve efficiency. In agriculture, the production process can be simulated and deduced to predict adverse

Figure 8 Digital twins — digital mirror of the physical world

factors and improve production as well as utilization of the land. In network O&M, networks can quickly adapt to complex and dynamic environments through physical and digital interaction, cognitive intelligence, and automatic O&M, bringing autonomy throughout the O&M lifecycle, from planning to construction, monitoring, optimization, and self-healing.

However, this will pose many challenges to 6G networks' architecture and capabilities. 6G networks must support trillion-level device connections and sub-millisecond-level latency to precisely detect subtle changes in the physical world in real time. The quality of data also needs to be ensured by using data models and standard interfaces with self-correction and self-generation capabilities. To meet the requirements for data privacy and security, 6G networks also need to support data storage, collection, processing, training, and modeling in both centralized and distributed architectures. In addition, a Tbps-level transmission rate will be required to meet the requirements on data volume for precise modeling, simulation, and verification. Through fast iterative optimization and decision-making, digital entities can also be generated in centralized or distributed mode as required.

3.8 Global Seamless Coverage — Three-Dimensional Connections

Currently, more than 3 billion people around the world do not have basic Internet access [7], most of whom live in rural and remote areas. The high cost of constructing terrestrial communications networks is difficult for telephone communication companies to afford. On top of this, terrestrial networks cannot provide high-speed communications required in uninhabited or oceanic areas for Antarctic expeditions and ocean freighters. In addition, the demand for connections for aerial devices such as UAVs and airplanes is increasing. As services converge and deployment scenarios expand, terrestrial cellular networks will also be integrated with non-terrestrial networks, including the high-, medium-, and low-orbit satellite; high-altitude platforms; and UAVs, to build a 3D integrated network with global coverage, providing users with ubiquitous broadband mobile communications services.

Global seamless coverage can enable broadband access anytime and anywhere, particularly for remote areas, airplanes, UAVs, vehicles, and ships. It can also enable wide-area IoT access in areas not covered by terrestrial networks, ensuring emergency communications, crop monitoring, endangered animal monitoring in uninhabited areas, as well as collection of information on marine buoys and ocean containers. In addition, centimeter-level positioning will enable high-precision navigation and precise agriculture. With high-precision surface imaging of the earth, services such as emergency rescue and traffic dispatching can also be implemented.

Figure 9 Global seamless coverage — three-dimensional connections

To meet the requirements of emerging 6G applications and delivering the ultimate performance in the future, breakthroughs in key technical fields need to be made in addition to exploring a new network architecture. Currently, the global industry is still exploring candidate 6G technologies and has proposed some key wireless and new network technologies.

4.1 New Network with Native AI

In the future, AI will be integrated in mobile communication systems, which will emerge as a new intelligent network technology system through aspects such as the wireless architecture, data, algorithms, and applications. For 6G networks, the AI technologies will natively exist, which means instead of being used as an optimization tool, the AI technologies will be supported at the very beginning of design considerations of 6G networks. In general, the direction of wireless AI development in the 6G era can be viewed from the following two perspectives: a new air interface with native AI and a new network architecture with native AI.

1. New Air Interface with Native AI

This new air interface will make a breakthrough to the incumbent modular-based air interface design by deeply integrating AI and machine learning technologies. It will realize deep mining and utilization of multi-dimensional characteristics such as the radio environment, resources, interference, services, and users, and significantly improve the efficiency, reliability, real-time performance, and security of wireless networks. This will also help networks achieve self-operation and self-evolution.

The air interface with native AI can enhance the connectivity, efficiency, and reliability of the data and control planes through end-to-end learning and enable customization based on deep sensing and prediction in specific scenarios. In addition, technical building blocks of the air interface can be flexibly combined to meet the requirements of various scenarios. With its learning, prediction, and decision-making capabilities, AI can help communication systems to proactively adjust wireless transmission formats and communication operations based on traffic and user behaviors, which will reduce the power consumption at both the transmitter and the receiver. Leveraging AI methods, such as the multi-agent technology, can enable efficient collaboration between communication participants and maximize the energy efficiency of bit transmission.

With the help of the black-box modeling

capability of deep neural networks (DNNs), we can subtract features of unknown physical channels from the wireless data and reconstruct them to optimize the transmission. In multi-user systems, through reinforcement learning (RL), base stations and user equipment can make automatic coordination on channel access and resources based on the received signals. Each node may adjust its transmission schemes such as transmit power and beam direction based on the feedback, which will help eliminate the interference between the nodes and maximize the capacity of the system.

In addition, with the cross-fusion and further development of the machine learning technology and the information theory, semantic communications will become one of the ultimate goals of the new air interface with native AI. A communication system will no longer focus only on bit transmission. More importantly, information can be exchanged based on its content, which may be diverse across users, applications, and scenarios. Meanwhile, the efficient sensing and acquisition of the wireless data and privacy will be key challenges in this regard.

2.New Network Architecture with Native AI

In regarding of new networks with native AI, the 6G networks will natively support diverse AI applications, build a new ecosystem, and deliver user-centric service experience through fully leveraging the built-in communicating, computing, and sensing capabilities of network nodes under the framework of distributed learning, group intelligence, and integrated cloud-edge-device algorithm deployment.

With native AI, 6G networks can better help base stations and terminals with sensing, communicating, and computing capabilities realize large-scale intelligent distributed collaboration services, and maximize the utility of communicating and computing capabilities to adapt to different data distributions and protect the data privacy. This will lead to three evolution megatrends: the intelligence moves from applications and clouds to networks, that is, evolution from cloud AI to network AI, making self-O&M, self-detection and self-repair of networks possible; the intelligent coordination among clouds, edges, devices, and networks will enable adaptation of resources such as spectrum, computing, and storage, which will improve the overall efficiency of the network; and intelligent services will be provided to users, which will make the network deeply integrated with the smart industry and create new market value. Currently, there are clear requirements for networks with native AI in fields of IoT, mobile edge computing (MEC), distributed computing, and distributed control, where it also has become a popular focus of research.

The implementation of networks with native AI calls for more compact chips with stronger computing power, such as nanophotonic chips; algorithms that are more suitable for network collaboration such as federated learning; and new interfaces between networks and devices that help with generation and exchange of intelligence among all layers.

4.2 Enhanced Wireless Air Interface Technologies

1. Basic Physical Layer Technologies

With more diversified 6G applications and performance indicators, basic technologies at the physical layer of the air interface need to be specifically designed to meet the requirements on throughput, latency, and performance in specific scenarios.

In terms of modulation and coding technologies, a unified encoding and decoding architecture needs to be built, with the requirements of diversified communications scenarios in mind. For example, polar codes have excellent performance under a wide range of code lengths and rates. Their performance is consistent and reliable with simple and unified code construction description and compiled code. Polar codes and quasi-cyclic low-density parity-check (QC-LDPC) codes have high decoding efficiency and concurrency, which are suitable for high-throughput services.

For new waveform technologies, different solutions need to be adopted to meet more complex and varying scenarios and performance requirements of 6G. For example, in high-speed mobility scenarios, a transform-domain waveform can be utilized to more accurately describe dimensional information such as latency and Doppler information. In high-throughput scenarios, faster-than-Nyquist (FTN), spectrally efficient frequency division multiplexing (SEFDM), or overlapped x-domain multiplexing (OVXDM) can be used to achieve higher spectral efficiency.

For multiple access technologies, to meet the access requirements of 6G networks in dense scenarios with high reliability and low latency at low costs, the non-orthogonal multiple access (NOMA) will become a focus of research. Its signal structure can be optimized to increase the user capacity at a rate that the system can cope with and reduce the access overhead, meeting the low-cost and high-quality access requirements in 6G high-density scenarios. Its access process can also be enhanced to meet the access requirements of all types of terminals in all 6G scenarios.

2. Ultra-Massive MIMO

The ultra-massive multiple-input multiple-output (MIMO) technology is an upgrade of the massive MIMO technology. The continuous improvement of the integration of antennas and chips will increase the scale of antenna arrays. With new materials as well as technologies and functions — such as ultra-large aperture array, reconfigurable intelligent surface, AI, and sensing technologies — the ultra-massive MIMO technology can achieve higher spectral efficiency, wider and more flexible network coverage, higher positioning precision, and higher energy efficiency in a wider frequency range.

It can also adjust beams in a 3D space, and, therefore, in addition to ground coverage, provide non-ground coverage for UAVs, civil aircrafts, and even satellites at low orbit. With the development of new material technologies and antenna forms and layouts, ultra-massive MIMO will be better integrated with the environment, considerably improving network coverage and multi-user capacity. As the network architecture is nearly scale-free, distributed ultra-massive MIMO will help achieve consistent user experience, obtain higher spectral efficiency, and reduce the energy consumption of transmission through ultra-large antenna arrays.

Precise 3D positioning can also be implemented with ultra-massive MIMO's high spatial resolution capabilities even in complex wireless communications environments. Its ultra-high processing gain can compensate for the path loss of high frequency bands and increase the communications distance and coverage using the same transmit power. Applying AI can also help implement intelligence in multiple phases such as channel detection, beam management, and user detection.

However, ultra-massive MIMO will face challenges, such as high costs, difficult channel measurement and modeling, heavy signal processing load, high reference signal overhead, and limited fronthaul capacity. Antenna arrays and RF chips that feature low power consumption, low costs, and high integration will be the key to the commercial application of ultra-massive MIMO.

3. In-band Full Duplex

The In-band full duplex technology transmits and receives electromagnetic wave signals simultaneously on the same carrier frequency. Compared with traditional duplex modes such as FDD and TDD, it can not only effectively improve spectral efficiency, but also flexibly configure transmission resources.

The core of the full-duplex technology lies in its self-interference suppression. In terms of technology maturity, low-power and small-scale antennas for single-site full-duplex operations have been practically used. Some full-duplex devices in relay and backhaul scenarios have also been used. However, inter-site interference and self-interference suppression technologies of large-scale antennas still need to be improved. In this regard, miniaturized high-isolation transceiver antennas will significantly improve self-interference suppression. The use of large-range latency-adjustable chips required for self-interference suppression in the RF domain will also promote research in high-power self-interference suppression. In terms of signal processing, suppression of non-linear components of a large-scale antenna power amplifier is a challenge that current digital-domain interference cancellation technologies face. When channel environments change rapidly, the convergence time and robustness of self-interference cancellation in the RF domain will also affect the performance of the entire link.

4.3 Wireless Transmission Technologies on New Physical Dimensions

In addition to enhancing incumbent air interface technologies, the industry is also actively exploring new physical dimensions to revolutionize data transmission. Such new technologies include reconfigurable intelligent surface, orbital angular momentum, and intelligent holographic radio.

1. Reconfigurable Intelligent Surface (RIS)

Using new, programmable 2D metamaterials of subwavelength, RIS dynamically and intelligently controls electromagnetic waves by using digital encoding to adjust the amplitudes, phases, polarizations, and frequencies of electromagnetic waves to form controllable electromagnetic fields. With this proactive control over the radio propagation environment, the technology adjusts the signal propagation direction, enhances signals, or suppresses interference in the three-dimensional space, offering a new paradigm of intelligent, programmable radio environments. Its potential includes enhancing high-frequency coverage, avoiding coverage holes, improving cell-edge transmission rate, achieving green communication, and assisting in electromagnetic environment sensing or high-precision positioning.

RIS enhances coverage in communications systems, and significantly improves the network transmission rate, signal coverage, and energy efficiency. It also enables customization of radio propagation environments: Radio signals can be flexibly adjusted and controlled to implement the required radio functions, such as reducing electromagnetic pollution and facilitating positioning or sensing. RIS does not need an RF link comprising a filter, a mixer, and a power amplifier that conventionally make up a transmitter, making it ideal for simplified hardware, reduced costs, and high energy efficiency.

But RIS also faces challenges such as physical modeling and design of surface materials, channel modeling, channel state information collection, beamforming design, passive transmission, and AI-enabled design.

2. Orbital Angular Momentum (OAM)

OAM is an inherent physical quantity of electromagnetic waves representing a new dimension of wireless transmission. The eigenstates of OAM electromagnetic waves are mutually orthogonal to each other in different modes, which greatly improves spectral efficiency of systems. OAM electromagnetic waves, also called vortex electromagnetic waves, demonstrate spiral phase plates, which are different from the traditional planar phase wavefront. OAM electromagnetic waves can be further divided into traditional electromagnetic beams emitted by classical antennas, and electromagnetic quantum states emitted by cyclotron electrons.

The OAM beam is a spatially structured beam and can be viewed as a special case of MIMO beamforming. OAM beams may be generated by special antennas, such as uniform circular antenna arrays, spiral phase plates, or special reflector antennas. Beams in different OAM modes have spiral phase plates mutually orthogonal to each other. Compared with traditional MIMO beams, OAM beams greatly simplify the complex of beamforming and digital signal processing in point-to-point transmission scenarios. The biggest problems of transmitting OAM beams are the limitation of transmission distance and beam alignment requirement due to the inverted conical divergence beams. With a further increase in carrier frequencies and bandwidths, the component process, antenna design, and RF signal processing will be the key technical challenges for commercial applications.

The OAM quantum state requires each photon or microwave quantum to have an OAM mode, which makes both transmitting and receiving different from the traditional antennas, and requires a large transmitting and receiving apparatus. This shows that, compared with OAM beam transmission, OAM quantum state transmission still has a long way to go. Prevailing research on the OAM quantum state, which is still in the exploratory period, focuses on specific methods such as efficient excitation, transmission, reception, coupling, and modal separation of the OAM electromagnetic wave quantization, as well as device miniaturization.

3. Intelligent Holographic Radio (IHR)

Based on how holographic interference of electromagnetic waves works, IHR dynamically reconstructs the electromagnetic space with real-time precision control. It maps RF holography to optical holography and implements 3D holographic image-based, pixelized ultra-high-resolution spatial multiplexing by using RF space spectrum holography and holographic space wave field synthesis. It also provides quasi-continuous and quasi-infinite multiplexing space, meeting the requirements for ultra-high spectral efficiency, ultra-high traffic density, and ultra-high capacity.

With this ultra-high resolution spatial multiplexing, IHR is mainly applied in wireless access that requires ultra-large capacity and ultra-low latency, wireless industrial buses operating in ultra-high traffic density in smart factories, and high-precision positioning, precise wireless power supply, and data transmission for a massive number of IoT devices. Not only this, IHR can converge imaging, sensing, and wireless communications to achieve high-precision sensing of complex electromagnetic environments, making intelligent electromagnetic space possible.

Based on coherent optical up-conversion of microwave photonic antenna arrays, IHR can achieve ultra-high coherence and high parallelism of signals, which facilitates signal processing and calculation in the optical domain, reducing the power consumption and latency of IHR systems.

Extensive research has been carried out on IHR in the fields of RF holographic imaging and sensing. However, its application in wireless communications still faces challenges, the most pressing include theorizing and modeling IHR communications as well as hardware and physical layer design issues relating to efficient coordination, transparent fusion, and seamless integration between filled-aperture active antenna arrays and high-performance optical computing based on microwave photonics.

4.4 Terahertz and Visible Light Technologies

1. Terahertz Communications

The terahertz (THz) frequency bands (0.1–10 THz) are somewhere between microwave and optical waves, featuring abundant spectrums and supporting a high transmission rate, strong anti-interference, and easy integration of communications and sensing. THz communications mainly meet the system requirements of Tbps-level transmission rates.

THz communications will be a beneficial supplement to incumbent transmission mechanisms, and is mainly applied to potential application scenarios such as holographic communications, small-scale communications (inter-chip or nano-communications), ultra-large-capacity data backhaul, and short-range ultra-high-speed transmission. High-precision positioning and high-resolution sensing based on THz communication signals are also important applications.

To achieve that, some of the key technologies and challenges for THz communication are as follows. In terms of transceiver architecture design, there are three representative solutions, including all-solid-state frequency mixing modulation architecture, direct modulation architecture, and opto-electronic combination modulation architecture. In a word, the main considerations of the architecture design are for high compact, low-cost and high energy efficiency. Regarding RF-end components, the main entities of a THz system include THz signal source, mixer, multiplier, detector and amplifier, etc.. Currently, the operating frequencies and output power of THz components cannot meet commercial requirements such as low power consumption, high efficiency, and long service life yet. As such, advanced semiconductor materials such as silicon germanide (SiGe) and indium phosphide (InP) need to be explored. In terms of baseband signal processing, THz systems need to process Tbps transmission rates in real time. The breakthrough of advanced high-speed baseband signal processing technology with low complexity and low power consumption is essential. As for antennas, most high-gain antennas nowadays have large reflectors, which urgently require miniaturized and arrayed THz ultra-large-scale antenna technology. Moreover, in order to feature the channel characterization and measurement, THz systems require scenario-specific channel measurement and modeling to ensure accuracy and simplify implementation.

2. Visible Light Communications

Visible light communications (VLC) provide high-speed communications on ultra-wide spectrums ranging from 400 to 800 THz, which is green, highly secure, and free of authorization and electromagnetic radiation.

VLC is ideal for indoor environments and can greatly improve indoor coverage. It can also be used in special environments such as underwater or space communications and electromagnetic-sensitive environments such as hospitals, gas stations, and underground mines.

Most modulation and coding schemes, multiplexing modes, and signal processing technologies currently available for wireless communications can be applied to VLC to improve system performance. The biggest challenge lies in the R&D of high-bandwidth

LED components and materials. Even though the spectrums on VLC bands are abundant, the actual available bandwidths are very small due to the limited response performance of opto-electronic and electro-optic devices. One pressing challenge facing high-speed VLC is improving response frequency and bandwidth of transmitters and receivers. Uplink is also a big challenge for VLC, which can be solved with heterogeneous, converged networking with other communications technologies.

4.5 Integrated Communications and Sensing

The concept of integrated communications and sensing is that the two functions — wireless communications and sensing are implemented in the same system in a reciprocity way. The communications system can complete different types of sensing services by using the same spectrums or even the same hardware or signal processing modules. The sensing results can then be used in communications access or management to improve service quality and communications efficiency.

Future communications systems will be able to have higher frequency bands (mmWave, THz, or even visible light), wider bandwidths, and larger antenna apertures. This allows wireless sensing capabilities to be integrated in communications systems. In a 6G communications system, characteristics such as shape, material, distance, and mobility of environmental objects can be obtained by collecting and analyzing scattered and reflected signals to implement different functions such as positioning and imaging by using classic sensing or AI algorithms.

Although system components such as antennas can be shared, communications and sensing are still used for different purposes. This poses technical challenges for integrated designs, such as the integrated signal waveform design, signal and data processing algorithms, joint design of positioning and sensing, and sensing-assisted communications. Portable terminals that can be integrated are also an important consideration.

4.6 Distributed Autonomous Network Architecture

6G networks will be massive, provide the ultimate experience, and applicable to diversified scenarios, achieving ubiquitous connections for all scenarios. Research needs to be carried out on the 6G network architecture, focusing on both the access network and core network. For the access network, the architecture should be simplified to reduce the processing latency and elastic to provide the required capabilities. The research can go into requirement-driven intelligent control mechanisms and radio resource management, while stressing the value of software-based, service-oriented design. As for the core network, distributed, decentralized, and autonomous network mechanisms can be designed to implement flexible and universal networking.

The distributed autonomous network architecture involves a number of key technologies, including decentralized, user-centric control and management; deep edge nodes and networking; a requirement-driven lightweight access network architecture, an intelligent control mechanism, and radio resource management; network and service operations decoupling; dynamic sharing and deployment of network, computing, and storage resources; task-centric intelligent connections and intelligence-native architecture with self-growth and self-evolution capabilities; architecture design with privacy preserving, high reliability, and high-throughput blockchain; trusted data governance.

To improve network autonomy and automation capabilities, new technical concepts, for example the application of digital twins in the network, must be fostered. Conventional network optimization and innovation have profound impact on the network operation with a huge expense of time, because they have to be implemented directly on the real networks. Digital twins, however, can steer network development towards higher visibility, more accurate simulation and prediction, and more intelligent control. A digital twin network (DTN) is a network system that not only has physical network entities and virtual twins, but allows them to interact and map in real time. The twin network maps and manages the physical network through closed-loop simulation and optimization. The challenge here is effective utilization of network data and network modeling.

Changes in the network architecture will have profound impact, so bringing in new technical elements and integrating them into existing networks are equally important.

4.7 Deterministic Network

With the integration of new generations of information technologies and industrial field operation technologies, mobile communications networks are evolving into "deterministic networks". Latency-sensitive services, such as industrial manufacturing, vehicle-to-everything (V2X), and smart grid, require deterministic network performance. This includes fast end-to-end delivery dependent on deterministic minimum and maximum latency and latency jitter, bounded packet loss rate in various running states, and upper limit of out-of-order packets during data delivery.

Deterministic capabilities involve end-to-end systematic optimization of radio access, core, and transport networks in terms of resource allocation, protection, measurement, and coordination. For resource allocation, resources are allocated hop by hop along the data flow path, including the buffer space or link bandwidth in the network to eliminate packet loss caused by data packet contention in the network. Pre-allocation and optimized scheduling reduce the scheduling latency and overhead. In terms of service protection, research should be carried out on data packet encoding to eliminate packet loss caused by random medium errors, and also on the design of data packet duplication and elimination mechanisms to prevent equipment faults as well as service protection over the air interface when moving, being interfered, or roaming. In terms of quality of service (QoS) measurement, more dimensions for QoS definition, such as throughput, latency, jitter, packet loss rate, and upper limit of out-of-order packets, should be added to explore methods for multi-dimensional QoS evaluation and establish a precise measurement system. In terms of multi-network cross-domain collaboration, the control methods and deterministic performance achievement technologies for multi-domain convergence across air interfaces, core networks, transport networks, edge clouds, and data centers should be taken into account.

In addition to many challenging technological issues, how to realize deterministic network with high efficiency and low cost and reduce the high cost brought by high precision are key to be solved in its industry-wide application.

4.8 Computing-Aware Network

To meet the requirements of future network services and lightweight, dynamic computing, the industry has begun evolving towards network and computing convergence. As such, computing-aware networking (or computing networking for short) has been proposed to connect and coordinate computing power located on the cloud, on devices, and at edges, achieving in-depth convergence and collaborative perception of computing and networks, as well as on-demand scheduling and efficient sharing of computing services.

In addition to data transmission, 6G networks will also be used for communication, computing, and storage. Unified modeling and measurement of ubiquitous and heterogeneous computing resources will serve as the basis for computing resource scheduling. As a result, different computing resources can be mapped into a unified dimension through model functions to form an understandable and readable resource pool for scattered computing at the service layer, ensuring resource matching and scheduling on the computing network. In addition, a unified management and control system is critical for the computing network.

As applications, devices, and networks in traditional information systems are separated from each other, no unified architecture exists for centralized management, control, and collaboration. Consequently, the management and control system of the computing network will be extended from networks to devices, and services at the application layer will be sensed through the network layer, creating a new network architecture with device-edge-cloud synergy for non-differentiated delivery, automatic matching, and intelligent network scheduling of computing resources. This approach will also address issues relating to multi-party collaboration and operation modes in the computing network.

At present, the industry is transforming the separated computing and network mode into a unified mode for computing-network synergy. This requires the development combination of the application and network layers from cloud to network and from network to cloud, as well as the coordination of centralized and distributed control.

4.9 Integrated Terrestrial and Non-Terrestrial Network

6G networks will integrate the terrestrial network, satellites at various latitudes (high-, medium-, and low-orbit), and aircrafts operating within different airspace to form a new mobile information network. The terrestrial network can implement standard coverage for urban hotspots, while the space-based and air-based networks can achieve on-demand coverage in remote areas, at sea, and in the air, featuring flexible networking, high resilience, and ultra-reliability. Rather than just simple interconnections between satellites, aircrafts, and terrestrial networks, such integrated terrestrial and non-terrestrial networking will be deep convergence of space-based, air-based, and terrestrial networks resulting in a service-oriented network architecture that contains unified devices, air interface protocols, and networking protocols. Consequently, information will be provided anytime, anywhere, and by any means to meet the unified access and application requirements of various devices.

In the 6G era, multi-dimensional networks consist of multi-layer satellites, high-altitude platforms, and terrestrial base stations. Problems inherent to multi-dimensional networks include the converged access, coordinated coverage, frequency coordination, integrated transmission, and unified service of networks. Solving those problems will require thorough research into various key technologies, such as multi-dimensional network architecture, integrated air interface technology, coordinated mobile protocol, on-board processing, regenerative payload, and inter-satellite communications. Due to the dynamic topology change of non-terrestrial networks and different running environments, terrestrial networking technologies cannot be directly applied to non-terrestrial scenarios. New technologies must be developed for integrated terrestrial and non-terrestrial networks, capable of naming and addressing, routing and transmission, dynamic network element deployment, mobility management, and interoperability between terrestrial networks and non-terrestrial networks.

Integrated networks need to streamline the non-terrestrial communications and terrestrial mobile communications fields, which involve mobile communications devices, satellite devices, and terminal chips, and which face challenges relating to both technologies and industries. In addition, the limited energy and computing resources of satellites will also pose higher requirements on architecture and technologies.

4.10 Native Network Security based on Multi-Lateral Trust Model

The convergence of information communications technologies, data technologies, industrial operation technologies, network marginalization, and device virtualization will blur the boundaries of 6G network security. The traditional security trust model is insufficient for 6G security, as multiple trust models such as centralized and decentralized models, as well as third-party endorsements are now required.

Distributed 6G network architecture will play a dominant role in the future, moving network service capabilities closer to users and transforming the centralized security architecture. Brand-new service experiences, such as integrated sensing and communications and holographic communications, will be accompanied with unique user-centered services, necessitating a multi-mode and cross-domain security and trustworthiness system. As such, traditional "external" and "patch" network security mechanisms will be insufficient for handling potential attacks and security risks on future 6G networks, while the in-depth convergence of AI, big data, and 6G networks will also introduce entirely new challenges to data privacy protection. The development of new transmission and computing technologies will drive the evolution of cryptographic technologies, intelligent and resilient defense systems, and security management architectures into native security architectures with autonomous defense capabilities.

Based on a more inclusive trust model, 6G security architecture will be more resilient and cover the entire lifecycle of 6G networks, internally carrying more robust, smarter, and scalable security mechanisms that involve multiple security technologies. The 6G security system architecture and the key technologies that integrate the computer network, mobile communications network, and satellite communications network can enable native and dynamic security. Key technologies for security collaboration among devices, edge computing, cloud computing, and 6G networks will support multi-lateral trust architecture, and the centralized, decentralized, and third-party trust modes of heterogeneous converged networks will coexist to form this architecture. In addition, the security architecture will also support cryptography application technologies and key management systems that fit the characteristics of 6G wireless communications, such as quantum security cryptography and novel key distribution technologies that continuously approaching the Shannon's one-time-pad limit; large-scale data flow monitoring, privacy preserving computing theories and key technologies; high-throughput and high-concurrency data encryption or decryption and signature verification; basic blockchain capabilities featuring high throughput, easy scalability and simple management for security and privacy protection. Furthermore, the access control model and mechanism of topology high dynamic changes and WAN sharing, as well as the key technologies of isolation and exchange, will also be supported.

Integrated architecture for security and networks is essential. Both communication and security are crucial for wireless networks and require a careful balance between cost and gain. In addition, security improvement is an endless task. The security status of networks shall be dynamically measured to ensure security protection against malicious threats. In this regard, technologies such as blockchain enable secure communication networks to continuously evolve.

5.1 The Successful Commercial Deployment of 5G Will Lay a Solid Foundation for 6G

From 1G to 4G, mobile communications networks worldwide have improved by leaps and bounds. Now, 5G has entered a new stage of commercial expansion. It usually takes two generations for networks to make new services full-fledged. For example, voice services emerged in the 1G era, but were actually widely used in the 2G era. 3G networks opened the door for mobile multimedia services, while 4G witnessed the full boom of mobile Internet. With 5G, applications were firstly expanded from mobile Internet to IoT, implementing intensive integration with vertical industries to bring the industrial Internet to new heights.

With the development of sensing technologies, AI, communications technologies, new materials, and new components, the tremendous growth of information consumption and production efficiency is occurring, posing higher requirements on mobile communications, and eventually pushing towards another network evolution. 6G, as the next evolution, will further expand and deepen the application scope of IoT, with continuous enhancements made to the basic capabilities of existing networks. Together with new applications to empower intelligent society and life, they will enable a successful transition from "connecting things" to "connecting intelligence". The successful commercial deployment of 5G, especially in vertical industries, will lay a solid foundation for the development of 6G. 3GPP is expected to initiate the research and development of the 6G international technical standard by around 2025 and 6G commercialization is expected to be around 2030.

5.2 Native AI Intelligence Plays a Pivotal Role in 6G

Mobile communications will be further integrated with emerging technologies such as AI, big data, and cloud computing, making intelligence one of several new development trends. The in-depth convergence of data, operation, information, and communication technology (DOICT) will be a catalyst for the innovation of next-generation networks, including breakthroughs in sensing, storage, computing, and data transmission, all which will successfully evolve from 5G to 6G. In addition, AI will lead networks into an era of intelligence. AI is expanding from auxiliary O&M to multiple fields, such as network performance optimization, network mode analysis, deployment management, and network architecture innovation, facilitating the all-round innovation of network technologies.

Therefore, 6G will enable ultra-large-scale intelligent networks to become a reality. People, devices, and physical environments will be mapped onto intelligent networks through dynamic digital modeling. Through continuous learning, communications, cooperation, and competition, intelligent agents connected to the 6G network will be able to effectively simulate and predict the operation and development of the real world to make faster and better decisions.

5.3 Efficient Use of High-, Medium-, and Low-Frequency Bands to Fulfill 6G Spectrum Needs

Spectrum resources are the basis for the development of mobile communications. 6G will continue to develop high-quality, available spectrum resources and further expand to higher frequency bands, such as mmWave, THz, and visible light, effectively utilizing various bands to meet the requirements in different development levels of 6G.

6GHz and sub-6GHz bands are still strategic resources for 6G. Spectral efficiency can be further improved through resource refarming, aggregation, and sharing. (Sub)6GHz can provide 6G with basic continuous terrestrial coverage, achieving fast and cost-effective deployment.

High frequency bands can meet the requirements of ultra-high speeds and capacity. As the industry continues to develop and mature, mmWave will play an important role, with great improvement in performance and efficiency. High frequency bands, such as THz and visible light, given their limited propagation characteristics, first targets at specific scenarios with short-range and large-capacity. These high frequency bands will also be critical for scenarios such as integrated sensing and communication and intra-body communications.

5.4 Satellites Assist Cellular Terrestrial Networks to Achieve Full 6G Coverage

6G will further expand the breadth and depth of network coverage to achieve a seamless global coverage. Non-terrestrial facilities such as satellite and UAVs can achieve wider coverage and provide communications and networking services for ships, aircrafts, wide IoT, and mobile Internet terminals. However, the capacity-per-unit area of a satellite is low due to its wide coverage, which cannot meet the large-capacity requirements of densely-populated urban areas. In addition, the distance between satellite nodes and terrestrial terminals causes high transmission latency, meaning it cannot meet the ultra-low latency requirements of vertical industries. The advantages of terrestrial cellular mobile communications lie in its powerful computing, big data storage capability, high data transmission rate, low latency, and massive connectivity. It can effectively meet the requirements of large-capacity networks in densely-populated areas. But the existing terrestrial cellular networks cover only 10% of the earth's surface. In remote areas with low population density and a low return on investment (ROI), network deployment is costly, and is vulnerable to terrains and geological disasters. In the 6G era, satellites and other non-terrestrial communications will be used as a supplement to terrestrial networks, achieving global seamless coverage.

In the future, the integrated terrestrial and non-terrestrial network will be interconnected and interworked by satellites, high-altitude platforms, and near-ground communication platforms, as well as multiple network nodes on land and at sea, each with different functions and set at different latitudes. These network nodes will complement each other and form wide 3D communications networks that are based on terrestrial cellular networks and support multiple non-terrestrial communications. 6G networks will implement seamless roaming of one terminal among the ground, air, and sea areas, and provide diversified applications and services for various users.

Acronyms and Abbreviations

Abbreviation	Full Spelling
AI	Artificial Intelligence
AR	Augmented Reality
DNN	Deep Neural Network
DOICT	DT, OT, IT, and CT
DTN	Digital Twin Network
FDD	Frequency Division Duplex
FoV	Field Of View
FPS	Frame Per Second
FTN	Faster-Than-Nyquist
IHR	Intelligent Holographic Radio
IoT	Internet of Things
LDPC	Low Density Parity Check
MEC	Mobile Edge Computing
MIMO	Multiple-Input Multiple-Output
MR	Mixed Reality
MTP	Motion-To-Photon
NOMA	Non-Orthogonal Multiple Access
OAM	Orbital Angular Momentum
OVXDM	Overlapped X Domain Multiplexing
PAPR	Peak to Average Power Ratio
PPD	Pixel Per Degree

Abbreviation	Full Spelling
QC-LDPC	Quasi-Cyclic Low-Density Parity-Check
QoS	Quality Of Service
RIS	Reconfigurable Intelligent Surface
ROI	Return On Investment
SEFDM	Spectrally Efficient Frequency Division Multiplexing
TCA	Tight-Coupling Antenna
TDD	Time Division Duplex
UAV	Unmanned Aerial Vehicle
UCA	Uniform Circular Array
UHD	Ultra-High-Resolution
uHDD	Ultra High Data Density
UTC-PD	Uni-Traveling-Carrier Photodiode
V2X	Vehicle-To-Everything
VLC	Visible Light Communications
VR	Virtual Reality
XR	Extended Reality

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