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Vision, application scenarios, and key technology trends for 6G mobile communications

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Abstract With the global commercialization of the fifth-generation (5G) network, many countries, including China, USA, European countries, Japan, and Korea, have started exploring 6G mobile communication network, following the tradition of “planning the next while commercializing one generation”. Currently, studies on 6G networks are at the infancy stage. Research on the vision and requirements for 6G is still ongoing, and the industry is yet to clarify the key enabling technologies for 6G. However, 6G will certainly build on the success of 5G. Therefore, developing high-quality 5G networks and seamlessly integrating 5G with verticals are the priorities before 2030, when 6G is projected to be commercialized. Also, global 5G standards will keep evolving to better support vertical applications. As a milestone, the Third-Generation Partnership Project (3GPP) published Release 16 in July 2020, which continuously enhanced the capabilities of mobile broadband service based on Release 15 and realized the support for low-delay and high-reliability applications, such as Internet of Vehicles and industrial Internet. Currently, 3GPP is working on Releases 17 and 18, focusing on meeting the demands of medium- and high-data-rate machine communication with low-cost and high-precision positioning, which will be published in June 2022. Thus, 6G networks will further expand the application fields and scope of the Internet of Things to accommodate those services and applications that are beyond the capabilities of 5G networks. Herein, we present our vision, application scenarios, and key technological trends for 6G networks. Furthermore, we propose several future research opportunities in 6G networks with regard to industrialization and standardization.

Keywords sixth-generation (6G) mobile communication, 6G vision, application scenarios of 6G, terahertz communication, integrated sensing and communication, integrated intelligence and communication, ultra-massive MIMO, reconfigurable intelligent surface, co-frequency co-time full-duplex, holographic radio technology

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1 Introduction

In the past decade, we witnessed and experienced the development of the fifth-generation (5G) technologies, standards, trails, and commercialization efforts. With the commercialization of the 5G network, both academia and industry have shifted their focus toward the development of 6G technologies. From 2030, society will enter an era of intelligence. Balanced, high-quality social services, scientific, precise

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social governance, 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.

Based on breakthroughs in mathematics, physics, materials, biotechnology, and other fields, 6G network will integrate 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, making the 6G network the foundation of our daily lives, industrial production, and green development. 6G network will also maximize the potential of low-, medium-, and high-band spectra to achieve a seamless global coverage, meeting the requirements for unlimited secure and reliable connections among people, machines, and things anytime, anywhere.

6G network will provide fully immersive interaction scenarios and support precise spatial interactions 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. In summary, the 6G network will realize the digitization and intelligence of physical entities in the real environment and penetrate all aspects of production, life, and social governance.

Research on the 6G network is already ongoing, and both academia and industry have started to define what 6G networks should be. The IMT-2030 (6G) Promotion Group officially released the white paper on 6G networks, named "6G Vision and Candidate Technologies" [1], to illustrate the vision, driving forces, candidate use cases, and technologies of 6G, highlighting several thoughts on 6G development. The latest book of 6G [2] provides a comprehensive view of the 6G wireless network through a technical lens, including the vision, use cases, and target key performance indicator (KPI) of 6G, theoretical foundations for 6G, enabling technologies for 6G air interface design, and new features for 6G network architecture. Specifically, the book proposes the key driving force of 6G: shifting from connected people and things to connected intelligence. A comprehensive survey of recent advances and future trends of 6G wireless networks has been provided [3]. It is envisioned that 6G networks will have the following four new paradigm shifts: developing space-air-ground-sea-integrated networks to provide a complete global coverage; leveraging all spectra (sub-6 GHz, millimeter wave (mmWave), terahertz (THz), optical frequency bands, etc.) to deliver a higher data rate and network capacity; machine learning (ML), big data, and artificial intelligence techniques are explored to support full applications; strong network security for both physical and network layers would be guaranteed. Authors in [4] illustrated several potential physical layer technologies for 6G, including four revolutionary technologies (i.e., holographic radio, THz communication, large intelligent surface, and orbital angular momentum) of the exploratory nature and three technologies with more maturity (i.e., advanced channel coding/modulation, visible light communication, and advanced duplex) for possible usage in the near future.

Unlike previous studies, herein, we present the vision, application scenarios, and key technological trends of 6G from the perspective of the industry. The rest of this article is organized as follows: the vision and three types of application scenarios of 6G are introduced in Section 2; key enabling technologies of 6G, including THz communication, integrated sensing and communication, integrated intelligence and communication, ultra-massive multiple-input multiple-output (MIMO), reconfigurable intelligent surface, co-frequency co-time full-duplex, holographic radio technology, and ultralow-power Internet of Thing (IoT) communication, are described in Section 3; the conclusion is presented in Section 4.

2 Vision and application scenarios of 6G

6G would provide terabit-level transmission rates, submillisecond-level latency, centimeter-level positioning accuracy, trillion device connectivity capabilities, a thousand times increase in network capacity, and a further reduction in overall network energy consumption. 6G would also build up a commonly interconnected intelligent network, realizing the vision of "intelligent connection of everything, digital twin" society.

Considering the services of 6G, several new application scenarios would appear with the features of immersive, intelligent, and ubiquitous. In this section, three application scenarios (immersive, intelligent, ubiquitous applications) of 6G, including eight candidate use cases, are introduced, which present higher performance requirements for 6G and penetrate all aspects of production, life, and governance. For each application scenario, we envisage the corresponding technical trends to illustrate the motivation and guiding principle for 6G technology development.

2.1 Immersive application

The immersive application of 6G means that the 6G network will enable deep connections and interactions for everything, offering the ultimate immersive experience for humans. This includes four typical use cases: immersive cloud extended reality (XR), holographic communications, sensory interconnection, and intelligent interaction.

2.1.1 *Immersive cloud XR: a broad virtual space*

XR is a term encompassing virtual reality (VR), augmented reality (AR), and mixed reality (MR). In cloud-based XR, contents are stored, and all rendering and computing operations are implemented on the cloud. This greatly reduces the computing load and energy consumption of XR devices while freeing users from the constraints of cables. Thus, lightweight XR devices would become the mainstream to guarantee more immersive and intelligent experiences, facilitating commercialization.

From 2030, immense improvement of networks and XR terminals will drive XR technology to 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 using audio and motion, including eye, head, and hand movements. This premium experience can be delivered only when ultralow latency, ultrareliable, and ultrahigh bandwidth are provided in deterministic environments, which demand novel designs, ranging from physical layers, through link layers to network layers [5].

2.1.2 *Holographic communications: extremely immersive experience*

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

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 communication networks cannot meet the requirements for real-time 3D display and fast transfer of holographic images. To send $1920 \times 1080 \times 50$ 3D target data 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 with 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 results in a retransmission, which, in turn, fails to meet the requirements of reliability and latency. This further raises the standards for networks in transmission security and reliability.

2.1.3 *Sensory interconnection: fusion of all senses*

Sight, hearing, touch, smell, and taste are essential for us to understand our world. From 2030, signal transmission of not only the hearing and sight but also other main senses, including touch, smell, and taste, will become a major part of communications and be used in various fields, including healthcare, education, entertainment, traffic control, production, and social interactions. In the future, people will be able to feel the warmth of a hug from a family member through their mobile devices when living far apart. Even in their own homes, users may be able to enjoy experiences, such as beautiful scenery and even a walk on the sandy beach while feeling the sea breeze in the Maldives.

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

2.1.4 *Intelligent interaction: interactions of feelings and thoughts*

6G mobile communications will provide opportunities to achieve breakthroughs in many areas of research, such as emotional and brain-computer interactions. Intelligent agents will be able to perceive, recognize, and think, resulting in a complete alternative to traditional intelligent devices. The user-tool relationship between people and intelligent agents will evolve to human-like interactions with emotions and mutual understanding. Such intelligent agents will be able to sense the psychological and emotional states of users through dialogues and facial expressions to help users mitigate health risks. Supporting lossless transmission of brain information, mind-controllable machines will be available to help the disabled overcome physiological difficulties in their daily lives and work while quickly accumulating knowledge and skills.

Considering the technical trends for immersive applications, we conclude the following points.

- **6G will leverage all spectra up to THz or even visible light to deliver ultrahigh data rates.** To support ultimate immersive applications, such as immersive XR and holographic communication, extremely high data rates (up to tens of Tbps) are required, hence the need for additional spectrum resources. Therefore, in addition to sub-6 GHz and mmWave, new spectra of up to THz and optical bands would be fully explored and used to enable remarkable data-hungry and delay-sensitive services and applications that require high-resolution sensing. To this end, the THz communication techniques, illustrated in Subsection 3.1, will be developed in 6G.

- **6G will further upgrade the massive MIMO technique for higher network throughput and link reliability.** To satisfy the ever-increasing demand for network throughput, user density, link reliability, and massive MIMO techniques with even higher orders (ultra-massive MIMO) are investigated and developed along with the evolution of wireless communication. We envision that the success of ultra-massive MIMO in 6G would hinge on not only the enhancement of existing 5G methods but also new solutions, including new antenna architectures, materials, and radio frequency (RF) techniques [2], which are illustrated in Subsection 3.4.

- **6G will explore multiple physical dimensions to revolutionize data transmission, achieving higher spectrum efficiency and capacity.** Since the spectrum resources, particularly the sub-6 GHz bands, are becoming scarce, it is necessary to fully explore multiple physical dimensions, especially the spatial and spectral dimensions, to support higher spectrum efficiency and deliver ultrahigh data rate and capacity for better user experience. To this end, novel techniques, including reconfigurable intelligent surfaces (RIS), full-duplex design, and holographic radio, have been developed for potential use in 6G. Using programmable meta-materials, RIS can dynamically control electromagnetic waves (adjust their amplitudes, phases, etc.) through digital encoding to form controllable signals, enhancing network coverage and improving the cell-edge transmission rate, which is illustrated in Subsection 3.5. The co-frequency co-time full-duplex technique has been proposed to support concurrent transmission and reception in a single time and frequency resource to deliver ultrahigh spectral efficiency and throughput and low latency, which are discussed in Subsection 3.6. The holographic radio technique employs RF spatial spectrum holography and holographic spatial wave field synthesis technologies to achieve ultrahigh-resolution (UHR) spatial multiplexing with ultrahigh capacity and spectrum efficiency, enabling immersive human-centric communication, such as XR, holographic display, and multisensory communication (Subsection 3.7).

2.2 Intelligent application

As society moves toward "intelligent of everything", the future 6G is the key for proliferating AI and delivering several use cases with high intelligence to humans and everything, such as the proliferation of intelligence, communication for sensing, and digital twins.

2.2.1 *Proliferation of intelligence: ubiquitous smart core*

By 2030, there will be more smart terminals, including smart personal and household devices, sensors in cities, unmanned vehicles, and smart robots. Unlike current smart phones, 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 would reach trillions in the future. Through continuous learning, communication, cooperation, and competition, these devices can efficiently simulate and predict physical world scenarios and provide optimal decisions.

Applying AI is essential to explore and continuously learn from big data with enhanced computing power. In the era of 6G, network self-learning, -operation, and -maintenance would be developed based on AI and ML. 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 every individual, home, and industry. Through this, real inclusive intelligence can be realized.

2.2.2 *Communication for sensing: extending the functions of converged communications*

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

With real-time wireless sensing, advanced signal processing algorithms, and the exploration of edge computing and AI technologies, 6G will help sense environmental information and reconstruct the target environment with ultra high definition (UHD) RF images and enable centimeter-level positioning. This significantly accelerates the realization of virtual and smart cities. Sensor networks 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 controls, and action recognition, a millimeter-level resolution will be required to provide high-precision real-time sensing services to users. Besides, higher frequency bands, such as THz, environmental pollution source detection, and air composition monitoring, such as PM2.5 analysis, can also be implemented with sense.

2.2.3 *Digital twins: digital mirror of the physical world*

With advances in sensing, communication, and AI technologies, objects or processes are digitally replicated. Interactions, including 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 to diagnose and provide 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 factors and improve the production and use of land. In network O&M, networks can quickly adapt to complex and dynamic environments through physical and digital interactions, cognitive intelligence, and automatic O&M, resulting in autonomy throughout the O&M lifecycle, from planning through construction, monitoring, optimization, to self-healing.

To realize use cases in intelligent application scenarios, the following technique trends are considered.

- **6G will support native AI and ML to intelligently connect intelligent things and devices.** One of the key features and objectives of 6G is to enable ubiquitous intelligence by fully integrating both AI and ML into communication systems natively. This demands a new design principle in 6G to combine wireless and AI functionalities at the beginning instead of designing the wireless system first and applying AI next. The technique named integrating intelligence and communications would create opportunities for post-Shannon communication theory breakthrough and invocations in learning theories, as illustrated in Subsection 3.3.

• **6G will seamlessly integrate sensing capability, enabling the fusion of digital and physical worlds.** We envision that diversified new killer applications and services, such as autonomous driving, intelligent industrial, and intelligent healthcare, will be achieved and supported by 6G networks. These trends inspire novel technical design principles that seamlessly integrate two originally decoupled functionalities, i.e., wireless communication and sensing, into one system symbiotically, which is dubbed integrated sensing and communications (ISAC), to endow the 6G wireless network with the ability to "see" and "talk" to the physical world simultaneously [6]. Specifically, ISAC can utilize electromagnetic wave signals to wirelessly detect, localize, track, and image objects, recognize different activities or statuses, or even reconstruct the environments, and the sensing results can be used to enhance the performance of radio access and resource management in wireless communications. The ISAC technique is discussed in Subsection 3.2.

2.3 Ubiquitous application

6G network will be able to provide broadband access anytime and anywhere, particularly for remote areas, airplanes, unmanned aerial vehicles (UAVs), vehicles, and ships, called ubiquitous applications with globally seamless coverage capability.

Currently, more than 3 billion people around the world do not have basic Internet access, most of whom live in rural and remote areas. Due to the high cost of constructing terrestrial communication networks, it is difficult for telephone communication companies to afford them. Moreover, terrestrial networks cannot provide high-speed communication required in uninhabited or oceanic areas for Antarctic expeditions and ocean freighters. In addition, there is an increase in the demand for connections for aerial devices, such as UAVs and airplanes. As services converge and deployment scenarios increase, terrestrial cellular networks would be integrated with nonterrestrial networks, including high-, medium-, and low-orbit satellites, high-altitude platforms, and UAVs, to build a 3D integrated network with global coverage, providing users with ubiquitous broadband mobile communication services.

Global seamless coverage can enable broadband access anytime and anywhere for everything, which implies providing ubiquitous connections 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, and the collection of information about marine buoys and ocean containers. In addition, centimeter-level positioning would enable high-precision navigation and precise agriculture. With high-precision surface imaging of the Earth, services, such as emergency rescue and traffic dispatching, can be implemented.

Consider the technical trend for enabling ubiquitous applications. 6G will support seamless mobile services everywhere, realizing ubiquitous connectivity and global coverage for all users. To achieve this goal, 6G networks will integrate the terrestrial network, satellites at various latitudes (high-, medium-, and low-orbit), and aircraft operating within different airspace to form a new mobile information network that can provide mobile services anytime and anywhere. Specifically, terrestrial networks can implement standard coverage for urban hotspots and most rural scenarios, whereas space- and air-based networks can achieve on-demand coverage in remote areas, at sea, and in the air, resulting in flexible networking, high resilience, and ultra-reliability [1, 3].

3 Potential key technologies of 6G

To achieve the above-mentioned vision of 6G, traditional air-interface technologies will be further developed, and new technological breakthroughs must be achieved. Based on the current research progress and the requirements of the proposed application scenarios of 6G, key enabling technologies include THz communication, integrated sensing and communication, integrated intelligence and communication, ultra-massive MIMO, reconfigurable intelligent surface, co-frequency co-time full-duplex, holographic radio, and ultralow-power IoT communication. These technologies will work together to further improve the technical abilities of future 6G networks and provide users with even more diversified applications and better service experiences.

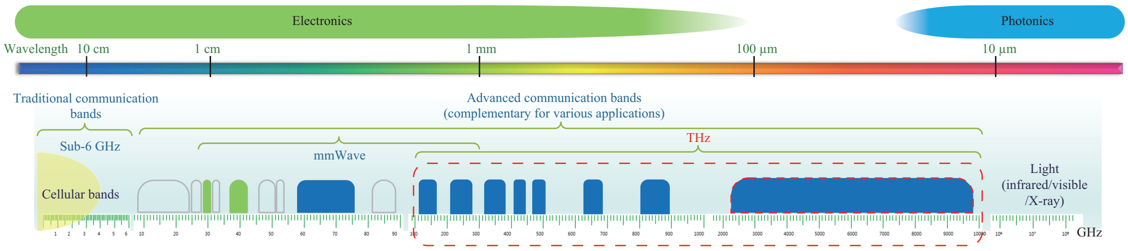

Figure 1 (Color online) THz frequency bands.

3.1 Terahertz communications

With the wide applications of big data analytics and ever-increasing popularization of immersive experience in the era of intelligent Internet of Everything, the expected data rate of 6G may reach the Tbps level, which is much higher than that of existing 5G systems. To achieve this goal, higher-frequency bands will be explored to obtain more spectrum resources.

THz waves are electromagnetic waves in the frequency range of 100 GHz to 10 THz (see Figure 1), which have the characteristics of microwave and light waves. Leveraging rich frequency resources, THz communication can support ultrahigh communication rates and is considered a useful supplement to existing air-interface transmission solutions. THz waves would be mainly employed in scenarios with ultrahigh rate transmission requirements, such as holographic communication, short- and medium-range wireless access, and data backhaul/fronthaul, as well as new communication scenarios, such as micro-size communication. In addition, with the help of ultralarge bandwidths and the ability to penetrate nonmetallic or nonpolarized materials with extremely low losses, THz communication can also enable high-accuracy positioning and high-resolution sensing and imaging.

To fully utilize the benefits of THz communications for 6G, further research is required in the following directions.

3.1.1 *Ultra-high-speed baseband signal processing*

THz communication systems based on the 6G network should process Tbps-level transmission rates in real-time, and existing high-speed signal processing capabilities and (analog-to-digital/digital-to-analog) AD/DA sampling capabilities will become important technical challenges. A potential solution is to utilize low-quantization precision signal processing technologies, including joint optimization design of bit quantization and signal algorithm, joint adaptive quantization threshold single-bit demodulation optimization, and low-complexity-hardware-integrated circuit designs based on probability calculations. By reducing the number of quantization bits per unit symbol and maintaining system performance within an acceptable range, a tradeoff between performance and complexity can be achieved. Furthermore, new signal processing system architectures, air-interface architectures, and compensation algorithms can be explored for low-performance components to tackle the challenges in THz communication.

3.1.2 *Ultra-large-scale array antenna*

Since THz wavelengths are very short, ultra-massive MIMO structures can be integrated into a smaller size, thereby realizing high gain of THz beams and flexibility of spatial signal preprocessing. However, current high-gain THz antennas mainly use reflector antennas. Developing miniaturized and arrayed ultra-massive THz MIMO is a key research issue to be addressed in the future 6G wireless network. For example, considering the miniaturization of array-associated circuits, it is challenging to arrange the array elements in a small package due to the small wavelength. As the physical space margin reserved for associated circuits is extremely limited, arranging the associated circuits of devices, such as power amplifiers and phase shifters, to be within several millimeters is unrealistic. A solution is a subarray design based on analog-digital hybrids, which transform associated circuits based on array elements into physically larger subarray-associated circuits. Another solution is the use of new antennas, such as liquid-crystal or reconfigurable intelligence surface antennas, instead of phased array antennas, to address the issues of miniaturization and power loss of associated circuits.

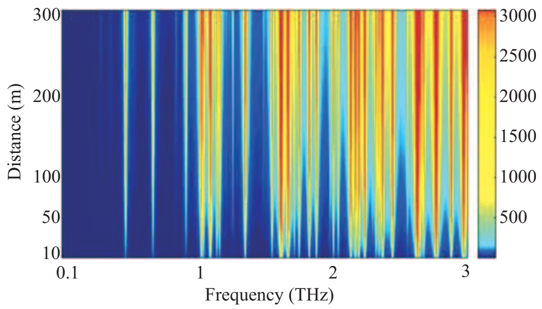

Figure 2 (Color online) Frequency and distance selective fading in THz transmission.

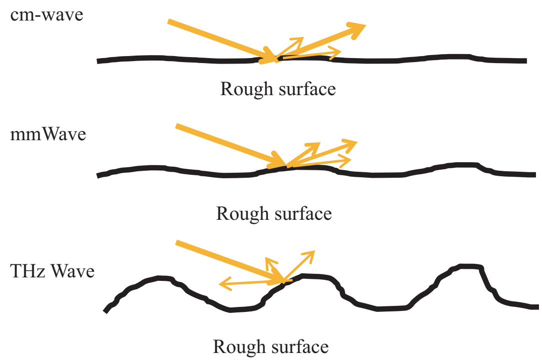

Figure 3 Reflection differences of electromagnetic waves at different frequencies.

3.1.3 *Channel measurement and modeling*

Considering air-interface algorithm and system designs, establishing an accurate channel model to characterize the propagation characteristics of THz waves is one of the key tasks to be conducted. Although THz wireless channel models have been rapidly developed in the past decade and have a certain research foundation, there is still a lack of a standard channel model for 6G. Therefore, the following research should be conducted.

- **Modeling THz-range propagation losses.** Polar molecules in the atmosphere absorb the energy of THz waves and convert it to molecular kinetic energy, i.e., the molecular absorption effect. Under different frequencies, the degree of molecular absorption varies, and strong absorption peaks are generated at certain specific frequencies, thereby dividing the entire continuous THz frequency band into discrete spectral windows of different sizes (Figure 2). Therefore, THz channels have dual selective fading of frequency and distance. Thus, building a propagation loss model in the full THz frequency domain is the prerequisite to evaluating the performance of 6G systems and designing related key technologies. To facilitate compatibility with existing 5G new radio (NR) evaluation models, path losses should be considered as a characteristic function of the frequency and distance based on the measured data in typical frequency bands and scenarios, and characteristic factors are added to improve existing models.
- **Modeling and characterizing THz physical propagation.** Since the interaction mechanism between THz wave and propagation environment differs from that of millimeter waves and optical wavebands, existing propagation models cannot be applied. For example, surfaces that can be considered smooth in the low-frequency band appear relatively rough in the THz band (Figure 3), and the diffuse reflection and scattering effects are further enhanced. Figure 4 shows the test results of the angular spectrum of the reflected beam after illuminating the wall with directional beams at different operating frequencies. There are frequency-related boundary conditions to validate the specular reflection. Therefore, it is necessary to conduct theoretical research on the mechanism of THz propagation and construct models for characterizing the reflection, scattering, and transmission features of THz waves on different materials and rough surfaces to better characterize small-scale propagation characteristics. This is vital for air-interface designs.
- **Methodology of THz-channel modeling.** Existing channel modeling methods include deterministic, stochastic, and hybrid channel modeling. Due to the large path loss in the THz band, its spatial multi-path propagation distribution model differs from the existing centimeter wave channel model. Traditional statistical channel modeling methods cannot fully characterize channel propagation features of the THz band in all scenarios. Therefore, there is a need to explore novel channel modeling methods to accurately describe the propagation characteristics of THz bands in the space-time domain and wider architecture models in typical scenarios with reasonable complexity. Considering factors, such as the universality and complexity of channels, deterministic channel modeling is unsuitable as an independent modeling method as it requires propagation environment and high complexity information. A more feasible method is deterministic channel modeling for some features based on stochastic channel modeling, i.e., hybrid channel modeling.

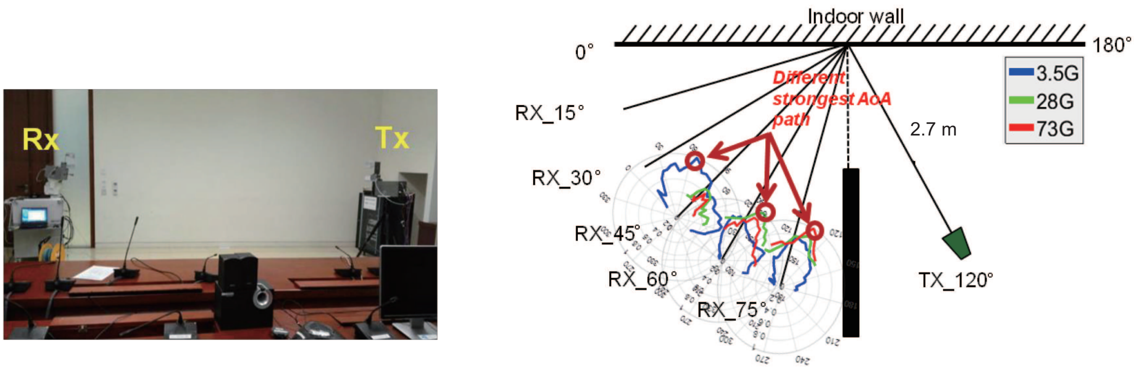

Figure 4 (Color online) Impact of material reflection on directional beams at different frequencies.

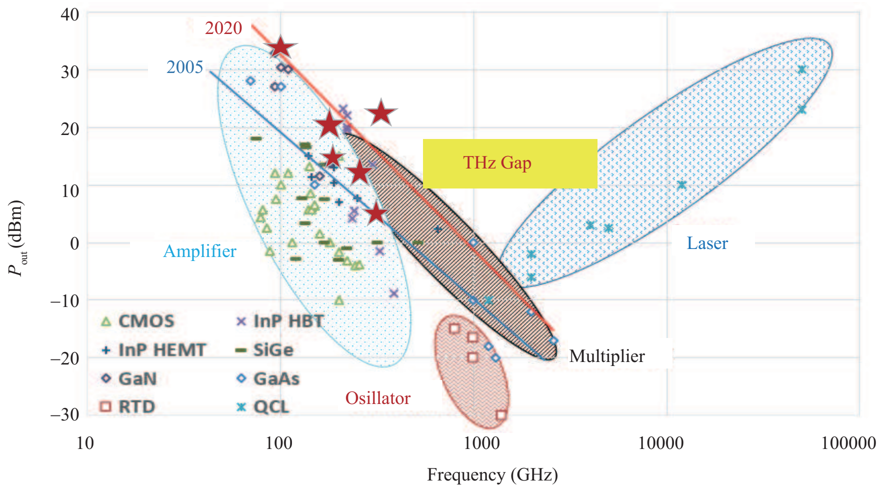

Figure 5 (Color online) Current technical capabilities of key circuits/devices in the THz system.

3.1.4 *Key technologies for THz circuits and devices*

THz circuits and devices are key components of THz systems; their performance directly affects the performance of the systems (Figure 5). THz circuits and devices are key components to realizing a THz system, and their performance directly affects the overall performance of that system. However, due to the constraints of materials and techniques, the current working frequency and output power of THz devices are limited, and it is difficult to meet commercial requirements, such as low power consumption, high efficiency, and long battery life. Current mature frequency bands for THz are mainly low bands (100–300 GHz). Thus, subsequent research on THz circuits and device technologies should focus on the following: higher frequency bands (> 300 GHz), lower loss, and higher efficiency. This includes new types III-V compound devices, which provide better electron mobility and higher saturation voltage than silicon devices; system-on-a-chip (SOC), system-in-a-package (SIP), and heterogeneous integration technologies to reduce the insertion loss caused by the discretization of existing THz systems or circuits and devices; microsystem integration and packaging technology to reduce the system volume and create conditions for large-scale integrated production.

In summary, as an important supplement for existing 5G systems, THz communications would enable various data-hungry and delay-sensitive applications, including holographic communications, short-range communications (e.g., inter-chip/nano communications), and ultrahigh capacity data backhaul. Moreover, THz-enabled high-accuracy positioning and high-resolution sensing are promising use cases for 6G. However, several technical breakthroughs should be achieved in THz, including novel transceiver architecture designs with high compact and low cost, novel antenna designs, development for advanced semiconductor materials, baseband signal processing algorithms with low complexity, channel measurement, and modeling. The research roadmap for THz communications should be further clarified step by

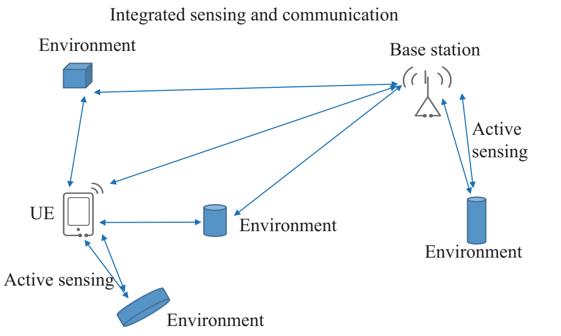

Figure 6 (Color online) Enhanced positioning by combing active positioning and passive sensing.

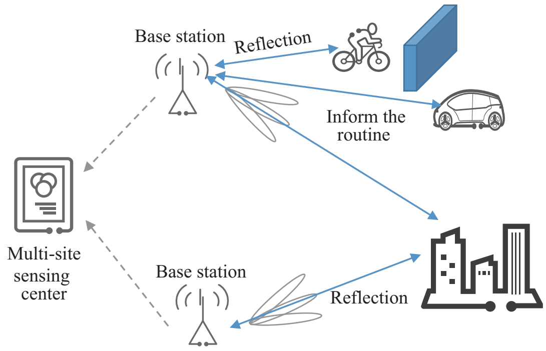

Figure 7 (Color online) High-resolution imaging.

step, and its industrialization should be developed.

3.2 Integrated sensing and communications

In the era of the intelligent Internet of Everything, as digital transformation continues to develop, services, such as interactive immersive experiences, machine collaboration in unstaffed factories, real-time sensing smart healthcare, and advanced autonomous driving, are promoted, and they have been applied on a large scale within this decade. These services require communication networks to support millimeter-level sensing accuracy.

RF sensing obtains information from the environment through RF signals and enables positioning, motion detection, imaging, and other functions. RF sensing has long been a separate system developing in parallel with mobile communication systems, and positioning is the only sensing service that existing 5G systems can provide.

Future communication systems would leverage higher frequencies (tens of GHz or even hundreds of GHz and THz), larger bandwidth, and larger antenna apertures, making it possible to integrate RF sensing into communication systems. Therefore, in high-frequency and large-bandwidth application scenarios, we can use radio-wave transmission, echo, reflection, and scattering analysis to explore the material world. Wireless sensing abilities are natively integrated into communication systems to provide high-accuracy positioning, imaging, environment reconstruction, etc. This improves communication performance, expands the service scenarios, and provides data portals for building a smart digital world. Using AI, the wireless sensing ability will be further integrated into people's life.

Integrated sensing and communication are based on the implementation of two independent functions (RF sensing and wireless communications) in a single system to achieve mutual benefits. On the one hand, communication systems can be used to complete different types of sensing services, using the same spectrum or even hardware or signal processing modules. On the other hand, sensing results can be used to enhance communication access or management and improve service quality and communication efficiency. This concept has the following prospective application scenarios and possible research directions.

- **Enhanced positioning.** 6G will further improve positioning accuracy to the centimeter level for both indoor and outdoor scenarios. Based on the integration of active positioning and passive sensing, objects (scatterers) in the environment can be used as anchor points to provide more confidence information for positioning, thereby improving positioning accuracy (Figure 6).
- **High-resolution imaging.** Sensing services should provide secure, high-precision, and low-power sensing and imaging capabilities. Based on the principle of integrated sensing and communications, portable terminals or base stations can sense their surrounding environments, making it easier to collect and integrate the information needed to maximally translate information about the physical world into the cyber world (Figure 7).
- **Simultaneous localization and mapping (SLAM).** In an unknown environment, mobile sensing devices can be used to recognize surrounding objects (or landmarks), and then a 2D/3D map of the environment can be reconstructed to further improve positioning accuracy. Due to the complexity of the actual environment, non-line-of-sight (NLoS) coverage occupies a large part of target service areas. In this case, reconstructing the virtual environment based on 6G can provide the latest environmental

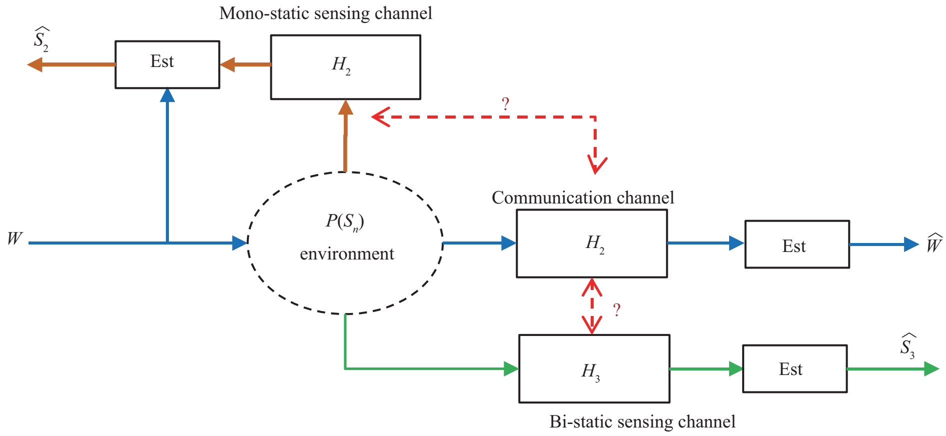

Figure 8 (Color online) Environment-associated system of integrated sensing and communication.

information. For example, in NLoS scenarios, 6G-based SLAM can achieve accurate centimeter-level positioning when the distance between the sensing device and the object is within 10 m.

- **Gesture and activity recognition.** Sensing services include typical gesture recognition, heartbeat detection, fall detection, breathing detection, sneeze detection, and intrusion detection. The recognition of these gestures and activities is associated with the detection of Doppler shift information.

Integrated sensing and communication include multilevel integration from the spectrum, RF hardware, baseband algorithm, protocol layer, and high-level applications. Future research directions are listed below.

3.2.1 *Fundamental theories*

Due to the various purposes of communication and sensing, there are still many technical challenges in integrated designs of communication and sensing. Achieving an appropriate balance between sensing resolution and communication ability, i.e., gaining sensing ability without reducing communication efficiency, should be considered. There would be a basic tradeoff because the more pilot resources used, the better channel estimation performance can be achieved but at the expense of communication spectrum efficiency.

Therefore, a proper cost function should be designed as a KPI to describe this tradeoff and facilitate the design of integrated sensing and communications. Assuming the environment function is $P(S_n)$ (Figure 8), the error function can be used as a cost function for assessing both communication and sensing. For example, the cost function for communication is given by

$$\lim_{n\to\infty} P(\hat{W} \neq W) = 0. \tag{1}$$

And the cost function for sensing is given by

$$\lim_{n\to\infty} \sup \mathbb{E}\left[\frac{1}{N}\sum_{i=1}^{n} d(S_i, \hat{S}_i)\right] \leqslant D. \tag{2}$$

An alternative is to let the sensed information be the messages for radar transmission, which can be characterized by the radar transmission rate. Then, the rates of communication and radar transmission form paired parameters for joint optimization and design.

Resource scheduling (time, frequency, and space) and interference management for integrated sensing and communication based on these basic theories are important research topics.

3.2.2 *Integrated hardware design*

Baseband and RF hardware sharing are important research topics for designing integrated sensing and communication. Hardware integration solutions can reduce the overall power consumption, system size, and internal exchange delay and enable sensing and communication systems to benefit from each other in distortion correction and compensation. Since they use different KPIs and algorithms to evaluate

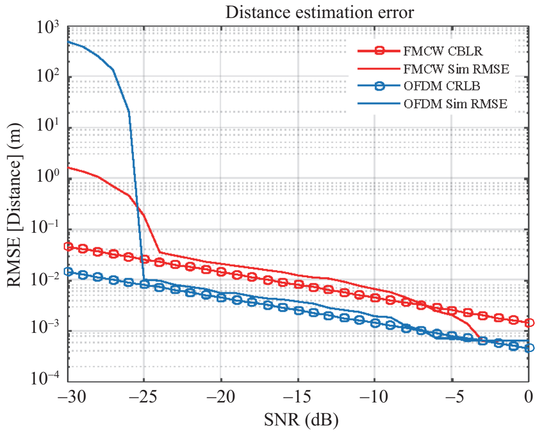

Figure 9 (Color online) Distance estimation performance of two different waveforms.

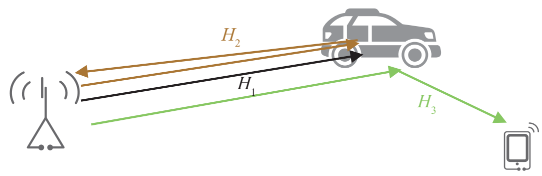

Figure 10 (Color online) Communication and sensing channels in vehicle-to-everything (V2X) cases.

system performance, sensing and communication systems have varying hardware requirements. Given both the cost and scale of communication and radar systems, hardware designs of integrated sensing and communication systems are similar to traditional communication architectures. Thus, it is essential to assess the impact of architecture on sensing performance. For example, full-duplex is the optimal solution to implement co-site reflection sensing while maintaining the base station transmission rates. Sensing requires lower signal-to-noise ratios (SNRs) than traditional communication, which simplifies the implementation of a full-duplex to some extent. However, remote target sensing is still a challenge.

3.2.3 *Joint waveform design*

Communication networks maximize spectral efficiency, whereas sensing systems focus on improving estimation (e.g., positioning and location tracking) resolution and accuracy. This is a major challenge in joint waveform designs for integrated sensing and communication. Cyclic-prefixed orthogonal frequency division multiplexing (CP-OFDM) has been adopted as a waveform design scheme for communication. Previous studies reported similarities between OFDM and continuous waveforms (CW), making them candidates for integrated sensing and communication. Different applications and scenarios result in different choices. For example, Figure 9 shows the estimation errors of the two waveforms with a center frequency of 26 GHz and a bandwidth of 400 MHz. When the SNRs are similar, the two waveforms have close estimation errors. For applications that require a low communication rate but high sensing precision, CW waveforms may be preferred. In contrast, OFDM waveforms are more suitable for applications that require a high communication rate but low sensing precision. However, it is still worth investigating optimal waveform designs to balance the performance of sensing and communication systems.

3.2.4 *Channel modeling and analysis*

Sensing performance greatly depends on the environment, so its channel model should be based on the geographical environment (or geometry-based channel model), which is different from the conventional statistical channel model in wireless communication. This makes it difficult to concurrently evaluate both communication and sensing performance and simulate their interference and influence in the same channels. In the case of communication and sensing systems for vehicles (Figure 10), the vehicles perform both tasks, where channels H_1 and H_2 are highly correlated in angle information (or spatial domain) but have a low correlation with channel H_3. H_1 refers to the communication channel, H_2 is the monostatic sensing channel, and H_3 is the bi-static channel (Figure 8). Therefore, the channel correlation between sensing and communication systems is a challenge regarding the improvement of mutually beneficial performance.

In conclusion, the main design principle of integrated sensing and communication is to seamlessly integrate and effectively utilize both functions in the same system (by sharing the same frequency, signaling, hardware, etc.) in a reciprocal and symbiotic way. This technique would not only alleviate the spectrum scarcity but further enhance the performance of a single sensing or communication system. Furthermore,

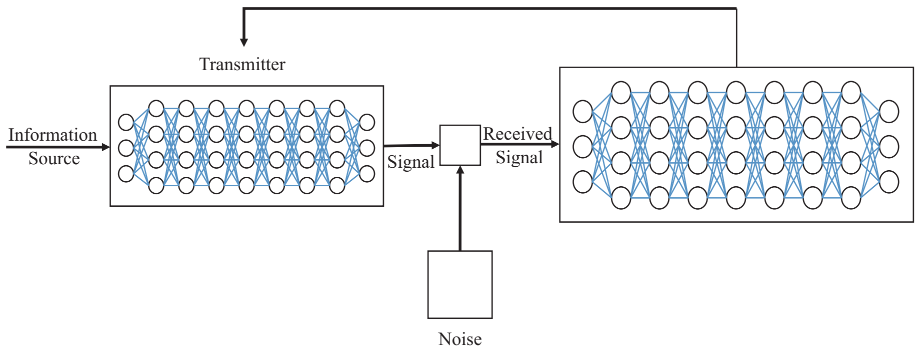

Figure 11 (Color online) End-to-end intelligent communication system.

the advancement of millimeter-wave, massive MIMO, and advanced radar techniques will also open up more possibilities for it. However, realizing the full potential of integrated sensing and communication in practical wireless networks is still challenging, and there are still many important open research problems, including joint waveform designs, optimal signal processing algorithm designs, network architectures and transmission protocol design, and security and privacy issues.

3.3 Integrated intelligence and communications

The existing 5G already supports three major application scenarios, including enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communications (mMTC), and 6G will evolve toward higher throughput, lower latency, higher reliability, several connections, and higher spectrum utilization. Also, AI is driving a new round of technological revolution with the continuous development of computing power, algorithms, and data sets. Therefore, integrating communication and AI is a major trend for future wireless network development. AI has shown a great potential to enable unknown environment modeling, channel prediction, intelligent signal generation and processing, network status tracking and intelligent scheduling, and network optimization and deployment. It is expected to promote the evolution of future communication paradigms and network architecture changes. Currently, the integration of communication and AI focuses on air interface technologies and AI datasets of wireless networks. In this regard, we discuss the preliminary research and ideas around these issues.

3.3.1 *Intelligent wireless network air interface*

- **AI- and ML-based physical layer air-interface techniques.** Traditional communication networks are designed by first dividing the whole system into several separate functional modules and then optimizing each module independently. Therefore, to apply AI/ML to wireless communication, the basic functional modules of the traditional physical layer are replaced with AI/ML methods, such as neural networks. These methods can improve performance, and they do not change the framework of existing communication systems and seamlessly integrate intelligence and communication. As shown in Figure 11, unlike modular optimization based on AI and ML, end-to-end intelligent air-interface technology directly uses neural networks to process and transmit signals at both the transmitter and the receiver. This method treats physical layer communications as an end-to-end signal reconstruction problem by jointly optimizing the design of the transmitter and receiver. For additive white Gaussian noise (AWGN) or other known fading channels, the entire encoding and decoding neural networks can be trained based on the stochastic gradient descent algorithm. For common channels, gradient estimation at the transmitter is necessary to address the unknown channel response.
- **AI- and ML-based link-layer air-interface techniques.** Existing wireless resource management method generally requires explicit mathematical modeling of communication systems and designs resource management strategies through optimization or heuristic methods. However, this method has several limitations. First, it is challenging to accurately model wireless networks. The solution based on approximated models inevitably causes some performance losses. Second, network planning and optimization adapt to dynamic environments, resulting in high system complexity and long communication delay.

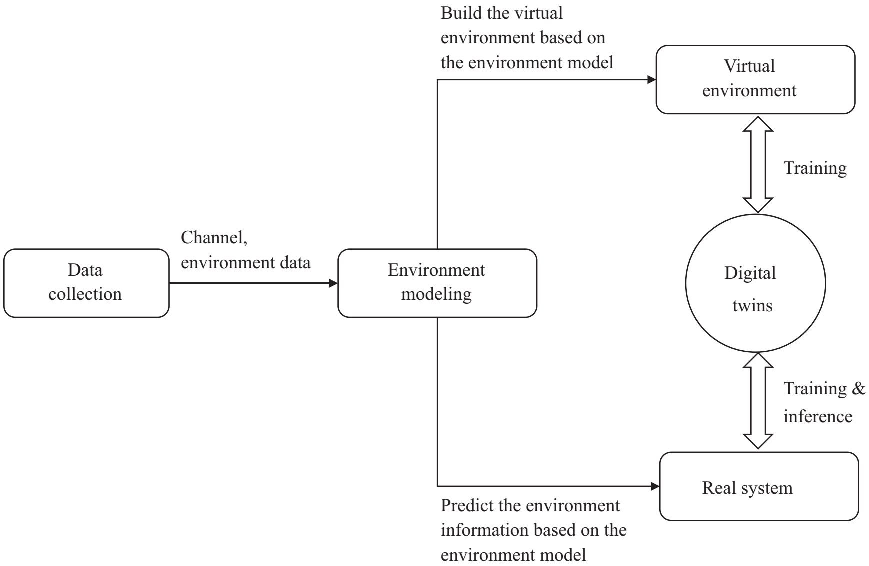

Figure 12 Framework of intelligent training and inference for radio resource management.

Several challenges must be well-considered and solved when applying intelligent wireless resource management methods. First, communication systems must support real-time status collection, action delivery, benefit calculation, and other key functions. Second, it is important to fully evaluate the influence of high complexity and active exploration in the training stage on system performance and stability. Third, the topology and terminals in communication systems vary with time; thus, the systems must be scalable enough to accommodate changes. Given these challenges, a training and inference framework shown in Figure 12 is proposed for intelligent radio resource management. In this framework, channel condition and environmental data are first collected through channel estimation, sensing, and other methods for environment modeling. Based on this environment model, a virtual environment is built to support background training. Moreover, to avoid the loss of performance and stability stems from early training decisions, the policies generated from training are used as the initial inputs.

3.3.2 *Wireless AI research dataset*

High-quality data are a prerequisite for wireless AI research. However, collective building and sharing of wireless AI research datasets are still a major challenge. Typical wireless AI research datasets may include the following five types: the channel dataset revealing the channel states, environment dataset showing environment information, experience dataset describing network states, decisions, and performance, user profile dataset (user properties and behaviors), and pretrained model dataset representing trained neural network models and parameters.

Each dataset is collected in real-time. Through training and inference of pretraining models, the data can assist various communication tasks to achieve an intelligent network. Figure 13 shows how a wireless communication system collects and utilizes each dataset. First, a channel model can be trained based on historical channel data. By learning the changing pattern of the channel state, frequency, and spatial domains, the model outputs a compressed representation of the channel. This representation data are then combined with some information, such as environmental data and user profiles, to explicitly describe the ongoing communication scenario. After that, neural network models of different tasks leverage the data to perform intelligent decision-making tasks, such as intelligent air-interface configuration, resource management and scheduling, and intelligent environment perception. The status, decisions, and performance indicators of these tasks are collected to form an experience dataset, which is fed back into the model training process in real-time.

In conclusion, we envision that intelligence (or AI) will be natively integrated into the 6G network at the beginning of designing the air interface and network architecture. Two designs are involved in integrated intelligence and communication: the AI for network, which leverages AI or ML as the tools to optimize wireless networks, and the network for AI that enables the wireless network to support and optimize AI applications, creating opportunities for post-Shannon communication research and innovations [2].

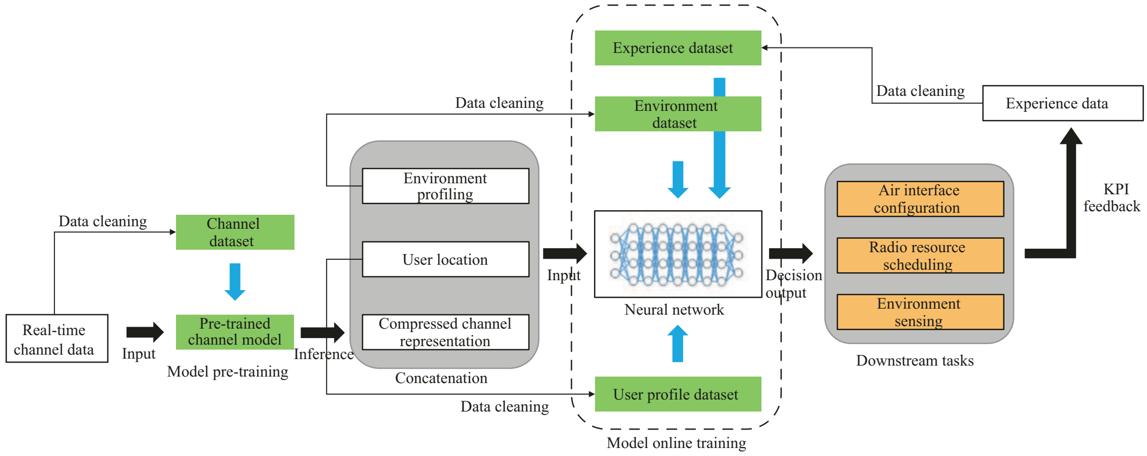

Figure 13 (Color online) Composition and application of wireless AI research datasets.

However, implementing networks with native AI demands more compact chips with stronger computation power (such as nanophotonic chips), algorithms more suitable for network collaboration (such as federated learning), and new interfaces between networks and devices that aid the generation and exchange of intelligence among all layers, which is a decade-long journey.

3.4 Ultra-massive MIMO

After almost a decade of development, the massive MIMO technology has achieved remarkable progress in theoretical research and system designs [7], and it has moved toward large-scale commercial use, making it one of the most important technical techniques to improve system spectrum efficiency. For the future development of 6G, improving the spectrum efficiency would remain an important performance metric. Ultra-large MIMO technology will be the further evolution and upgrade of 5G massive MIMO technology. Higher operating frequency bands also provide convenient conditions for the deployment of ultra-large MIMO. By deploying ultralarge-scale antenna arrays, applying new materials, and introducing new tools, higher spectrum efficiency, wider and more flexible network coverage, higher positioning accuracy, and higher energy efficiency can be achieved.

The power consumption, size, and weight of devices increase with the scale of antenna arrays, posing great challenges to network operators during deployment and applications. However, with continuous improvement of antenna and chip integration and the emergence of new materials and processes, the scale of antenna arrays can be increased under controllable size, weight, and power consumption. In the 6G era, the trends of ultralarge-scale antenna development include the larger arrays, smaller size, higher integration, and ability to support ultra-high-frequency and multiple frequency bands.

3.4.1 *Ultra-massive MIMO baseband processing algorithm*

Baseband processing in ultra-massive MIMO involves precoding processing, channel estimation, and resource scheduling. The complexity of baseband processing is positively related to the scale of antenna arrays. Theoretically, the maximum-ratio-transmit preprocessing algorithm can achieve good performance with several antennas [8]. However, the multiple antenna scheme poses serious challenges in baseband processing. In addition, using a larger channel bandwidth may go beyond the computing capability of devices. Therefore, leveraging the distributed computing and parallel processing algorithms can be an effective way to reduce the computational complexity and communication requirements of devices [9].

3.4.2 *Channel state information feedback*

The accuracy of channel state information highly affects the preprocessing performance of a transmitter equipped with ultralarge-scale antennas. In general, time division duplex (TDD) systems utilize channel reciprocity to obtain the channel state, whereas frequency division duplex (FDD) systems depend on the measurement and feedback of terminals for the same purpose. However, the limited capacity and delayed transmission in the feedback channel compromise the accuracy of the channel state information obtained in FDD systems. As the scale of the antenna arrays increases, the form types and deployment modes become more diverse. However, obtaining channel state information is increasingly challenging. Recent research [10] has shown reciprocity between the uplink and the downlink FDD channels, including delay and angle information. This is a breakthrough in compressing feedback overhead and reducing computing complexity. However, antenna calibration is the prerequisite to acquire channel state information through reciprocity. Highly integrated antennas make it difficult to design self-calibration circuits. A feasible solution is to measure the signals of ultra-massive MIMO arrays through terminals or network nodes and communicate with a base station to calibrate the antenna.

3.4.3 *Intelligent design for ultra-massive MIMO*

Enabling large-scale antenna systems needs several decision and optimization procedures, but the traditional algorithms may not guarantee its efficiency and performance. Intelligent ultra-massive MIMO can be a feasible solution by transforming modules, such as channel measurement, beam management, precoding, multi-user MIMO (MU-MIMO) user detection and scheduling, signal processing and channel state information feedback, and transmission point selection and planning. However, targeted research is required to determine ML algorithms that best suit wireless communication systems. Problems, such as dataset collection and generalization capabilities, must also be addressed.

3.4.4 *Channel measurement and modeling*

Channel modeling is the basis of wireless communication system simulations and performance analyses. For a 5G system, channel modeling is performed between a terminal and a base station under the assumption of a far-field. Thus, a received electromagnetic wave can be modeled as a relatively stable plane wave. In an ultra-massive MIMO system, antennas of a base station may be deployed in a wide area, thereby forming an ultralarge-scale antenna array. In this case, when the terminal is in the near-field of the antenna array, the received nonstationary electromagnetic wave cannot approximate a plane wave. Therefore, far-field modeling is not applicable. Thus, there is a need for novel channel modeling considering near-field scenarios. Moreover, as new antenna forms emerge, the propagation characteristics of electromagnetic waves and the impact on channels should also be considered in the modeling.

3.4.5 *Distributed ultra-massive MIMO*

Compared with centralized antenna systems, distributed ultra-massive MIMO facilitates the construction of the ultralarge-scale antenna arrays, providing higher spatial resolution and better performance. As its network architecture is nearly scale-free, its transmission shifts from network-centered to user-centered, achieving a consistent user experience. In addition, it can shorten the distance between network nodes and end-users, effectively reducing system power consumption. Practical and cost-efficient deployment would be a priority to implement distributed ultra-massive MIMO, followed by real-time information exchange and time-frequency synchronization issues among nodes.

In addition to effectively improving spectral efficiency, ultra-massive MIMO can enhance network coverage performance and positioning accuracy. In terms of coverage, 6G will further expand to mmWave or even THz bands. Despite larger bandwidth, the sensitivity of transmission and atmospheric loss will also significantly increase. However, with the ultra-narrow beam of ultralarge-scale antennas, communication distances and coverage can be effectively increased. Considering positioning accuracy, meter and even submeter level accuracies have already been achieved in 5G, which would be further improved in 6G. Ultra-massive MIMO features ultrahigh spatial resolution, which is inherently suitable for precise positioning [11]. In the real environment, there may be a little or weak line-of-sight (LoS) path. Precise spatial angle information from ultra-massive MIMO and temporal information of traditional positioning technologies would be combined to achieve higher accuracy in complex environments [12].

In summary, empowered by new materials and advanced techniques (e.g., ultralarge aperture arrays, AI, and sensing), ultra-massive MIMO techniques would achieve higher spectral efficiency, wider and more flexible network coverage, higher positioning precision, and higher energy efficiency in a wider frequency range. However, to actualize this technique in practice, several research challenges, such as complicated channel measurement and modeling, heavy signal processing load, high reference signal overhead, and limited front-haul capacity, should be addressed. Antenna arrays and RF chips that feature low power consumption, low costs, and high integration would be the key to the commercialization of ultra-massive MIMO [1].

3.5 Reconfigurable intelligent surface

Traditional network designs and technological evolution focus on better adaptation to the limitations of wireless transmission channels. For example, beamforming is employed to resist transmission losses and interference, and modulation and coding schemes and MIMO are utilized to improve transmission capacity [13, 14]. However, with the continuous expansion of future communication demand and network complexity, the increase in network construction (including energy overheads [15]) has become key in future communication [16]. RIS, with a "reconfigurable/programmable wireless transmission channel" as the core, opens a new direction for future networks owing to its intrinsic characteristics, including low cost, low energy consumption, high reliability, and large capacity [17]. Authors in [18] provided an overview of the fundamental physical layer issues of the RIS-assisted wireless systems, including the reflection principle, channel estimation, and system designs for RIS-aided wireless communication where RIS acts as a reflector and RIS-based information transmission where RIS functions as a transmitter. Moreover, several potential applications of RIS in 6G have been proposed.

Generally, RIS is the use of an artificial electromagnetic surface to realize the intervention of electromagnetic wave transmissions, such as ideal absorption and specific reflection [19, 20]. Compared with traditional meta-surfaces with fixed functions, RIS can enable real-time programming of electromagnetic characteristics [21, 22]. It includes several elements. In actual applications, control signals are applied according to the characteristics of the elements to realize a dynamic change in the electromagnetic properties of each element and then control the amplitude, phase, polarization, and frequency of electromagnetic waves. Current research is in the following directions.

3.5.1 *Lumped circuit based RIS*

The first one is the diode/varactor diodes. This method controls electromagnetic signals by adjusting the capacitance or inductance in the equivalent circuit [23–25]. For instance, multi-level phase adjustment can be achieved by increasing the number of diodes or multi-level bias voltages. The signal amplitude can be changed by adjusting the load impedance [26]. This kind of RIS can quickly respond to electromagnetic signals, and has low reflection loss and power consumption. It has high maturity and low cost in implementation.

The second one is the micro-electro-mechanical system (MEMS) assisted method. This method uses MEMS to adjust electromagnetic signals by controlling electromagnetic units, such as signal transmission delay change [27], electromagnetic units [28] rotation, and piezoelectric effect based capacitance change [29]. This kind of RIS has good linearity, low power consumption and high monolithic integration.

3.5.2 *New material based RIS*

This is achieved by adjusting material parameters. For example, nematic liquid crystals can enable voltage-controlled birefringence in different bias electric fields and then achieve electromagnetic absorption [30]. By introducing yttrium iron garnets into the backing material, the magnetic permeability can be adjusted through the magnetic field. In addition, graphene is also considered a new material for RIS [31]. Metals can help reduce the surface equivalent impedance, and improve its ability to adjust signal amplitude, phase and frequency [32, 33].

Based on the above characteristics, such RIS can be widely applied to various wireless transmission scenarios and frequency bands, including typical cellular scenarios, such as outdoor dense urban areas (e.g., for blind area coverage and capacity enhancement), suburban areas (e.g., for overcoming two-path loss), and indoor and outdoor-to-indoor (O2I) coverage.

Currently, research on RIS is still in the initial stage, and the following areas need to be investigated.

3.5.3 *RIS modeling and simulation*

Due to the diverse implementation and performance of RIS, effective and accurate modeling is needed to evaluate the performance of actual system design and algorithm. Electromagnetism-based full-wave simulations, such as the finite-difference time-domain (FDTD), finite-integral time-domain (FITD), finite element (FE), and method of moments (MoM), are necessary to analyze the performance of RIS elements and integrated systems. It is also helpful to extract simplified models, which can be applied to system simulations, and identify and analyze potential factors that affect performance. For instance, MoM

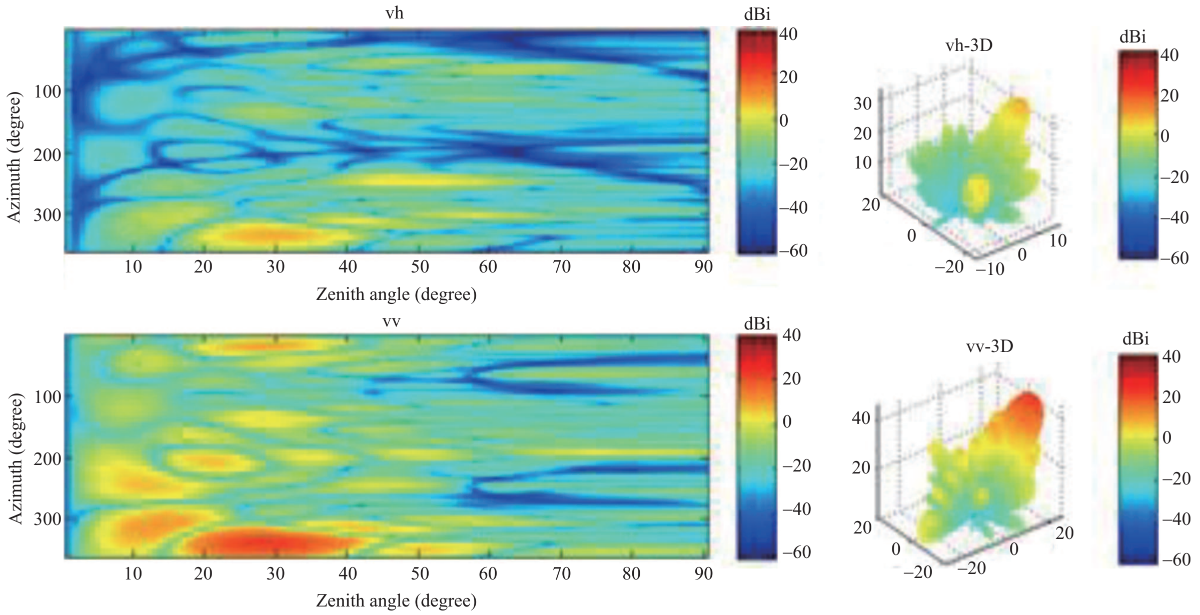

Figure 14 (Color online) RIS-based composite channel.

features high accuracy and computing efficiency and can be perfectly combined with classical high-frequency analysis methods, such as physical optics (PO) and uniform theory of diffraction (UTD). Therefore, they are suitable for the study of metasurfaces. For lumped-circuit-based RIS products, full-wave simulations can also be used based on the multiport scattering network model [34, 35]. In addition, it is of great value and research significance to extract an effective simplified model for the physical and electromagnetic characteristics of RIS. The model should reflect the RIS error on electromagnetic signals and the mutual coupling between electromagnetic units.

3.5.4 *RIS channel modeling*

For wireless communications, accurate channel modeling ensures precise and universal evaluation. In 5G research, various channel models, including stochastic and hybrid models, have been developed to reflect new scenario features, such as large-scale antennas, massive MIMO, and large bandwidth.

For the large-scale characteristics of a purely statistical model, a large-scale loss model in the LoS scenario with RIS has been proposed [36]. For small-scale fading, Rayleigh and Rician distributions are employed to model channels (such as LoS and NLoS). However, this method cannot accurately reflect important channel features in the performance evaluation, such as LoS or NLoS statistical features, after introducing RIS, multi-path delay, polarization, and reciprocity. Numerous measurements and simulations are needed to optimize the channel modes.

Considering RIS varying the certainty of propagation channels, Ref. [37] followed the scheme of map-based hybrid channel models and adopted the direct modeling of specific propagation environment and communication subject and ray tracing technology to analyze the channel with RIS. In this model, based on the high-frequency electromagnetic scattering theory, a RIS panel is modeled as an antenna wave source driven by multiple incident waves, and then a channel composed of gNB-UE, gNB-RIS, and RIS-UE is obtained (Figure 14). Because this model can analyze the characteristics of the main components of a channel, it can accurately and effectively evaluate the algorithm and system performance. In addition, it fits the concept of a "reconfigurable/programmable wireless transmission channel" in RIS applications. It has great research and application prospects.

3.5.5 *Algorithms of RIS*

The acquisition of channel state information is critical for beamforming, secure transmission, passive information transmission, and sensing positioning. However, RIS is characterized by several passive elements with spacing less than a half wavelength, all passive elements, and no complex signal processing capability, making it difficult to obtain segmented channels. Therefore, for effective channel estimation, it is necessary to minimize the complexity of channel estimation to avoid complex signal processing operations. This can be achieved by replacing RIS passive reflection elements with elements that contain certain sensing and signal processing functions and designing the number and layout pattern of active elements based on the tradeoff between segmented channel estimation and transmission performance [38]. The position-information-based RIS channel estimation method uses a fixed position of the base station and RIS, as well as the array characteristics of RIS, to obtain the signal angle of arrival and other key information. This method can reduce channel estimation complexity. Leveraging the sparsity of high-frequency channels and the programmable property of RIS, RIS channels can be obtained through compressed sensing, matrix filling, and other methods [39]. The cooperative solution of channel estimation and beam matching can be used to estimate RIS channels. However, segmented transmission poses challenges to the conventional codebook solution. There is a need to design a codebook and matching scheme of base-station-RIS and RIS-UE channels for random access design and beam selection. Due to limited feedback in downlink channel estimation, the tradeoff between channel estimation accuracy and nonideal channel feedback should be considered. To solve the problem of channel estimation when the channel model is unknown, recently developed AI can be applied to channel estimation [40], which can reduce the demand for channel modeling and has high robustness and anti-noise performance.

3.5.6 *Challenges to industrialization*

As a promising technology, RIS has attracted research interest from academia and the industry worldwide. Various verifications and tests have demonstrated its feasibility, which introduces a new paradigm for mobile communication. Based on the system mentioned in [41], the feasibility and high performance of single-input single-output (SISO) or MIMO multi-modulation transmission systems have been verified. NTT DoCoMo has also demonstrated that its prototype materials can be used on bands higher than mmWave (traditionally, 30–300 GHz). Moreover, EU's VISORSURF and ARIADNE projects have studied the software/hardware platforms, protocol stacks, and so on. Massachusetts Institute of Technology built a RIS test system named RFocus. Tests showed that it can increase the median received signal strength by 95 times and the median channel capacity by 20 times.

The following challenges should be addressed for the sustainable development and industrialization of RIS.

- **High-precision beam control.** Refined high-gain beamforming is crucial for RIS applications in mmWave or even higher frequency bands. Based on beamforming, high-precision control of signal phases is required in RIS. However, this single-dimensional method has high requirements in product costs, power consumption, and complexity. Therefore, joint optimization based on phase and amplitudes [21, 42] are expected to further reduce the control overhead. Moreover, increasing the number of elements to provide a higher gain increases the size of the reflecting surface, and reducing the spacing between elements causes severe mutual coupling.
- **RF linearity.** When RIS adjusts electromagnetic signals, aperture illumination results in RF intermodulation distortion (IMD), resulting in adjacent channel interference and harmonic wave. MEMS-based methods are expected to further improve this phenomenon [43].

In conclusion, wide-area seamless coverage and stable high throughput are the basis for applications in wireless communication networks. RIS will further facilitate the development of high-quality networks in the following aspects.

- **Coverage enhancement.** In cellular networks, coverage holes may occur in outdoor areas due to obstructions by buildings and plants. For cell edges, limited transmit power and strong interference reduce user received signal quality and uplink experience. For O2I and indoor deep coverage in complex environments, it is difficult to ensure the quality of the communications due to penetration loss and other factors, especially for high-frequency networks. RIS (such as simplified static passive RIS) can improve transmission quality in these areas (for example, introducing stable reflection or projection paths).
- **High capacity.** Currently, high-order modulation and multi-stream MIMO technologies are mainly employed to increase capacity. However, MIMO has high requirements for channel conditions (like stable multi-path transmission). RIS-based applications (such as dynamic active and controllable RIS) enable base stations to control the propagation between RIS and UEs to construct stable multi-path conditions (for example, increasing reflection path in LoS transmission) to support multi-layer MIMO transmission. With the extensive applications of RIS, the stability of the communication environment would be effectively improved, and the stable system performance and user experience are guaranteed.

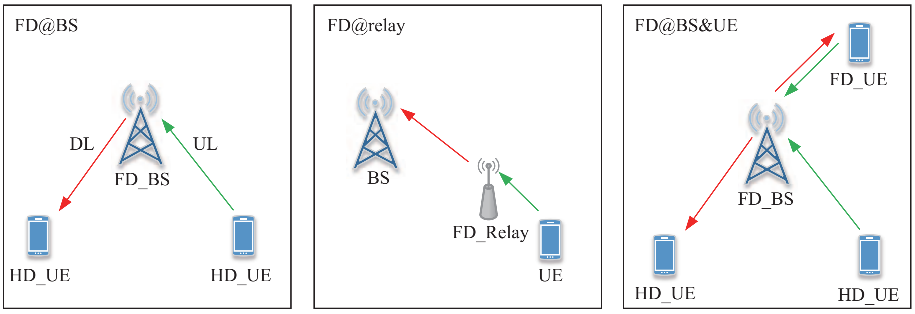

Figure 15 (Color online) Typical full-duplex architectures.

RIS will pave the way for more applications, such as positioning and simultaneous wireless information and power transfer (SWIPT). For positioning, in addition to effectively improving signal quality, RIS can be flexibly deployed in the service area to aid positioning and improve positioning accuracy. For SWIPT, RIS effectively transmits the mixed signal of information and energy, improves the service quality of weak users (such as large-scale IoT users) [44, 45], and enables these users to extend the service cycle through energy collection. RIS will provide new momentum for future communication networks (5G-Advanced/6G) by building a controllable wireless environment.

In summary, as a promising paradigm for designing wireless networks, the RIS technique can dynamically tune the signal reflection amplitude or phase via a digitally-controlled reflecting surface to further enhance wireless communication performance, such as creating effective LoS links, improving channel rank, and reshaping channel realizations. Moreover, it can improve the radio-sensing and computing performance of mobile networks. However, for practical use, RIS faces some challenges, including physical modeling and design of surface materials, channel modeling, channel state information collection, beamforming design, passive transmission, AI-enabled design, and industrial challenges, which are discussed in this subsection.

3.6 Co-frequency co-time full-duplex

Improving spectral efficiency and alleviating spectrum scarcity are the objectives of advancing wireless communication theories, technologies, systems, and standards. Self-interference cancellation (SIC) enables simultaneous transmission and reception in the same frequency band, creating new duplex technologies. For example, the uplink and downlink data transmission can be performed by different carriers in the same frequency band and by the same carriers simultaneously, thus called full-duplex. Theoretically, full-duplex technology doubles spectral efficiency for both FDD and TDD modes. For FDD, the unified duplex mode provides unified spectrum resource usage and management and implements a virtual spectrum without separate planning for the uplink and downlink. For TDD, full-duplex prevents time division that reduces delay and overhead, which is more favorable for low-delay services. It can also allocate more spectrum resources to uplink services for better uplink coverage. This technology has a great potential to improve network capabilities and satisfy the requirements of low latency, wide coverage, and high throughput.

Typical full-duplex architectures are shown in Figure 15, which can be deployed depending on the maturity of SIC technology. In the early stage, SIC is mainly implemented on the base station side, and full-duplex is employed in cellular hotspots and relay transmission. In cellular hotspot areas, a full-duplex base station can schedule uplink and downlink UEs simultaneously, improving spectral efficiency and flexibility. For a relay transmission, received and forwarded signals can be simultaneously transmitted in the same frequency band, significantly reducing end-to-end delay. As SIC develops, full-duplex will be applied to dense networking, macrobase stations, and other innovative scenarios, such as device-to-device (D2D). Moreover, future full-duplex terminals will improve the bidirectional data transmission rate and reduce feedback delay in UEs.

With over 115 dB self-interference cancellation for 20 MHz bandwidth signals of two transmitters and two receivers (2T2R) antennas, existing SIC technology can be used in low-power and small-scale antennas for single-site full-duplex operations, such as Wi-Fi and microcellular isolated sites. With integrated access and backhaul, full-duplex is implemented in specific scenarios by extending the distance between TX and RX antennas and fully utilizing the difference between the access and the backhaul

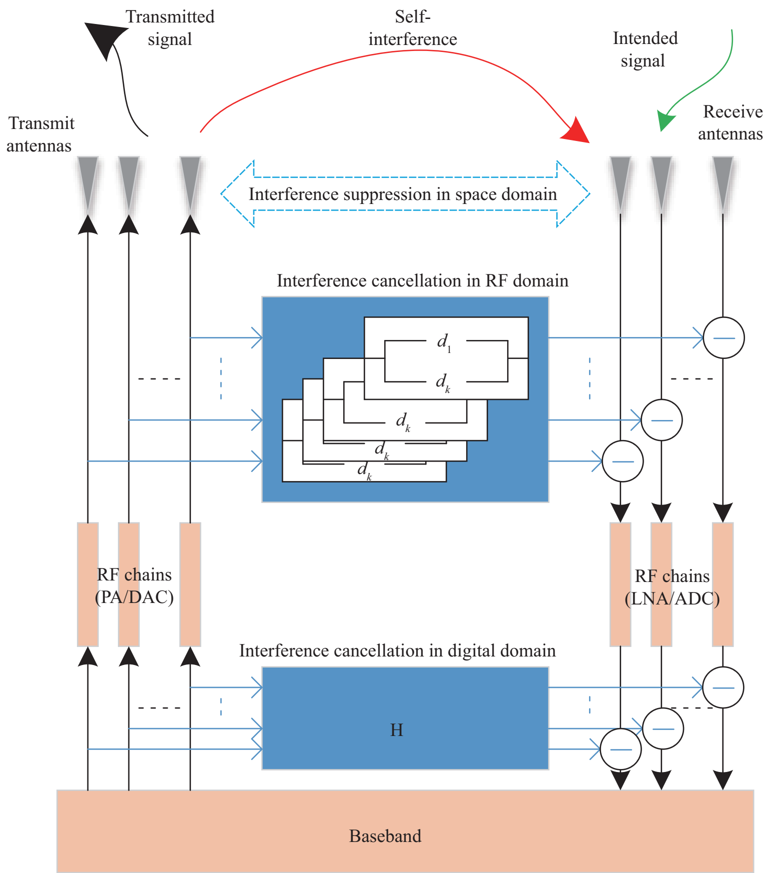

Figure 16 (Color online) SIC technology.

transmission directions. 6G communication systems will continue to evolve regarding high bandwidth, large-scale antennas, and dense networking, posing challenges on interference cancellation and networking.

3.6.1 *SIC technology*

SIC is a key full-duplex technology. Interference cancellation involves multiple domains, including space/RF/digital domains (Figure 16). Space-domain SIC can be implemented through antenna position optimization, spatial nulling beamforming, and high isolation of transmitter (TX) and receiver (RX) antennas. In the RF domain, SIC is implemented by constructing cancellation signals whose phases are opposite to those of the received self-interfering signals. This effectively cancels the interfering signals in the RF analog domain. Finally, digital-domain SIC further reconstructs signals and eliminates residual linear and nonlinear self-interferences. Research is required in the following directions to satisfy the requirements of high power, large bandwidth, and large-scale antennas.

- **Low-complexity algorithm for RF signal reconstruction and interference cancellation.** Constrained by the existing architecture, especially the delay line and interference cancellation matrix in the RF domain, the complexity of traditional RF interference cancellation links increases with the square of the number of antennas. Therefore, supporting large-scale antennas ($>$ 32T32R) and large bandwidth ($>$ 100 MHz) is a key challenge to implementing full-duplex. This can be solved by redesigning the antenna structure or optimizing the antenna position for high-isolation transceiver antennas. Moreover, low-complexity RF signal reconstruction and interference cancellation can be implemented through mirror antennas or heterogeneous multi-port networks.
- **Implementation of high-level interference cancellation.** The transmission power of macrobase stations can reach 23–46 dBm, which requires SIC of up to 118–141 dB (taking -95 dBm low noise as an example). High-level digital cancellation increases the requirements on the linearity of RF components. First, the linearity of RF components, such as the power amplifier, should be improved. Second, nonlinear effect modeling based on ML can be achieved in the digital domain for better interference cancellation.

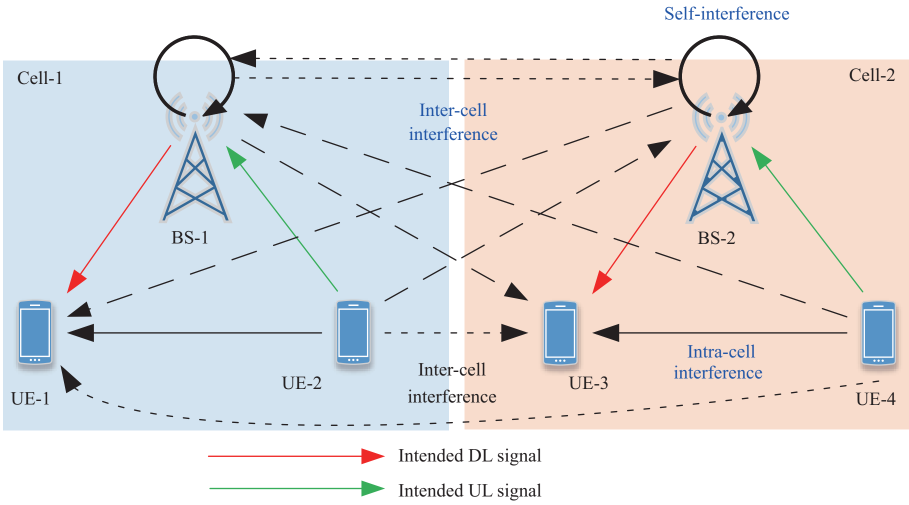

Figure 17 (Color online) Full-duplex networking.

• **SIC equipment minimization.** Small and lightweight SIC components, low power consumption, and low costs play an important role in implementing full-duplex in terminals, such as phones and laptops. In this regard, miniaturized high-isolation transceiver antennas and chip-based RF interference cancellation modules are essential for full-duplex terminals.

3.6.2 *Networking technology*

Another key technology of full-duplex is networking. A key challenge in full-duplex networking is the interference cancellation among base stations and UEs (Figure 17). Complex multi-point to multi-point interference is formed between base stations, and the high transmit power of the base station reduces the uplink signal-to-interference-plus-noise ratio (SINR). In addition, when uplink and downlink transmissions occur simultaneously in one cell, the uplink user transmission interferes with the downlink user reception. Especially in the case of MU-MIMO, multiple uplink users cause complex interference to downlink users, reducing the downlink SINR. To address the above-mentioned challenges, powerful network coordination capabilities and joint uplink and downlink optimization are required to improve the user experience of the entire network. Therefore, research is needed in the following directions.

• **Advanced inter-base station interference cancellation technology.** It is necessary to study the mechanism that enables channel estimation and interference cancellation between base stations, such as inter-base station channel estimation technology combining centralized radio access network (C-RAN) and air interface, and interference suppression technologies, such as beamforming of base stations with large-scale antenna arrays and downlink power control.

• **Uplink and downlink coordinated scheduling.** Realizing the joint optimization of uplink and downlink user performance through user pairing, base station and user power control, beam management, etc. For complex networking scenarios, AI can be used to realize intelligent scheduling based on location to reduce the huge overhead of channel and interference information acquisition.

In conclusion, compared with traditional duplex modes, such as FDD and TDD, the co-frequency co-time full-duplex technique facilitates simultaneous transmission and reception at the same carrier frequency, achieving much higher spectral efficiency as well as flexibly and optimally configuring transmission resources. Considering the commercialization of co-frequency co-time full-duplex, the following technical challenges should be addressed: suppression of high-power dynamic self-interference signal, novel interference-elimination mechanism under full-duplex systems, novel networking designs that support the coexistence of TDD or FDD systems [4].

3.7 Holographic radio technology

The 6G network will be a common ultra-broadband mobile network with ultrahigh data rates, ultrahigh data density (uHDD), and ultralow latency, which can support data exchange and computing collaboration among high-performance super-intelligent terminals. Intelligent driving and intelligent industrial

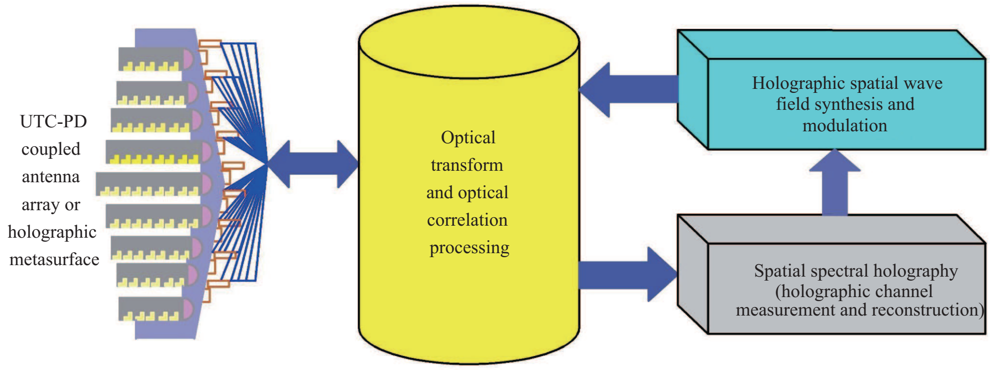

Figure 18 (Color online) Conceptual block diagram of holographic radio.

revolution have core requirements for 6G that create ubiquitous mobile ultra-broadband (uMUB), ultra-broadband with low latency (uBBLLC), and uHDD. These services require an end-to-end collaborative design of communication, sensing, and computing, causing challenges in computing capabilities, energy efficiency, and latency. Therefore, 6G, as a new generation of mobile communication systems, needs new theories and paradigms, as well as innovative technological breakthroughs [45, 46]. In addition, compared with 5G, 6G will have denser network deployment. The reduction of cell size and more antennas would result in more severe intra- and inter-cell interference. Traditional interference cancellation technology is no longer optimal, and innovative interference-processing methods are needed. A potential innovative approach is the holographic radio technology, which leverages interference as a useful resource to develop high-efficiency and high-precision holographic communication systems [46].

Holography, based on electromagnetic wave interferometry, records the electromagnetic field in space. It reconstructs the target electromagnetic field with the information recorded by the interference of the reference and signal waves. In holography, it is key that reference waves strictly cohere, and the holographic recording sensor must be able to record the continuous wavefront phase of the signal wave to accurately record high-resolution holographic electromagnetic fields [47]. Since both RF and light waves are electromagnetic waves, holographic radio is very similar to optical holography. Intelligent holographic radio (IHR) uses the holographic interferometry principle of electromagnetic waves to realize dynamic reconstruction and real-time precision control of electromagnetic space. Through RF spatial spectrum holography and holographic space wave-field synthesis technology, IHR realizes 3D holographic imaging level, pixel-based ultrahigh-resolution spatial multiplexing, and provides nearly continuous and nearly infinite multiplexing space, which can meet the 6G ultrahigh spectral efficiency, high data density, and capacity requirements [48]. As Fourier optics and optical holography are mature, optical signal processing techniques, such as fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT), can be employed to process RF signals. In the uplink, spatial spectrum holography employs the microwave photonic technique to perform coherent optical up-conversion and processing on the received RF signals and complete RF-to-optical mapping and correlation processing. This process is similar to real-time 3D RF "light"-field imaging. Holographic channel measurement and spatial reconstruction of RF holography are realized simultaneously by spatial spectrum holography, which can provide accurate feedback for space wave field synthesis and modulation in the downlink. In the downlink, space wave-field synthesis and modulation perform space-time precoding based on RF holographic space established by spatial spectrum holography in the uplink to realize complex and accurate structural distribution of the electromagnetic wave field in the target space. The entire process is similar to the "light"-field projection of real-time RF holography (see Figure 18).

Among the three capabilities of holographic radio, RF holography, spatial spectrum holography, and spatial wave field synthesis, the last two can modulate and adjust the electromagnetic fields of the whole physical space in a full closed loop. This greatly improves the spectral efficiency and network capacity and integrates imaging, sensing, and positioning into wireless communication [49]. In addition, IHR applies to very-near-field communication and wireless energy transmission in distributed scenarios owing to its evanescent wave property. The flexibility of IHR can be increased by deploying several holographic meta-surfaces (Huygens' meta-surface antennas) at ultra-low cost and power consumption and using distributed antenna systems as signal sources. As an interdisciplinary technology, IHR integrates wireless communication, microwave photonics, optical computing, computational electro-magnetics and computational holography, RF tomography, and integrated photonics. It is a broad field open for study, especially its unexplored techniques.

Holographic radio can not only realize RF holography, spatial spectrum holography, and spatial wave field synthesis but also precisely modulate and adjust the electromagnetic field of the entire physical space in a full closed loop through spatial spectrum holography and spatial wave field synthesis, which greatly improve the spectral efficiency and network capacity and integrate imaging, sensing, positioning, and wireless communication [49]. In addition, IHR can be applied to near-field communication and wireless energy transmission in distributed scenes owing to its evanescent wave characteristics. By deploying several ultralow-cost and -power-consumption holographic super surfaces (Huygens super surface antenna) and distributed antenna systems as signal sources, a more flexible IHR solution can be realized. As an interdisciplinary technology, IHR integrates wireless communication, microwave photonics, optical computing, computational electromagnetics and computational holography, RF tomography, and integrated photonics. However, many technologies still need to be researched [50].

3.7.1 *Filled-aperture active antenna array*

As mentioned above, holographic radio accurately reconstructs high-resolution holographic electromagnetic fields by recording the continuous wavefront phase of the signal waves. A filled-aperture antenna array is needed to receive and measure the continuous wavefront phase. To realize a continuous aperture antenna array, when the traditional discrete interval antenna array is used, the number of oscillators is nearly infinite, which is unrealistic, and the size, weight, and power (SWaP) of the system are unacceptable. Another scheme is to integrate several antenna elements into a compact space in the form of a spatial continuous electromagnetic aperture, but this method is limited to passive super surfaces because ultradense elements cannot realize RF feed networks.

This can be overcome using an ultra-broadband tightly coupled array (TCA) based on the current sheet. In TCAs, a uni-traveling-carrier photodiode (UTC-PD) is bonded to the antenna elements using the flip-chip technique to couple antenna oscillators [51]. The patch oscillator is directly integrated into the electro-optic modulator (EOM) [52]. The output current of UTC-PD directly drives the antenna oscillator, so the entire active antenna array has a very large bandwidth (about 40 GHz). Moreover, this innovative solution eliminates the need for an ultradense RF feed network. It is achievable and has obvious advantages in SWaP. Although UTC-PD tightly coupled antenna arrays can transform the limited beam space of traditional antenna arrays into nearly infinite and continuous multiplexing space, there is still a long way to go before practical applications. The main future research directions include high-power UTC-PD and advanced electro-optic modulator technology, electromagnetic theory and analysis models of integration and packaging of photodiode and EOM tightly coupled holographic antenna arrays, transparent fusion and seamless integration of UTC-PD tightly coupled antenna array and optical signal processing or optical computing transparent fusion and seamless integration, etc. In addition, RIS antenna, another form of holographic radio antenna, is an important research direction.

3.7.2 *Holographic radio channel modeling*

Unlike traditional large-scale MIMO, holographic radio uses Fresnel Fraunhofer interferometry, diffraction, and spatial correlation models, instead of the traditional Rayleigh propagation model, to model and compute holographic radio space. Accurate calculations of communication performance require detailed electromagnetic numerical calculations, i.e., algorithms and tools of computational electromagnetics and computer-generated hologram, instead of zero-forcing, maximum ratio combining (MRC), and minimum mean-square error (MMSE) in MIMO. Potential research directions on holographic radio theory and modeling include holographic radio theory and modeling based on FFT, the convolution theorem, green function, and sparse sampling, and compressed sensing Holographic radio theory and modeling based on coded aperture correlations.

3.7.3 *Integration of holographic radio and AI*

Holographic radio can not only realize RF holography, spatial spectrum holography, and space wave field synthesis but also precisely modulate and adjust the electromagnetic field of the entire physical space in a fully closed loop. It can greatly improve spectral efficiency and network capacity and integrate imaging, positioning, and wireless communication [49]. The generation and perception of extremely wide spectra and holographic radio frequency would produce massive data, which can provide big data and radio frequency spectrum datasets, enabling effective ML training. However, low-latency, high-reliability, and scalable artificial intelligence architectures should be developed. 6G systems will integrate full-spectrum, artificial intelligence, and RF holography. If only traditional electronic signal processing and computing are adopted, its SWaP and latency will be a big challenge. A hierarchical and heterogeneous optoelectronic computing and signal processing architecture would be an optimal solution for providing the required energy efficiency, latency, and flexibility in 6G [53–55]. Holographic radio achieves ultrahigh coherence and high parallelism of signals through coherent optical conversion of UTC-PD-integrated TCAs, facilitating direct processing of signals in the optical domain. Considering that optical computing is more suitable for linear computing [56], and more than 90% of holographic radio signal processing is linear computing, performing most of the linear computing in real-time in the optical domain is key to providing high energy efficiency and low latency over 6G air interfaces. Therefore, to integrate holographic radio and AI, it is necessary to study an effective hybrid optoelectronic computing architecture and strengthen the research on large-scale photonic integration [11] and electro-optic hybrid integration technology.

In summary, the holographic radio can dynamically reconstruct electromagnetic space with real-time precision control and provide a quasi-continuous and -infinite multiplexing space. With the provided ultrahigh-resolution spatial multiplexing, holographic radio can be used in wireless access, which requires ultrahigh capacity/traffic density and ultralow latency, for example, enabling wireless industrial buses operating in ultrahigh traffic density in smart factories. However, there are still some research challenges to be addressed before commercialization, including the study of the fundamental theories and modeling, hardware and physical layer design issues, integration of filled-aperture active antenna arrays, and high-performance optical computing based on microwave photonics.

3.8 Ultralow-power IoT communications

6G networks will support trillions of devices, which are driven by the surge of IoT devices covering several applications, such as smart cities, healthcare, and smart farms. An important category of applications needs to deploy power-constrained devices that can work for prolonged periods, even several decades. In these applications, devices are inaccessible, or it is difficult or expensive to reach them once they are installed. A typical use case is smart farms, where numerous devices need to be deployed, and they cannot be maintained or replaced. However, one major drawback of existing IoT solutions is the batteries need to be frequently replaced due to their communication power consumption. Therefore, there is an urgent need to develop novel communication technologies and system-level operational paradigms to enable batteries with life spans of up to the life cycle of an IoT device, thereby facilitating cellular networks to provide ubiquitous IoT connectivity for trillions of everyday objects.

Take backscatter communication (BackCom) technology as an example of extremely-low-power communication [57, 58]. A BackCom device can convey its data by reflecting and modulating an ambient or incident RF signal by switching antenna impedance. Without power-hungry and expensive radio components, BackCom devices can operate at sub-milliwatt power consumption, and they can be manufactured at extremely low cost. In addition, based on BackCom, symbiotic radio (SR), proposed in [59–61], can be used to enable the BackCom and primary systems to benefit from each other. The key idea of SR is to leverage cognitive radio to make BackCom and primary systems work at the same spectrum and create multipath to boost the performance of primary systems by BackCom devices. Thus, BackCom has attracted significant interest from both the academic and industry communities. However, to accommodate a practical BackCom system in cellular networks, the following technology issues must be addressed.

First, with power constraints and low-end hardware, BackCom devices cannot employ traditional physical-layer technology, and thus, it is necessary to develop new physical-layer technology for BackCom systems. The main study points may include: to investigate new modulation schemes and the corresponding SR technology so that both RF sources (e.g., cellular signal) and backscattered signals can be separated at the receiver side, avoiding their interference; to develop low-complexity coding techniques that can provide reliable transmission for resource-constraint BackCom devices; to evaluate the sources of excitation signals, including dedicated excitation devices, relays, and ambient signals.

Second, it is necessary to investigate new networking and media-access-control layer (MAC-layer) protocols to integrate BackCom with short ranges into wide-area cellular systems. Key research directions include: (1) to introduce efficient multiple access methods to boost the resource utilization efficiency of uplink and downlink to develop an appropriate network architecture so that the communication distance can be extended; (2) to design a low-complexity and robust security protocol to thwart security attacks, such as eavesdropping and jamming.

Third, low-complexity signal processing algorithms and circuits also need to be considered to further reduce power consumption. For example, low-power baseband chips and oscillators can be used to well balance the tradeoff between power consumption and communication rates, and a passive envelope detector can be devised to wake up BackCom devices with extremely low power consumption.

In summary, BackCom can reduce power consumption in communication to the sub-milliwatt level, making it a competitive technology for IoT applications in 6G networks. However, since BackCom is a passive communication manner, it is difficult to directly apply traditional communication algorithms to BackCom. There are several important open research problems, including new air-interface technology, low-complexity signal processing schemes, lightweight networking, and MAC-layer protocol designs.

4 Conclusion

With the scaled commercial deployment of 5G networks, the global industry has initiated the exploration of 6G. However, in general, 6G studies are still at the early stage. In this article, we present our vision on 6G with a particular focus on the key candidate enabling technologies, including THz communication, integrated sensing and communications, integrated intelligence and communication, ultramassive MIMO, reconfigurable intelligent surface, co-frequency co-time full-duplex, holographic radio, and ultralow-power IoT communication. Considering the industrialization and standardization promotion, potential application scenarios and challenges are analyzed, the main research directions are highlighted, and future research opportunities are identified. This study can provide a good reference for both academia and the industry to prompt the rapid development of 6G.

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