A Promising Technology for 6G Wireless Networks: Intelligent Reflecting Surface

Wenxuan Long, Rui Chen, Marco Moretti, Wei Zhang, Jiandong Li

***Abstract*—The intelligent information society, which is highly digitized, intelligence inspired, and globally data driven, will be deployed in the next decade. The next 6G wireless communication networks are the key to achieve this grand blueprint, which is expected to connect everything, provide full dimensional wireless coverage and integrate all functions to support full-vertical applications. Recent research reveals that intelligent reflecting surface (IRS) with wireless environment control capability is a promising technology for 6G networks. Specifically, IRS can intelligently control the wavefront, e.g., the phase, amplitude, frequency, and even polarization by massive tunable elements, thus achieving fine-grained 3-D passive beamforming. In this paper, we first give a blueprint of the next 6G networks including the vision, typical scenarios, and key performance indicators (KPIs). Then, we provide an overview of IRS including the new signal model, hardware architecture, and competitive advantages in 6G networks. Besides, we discuss the potential application of IRS in the connectivity of 6G networks in detail, including intelligent and controllable wireless environment, ubiquitous connectivity, deep connectivity, and holographic connectivity. At last, we summarize the challenges of IRS application and deployment in 6G networks. As a timely review of IRS, our summary will be of interest to both researchers and practitioners engaging in IRS for 6G networks.**

***Keywords*—6G, beyond 5G (B5G), intelligent radio environment, reconfigurable metasurface, intelligent reflecting surface (IRS)**

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I. INTRODUCTION

The fifth generation (5G) wireless communication networks have basically completed the preliminary basic tests, the construction and standardization of hardware facilities, and would be deployed globally from 2020. Compared with the fourth generation (4G) wireless communication networks, 5G networks have achieved revolutionary advancement in data rate, latency, reliability, mobility, and large-scale connectivity[1], which can achieve 20 Gbit/s peak data rate, 0.1 Gbit/s user experience data rate, 1 ms end-to-end latency and support 500 km/h mobility, 10^6 devices/km^2 connection density, 10 Mbit/$(\mathrm{s} \cdot \mathrm{m}^2)$ area traffic capacity. IMT 2020 has been proposed the three main communication scenarios of 5G networks: enhanced mobile broadband (eMBB), large-scale machine type communication (mMTC), and ultra-reliable and low-latency communication-interaction (uRLLC). To improve the communication performance, 5G networks apply various advanced technologies, such as the millimeter wave (mmWave), massive multiple-input multiple-output (MIMO), and ultra-dense network (UDN)[2]. However, the key technologies applied in 5G networks, such as UDN and massive MIMO, will bring high hardware costs and huge energy consumption expenditures[3,4]. Therefore, how to reduce hardware costs and energy consumption becomes a key issue that needs to be solved urgently in next-generation communication networks.

With the global commercialization of 5G networks, research institutions at home and abroad have begun to set their sights on the sixth generation (6G) wireless communication networks. In 2017, the European Union launched a three-year research project on the basic 6G technologies[5]. In 2018, Finland announced a research program "6Genesis" aiming at developing, implementing, and testing key enabling technologies for 6G networks[6]. Besides, the United States and the

United Kingdom have invested in some potential techniques for 6G networks such as terahertz (THz)-based communications and quantum technology[7].

The key drivers of 6G networks result not only from the challenges and performance limits that 5G networks present but also from the growing demand for wireless networks and the technology-driven paradigm shift. The intelligent information society[8] creates core requirements for 6G networks that will lead to the vision of intelligent connectivity, ubiquitous connectivity, deep connectivity, and holographic connectivity. Meanwhile, 6G networks will largely enhance and expand application scenarios on the basis of 5G networks. It is reported in Ref. [9] that ubiquitous mobile ultra-broadband (uMUB), ultra-high data density (uHDD) and ultra-high-speed with low-latency communications (uHSLLC) will become the main communication scenarios of 6G networks. The rapid growth of emerging applications has led to a surge in mobile data traffic. Therefore, the key performance indicators (KPIs) for 6G networks should be improved greatly to meet upcoming services. It is reported in Ref. [10] that the peak rate of 6G networks can be 1∼10 Tbit/s, the connection density can be up to 10^7 devices/km^2 and the energy efficiency is 10∼100 times compared to 5G networks. In order to provide satisfying services for the intelligent information society in the future, 6G networks need to further enhance their scalability, flexibility, and efficiency by embracing novel techniques. Like the emergence of many new technologies when the wireless world moves toward 5G networks, the new requirements of 6G networks will influence the main technology trends in its evolution process. In many potential technologies, the intelligent reflecting surface (IRS), benefited from the breakthrough in the manufacture of programmable meta-material, is conjectured as a crucial enabling technology for 6G networks to achieve intelligent radio environments.

In the existing 5G networks, the channel environment is uncontrollable and modeled by probability[11,12], which is a major limiting factor for wireless communication networks. Specifically, since mmWave frequencies have been allocated to 5G networks, high directivity makes mmWave communications vulnerable to blockage resulting in unstable network performance. To improve the performance of wireless networks, the concept of an intelligent information network with the controllable channel environment is proposed in 6G networks, in which IRS is an essential technology to address the blockage issue and realize uninterrupted wireless connectivity for mmWave and THz networks[7,9,13-19]. Generally, IRS is a planar antenna array that consists of a large number of low-cost passive reflecting elements, in which each element can intelligently reconfigure the amplitude, phase, frequency, and polarization of incident signals in real time and then reflects the specified receiver to enhance signals and suppress interferences. The typical architecture of IRS is shown in Fig. 1.

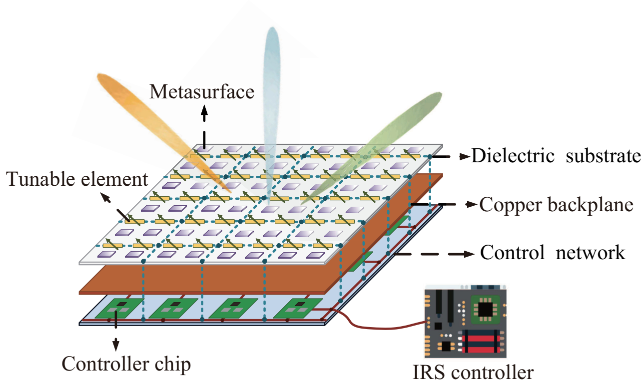

Fig. 1 The architecture of IRS

As a new concept, IRS is first proposed in 2017[20] and has attracted wide attention in the wireless communication fields[21-30]. In 2018, the authors in Refs. [21,22] prove IRS technology can be applied in wireless data transmission and position estimation for the first time. In the same year, the authors in Refs. [23,24] propose a novel IRS-assisted wireless communication network, which opens a new wireless communication paradigm. In 2019, the authors in Ref. [25] design and realize the IRS-assisted wireless communication system, which achieves a 2.048 Mbit/s data transfer rate with video streaming transmission over the air. In the same year, the authors in Ref. [26] propose an IRS-based 8-phase shift-keying (8PSK) wireless transmitter with 8×32 phase adjustable unit cells, which can achieve a 6.144 Mbit/s data rate over the air at 4.25 GHz with less hardware complexity. Besides, the authors in Ref. [27] propose an IRS-based resource allocation method for the downlink multi-user communication system, which is able to provide up to 300% higher energy efficiency in comparison with the use of regular multi-antenna amplify-and-forward relaying. In 2020, the authors in Ref. [28] propose IRS-space shift keying (IRS-SSK) and IRS-spatial modulation (IRS-SM) schemes, which bring the concept of IRS-assisted communications to the realm of index modulation (IM) for the first time. In the same year, the authors in Ref. [29] propose and develop a new type of high-gain yet low-cost IRS that can achieve 21.7 dBi antenna gain at 2.3 GHz and 19.1 dBi antenna gain at 28.5 GHz. Besides, the authors in Ref. [30] design an IRS-assisted radio-frequency (RF) sensing system for posture recognition, which has 23.5% higher recognition accuracy than the traditional RF sensing system due to the environment control capability of IRS. The above results have laid the foundation for the application of IRS in 6G networks.

It is worth noting that the IRS is different from other related technologies currently employed in wireless networks, such as relaying and backscatter communications[31]. Details will be provided in the sequel, but it suffices to say that IRS has the following distinguishable features.

- *Nearly passive:* IRS composes of a large number of low-cost passive reflecting elements that are only used to reflect signals and do not need to transmit signals. Hence, IRS is nearly passive, and, ideally, does not need any dedicated energy source.
- *Programmable control:* IRS can control the scattering, reflection, and refraction characteristics of the radio waves by programs, thus overcoming the negative effects of natural wireless propagation. Hence, IRS-assisted wireless communications can intelligently control the wavefront, such as the phase, amplitude, frequency, and even polarization, of the impinging signals without the need for complex decoding, encoding, and radio frequency processing operations.
- *Good compatibility:* IRS can be integrated into the existing communication networks only by changing the network protocol without changing hardware facilities and software of their devices. Meanwhile, IRS has a full-band response, which can work at any operating frequency ideally.
- *Easy deployment:* IRS is characterized by small size, light weight, conformal geometry, and thinner than wavelengths, which is easier to install and dismantle. Hence, IRS can be easily deployed, e.g., on the outside walls of buildings, billboards, ceilings of factories and indoor spaces, human clothing, etc.

These unique characteristics make IRS-assisted communications a distinctive technology, which can be regarded as the key to realize the intelligent information society in 6G networks. The application of IRS in 6G networks will be discussed and elaborated in the sequel.

The rest of this paper is summarized as follows. In section II, we summarize the vision, typical scenarios, and KPIs of 6G networks. In section III, an overview of the IRS technology is provided including the new IRS-assisted system model, the hardware architecture of IRS, and competitive advantages in 6G networks. Based on the vision of 6G networks, we propose a general idea of IRS-assisted 6G wireless networks and force on the application of IRS in the connectivity of 6G networks in section IV, the challenge of IRS application and deployment in 6G networks and the conclusion are summarized in section V.

II. 6G Networks: Vision, Usage Scenarios and Requirements

The intelligent information society, which is highly digitized, intelligence inspired, and globally data driven, will be deployed in the next decade[8]. 6G networks are the key to achieve this grand blueprint, which is expected to offer the connection for everything, full wireless coverage, and the integration of all functions so that it can support full vertical applications[10]. Hence, 6G networks are required to process a very high volume of data in near real time, with extremely high throughput and low latency. In the following, we summarize the vision, typical scenarios, and KPIs of 6G networks.

A. Vision

The development of an intelligent information society is the driver for 6G networks that will ubiquitously support high-precision and holographic communications for upcoming intelligent information services to provide a full sensory experience. Overall, the vision of 6G networks can be split into four main points[14,15].

- *Intelligent connectivity:* 6G networks will be an autonomous system with human-like intelligence, which will provide multiple ways, such as through voice, eyes, and brain waves, to interact with intelligent terminals. Therefore, "intelligent connectivity" will require simultaneously: 1) intelligent management should be provided for the complex network, 2) all the related connected devices are intelligent, and 3) the related information services need to be intelligent.
- *Ubiquitous connectivity:* With the rapid development of aerospace and deep-sea exploration technologies, the active space of human beings and intelligent devices will be expanded greatly, which puts higher requirements on the coverage of communication networks. Therefore, one goal of 6G networks is to achieve ubiquitous connectivity by integrating satellite communications, aerial communications, terrestrial communications, and underwater communications to provide global coverage[7,32].
- *Deep connectivity:* With the development of intelligent information services, such as the intelligent Internet of things (IoT), the types and scenarios of information interaction are becoming more and more complex. There is reason to believe that the information interaction in 6G networks will be greatly expanded in both space and information types. Therefore, "deep connectivity" will require simultaneously: 1) the active space of each connected intelligent devices is expanded in depth, and 2) the network itself has the ability of deep sensing, deep learning, and deep mind, which is expected to realize the mind-to-mind interaction with intelligent devices.
- *Holographic connectivity:* With the dramatic increase of augmented reality (AR) and virtual reality (VR) techniques, the form of information interaction in the next decade will likely evolve into high-fidelity VR/AR interaction, and even the holographic information interaction. Therefore, 6G networks will be required to provide ubiquitous high-fidelity VR/AR services and even support holographic communications.

In sum, 6G networks will be further developed and strengthened on the basis of the existing 5G networks, and truly realize ubiquitous intelligent interaction between human beings and everything, which is "wherever you think, everything follows your heart". The vision of 6G networks is illustrated in Fig. 2(a).

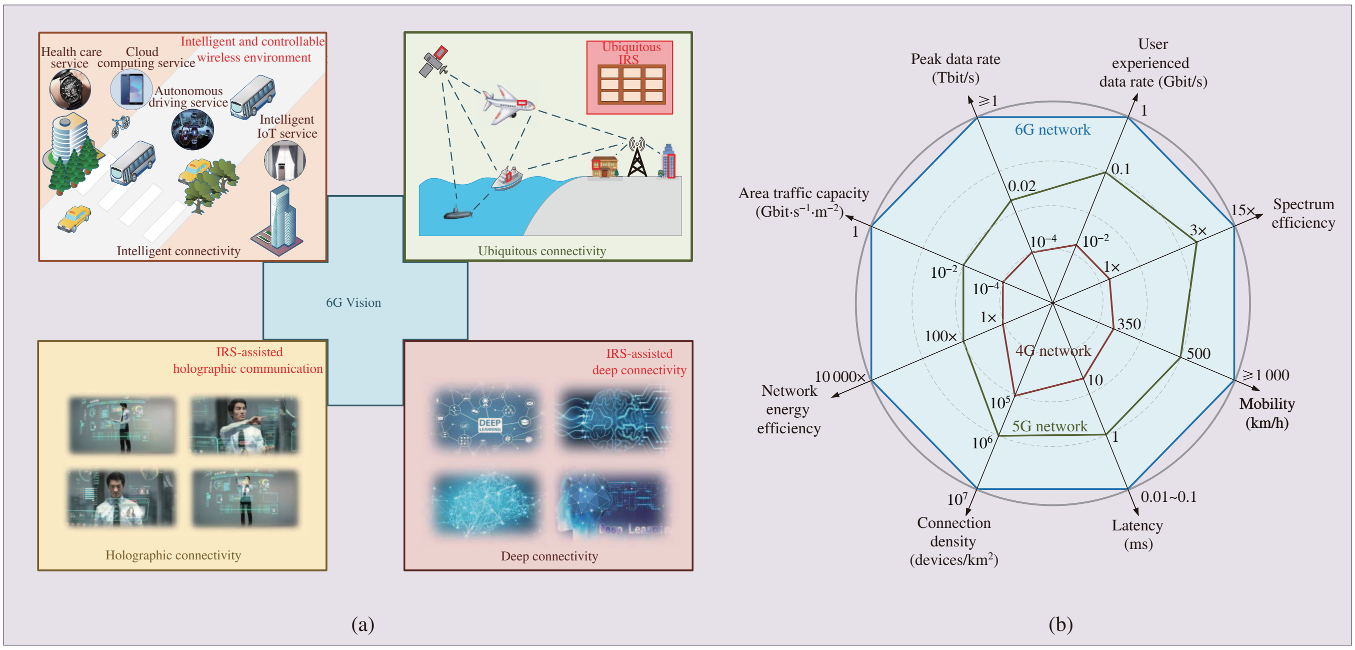

Fig. 2 The blueprint of 6G networks: (a) the vision of 6G networks with IRS technology; (b) the KPI comparison of 4G, 5G, and 6G networks

B. Typical Scenarios

As all known, 5G networks mainly focus on eMBB, mMTC, and uRLLC, while the goal of 6G networks is to further enhance and extend the application scenarios. In Ref. [9], the typical scenarios of 6G networks are summarized as uHDD, uMUB, and uHSLLC. The uMUB enables 6G networks to deliver any required performance within the space-aerial-terrestrial-underwater area, uHSLLC provides ultra-high rates and low latency, and uHDD meets the requirements of the data density and high-reliability. Similarly, in Ref. [10], the authors named the enhanced three scenarios in 6G networks as further-enhanced mobile broadband (FeMBB), ultra-massive machine-type communications (umMTC), and enhanced-uRLLC (euRLLC). Apart from the three main scenarios, several other scenarios, such as extremely low-power communications (ELPC), long-distance and high-mobility communications (LDHMC), and intelligent IoT, are also promising in 6G networks[10,33].

C. Core Requirements

Emerging intelligent information services are the driving force behind the evolution of wireless communication networks. The rapid development of emerging services, such as e-health, intelligent IoT and autonomous driving, results in an explosive growth in mobile data traffic, which will eventually exceed the limit of 5G networks. It is reported that 5G networks will reach their limits in a decade[7]. To meet the coming challenges, the KPIs for 6G networks will be as follows[10].

- The peak data rate is at least 1 Tbit/s[34], which is 50 times that of 5G networks. For THz-based 6G networks, the peak data rate is expected to reach up to 10 Tbit/s[34].
- The user experience data rate is up to 1 Gbit/s, which is 10 times that of 5G networks. For some special scenarios, such as indoor hotspots, the user experience data rate is expected to reach up to 10 Gbit/s.
- The end-to-end latency is reduced to 10∼100 µs and the mobility is at least 1 000 km/h, which is expected to provide potential applications for hyper-HSR and airline systems.
- The connection density is up to 10^7 devices/km^2 and the area traffic capacity is up to 1 Gbit/(s $\cdot$ m^2), which is 10 times that of 5G networks.
- The 10∼100 times energy efficiency and the 5∼10 times spectrum efficiency compared to 5G networks.

Upcoming intelligent information services have more stringent requirements for the KPIs of wireless communication networks. To satisfy typical scenarios and applications for the intelligent information society, 6G networks are required to provide superior network performance. Fig. 2(b) compares the KPIs of 4G, 5G, and 6G networks. In order to achieve the aforementioned system performance metrics, lots of novel enabling technologies, such as THz communications[34], ultra-large-scale antenna arrays (i.e., UM-MIMO)[35], OAM multiplexing[36,37], and IRS[38] will be used in 6G networks. In many technologies of 6G networks, the most spectacular technology is IRS that can be widely deployed in 6G networks to achieve intelligent connectivity, ubiquitous connectivity, deep connectivity, and holographic connectivity. In the following, we will first introduce IRS technology and focus on the application of IRS in 6G networks.

III. Intelligent Reflecting Surface: Theory and Core Advantages

IRS is regarded as a promising technology that can intelligently reconfigure the channel environment with massive passive reflecting elements to effectively improve the performance of wireless communication networks. In this section, we summarize the IRS technology, involving the new IRS-assisted system model, the hardware architecture of IRS, and competitive advantage in 6G networks.

A. The IRS-Assisted Two-Ray System Model

As multi-path propagation exists in a typical wireless communication environment, received signals are the compound signals with unpredictable time attenuation and propagation delay. Due to the constructive and destructive summation of compound signals, received signals will be significant distortions. This effect, terming as fading, is a major limitation in the next wireless communication systems. The main purpose of using IRS is to realize a reconfigurable wireless environment, in which the highly probabilistic wireless channel is converted into a deterministic space by intelligently controlling the propagation of the electromagnetic (EM) waves in a software-controlled method[31].

For easier analysis, we first consider the two-ray channel model in the IRS-assisted single-input single-output (SISO) network as shown in Fig. 3, in which the received signal consists of two components: the line-of-sight (LoS) ray and the ray reflected from IRS. In the proposed model, IRS is made of $N\times N$ reconfigurable metasurfaces each of which can independently control the amplitude and phase shift of reflection, the distance between the transmit and receive antennas is denoted as d, and the distances between the (m,n)-th element of IRS and the transmit and receive antennas are denoted as $r^{\text{T-I}}_{m,n}$ and $r^{\text{I-R}}_{m,n}$ respectively, $m,n=1,2,\cdots,N$. Without loss of generality, we assume unit gain transmit/receive antennas and a narrow-band transmission signal[31], i.e., $x(t)=x(t-\tau_{m,n})$, where $x(t)$ is the complex baseband transmitted signal, $\tau_{m,n}=(r^{\text{T-I}}_{m,n}+r^{\text{I-R}}_{m,n}-d)/c$ is the relative time delay between the ray reflected from the (m,n)-th element of IRS and the LoS ray, c is the speed of light. Then, the received baseband signal can be expressed as

$$y(t)=\frac{1}{2k}\left(\frac{\mathrm{e}^{-\mathrm{i}kd}}{d}+\sum_{m=1}^{N}\sum_{n=1}^{N}\frac{\beta_{m,n}\mathrm{e}^{-\mathrm{i}k(r^{\text{T-I}}_{m,n}+r^{\text{I-R}}_{m,n})}}{r^{\text{T-I}}_{m,n}+r^{\text{I-R}}_{m,n}}\right)x(t)+z(t), \tag{1}$$

where $\mathrm{i}=\sqrt{-1}$ is the imaginary unit, $k=2\pi/\lambda$ is the wave number, λ is the wavelength, $\beta_{m,n}=A_{m,n}\mathrm{e}^{\mathrm{i}\theta_{m,n}}$ is the programmable reflection coefficient of the (m,n)-th element in

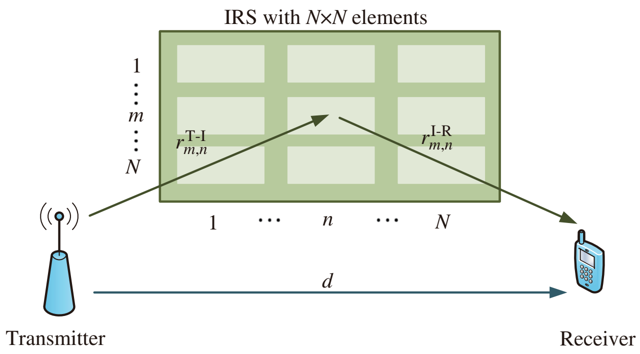

Fig. 3 The IRS-assisted two-ray channel model

IRS, $A_{m,n}\in[0,1]$ and $\theta_{m,n}\in[0,2\pi]$ are the reconfigurable amplitude and phase of $\beta_{m,n}$ respectively, $m,n=1,2,\cdots,N$, $z(t)$ is the related additive noise.

From (1), we can see that the received signal can be controlled and reconstructed spatially by IRS through smartly adjusting the reflection coefficients $\{\beta_{m,n}|m,n=1,2,\cdots,N\}$. For instance, each $\beta_{m,n}$ can be optimized so that the phase of the received signal from $N\times N$-element IRS is aligned with the phase of the LoS path, i.e., $\beta_{m,n}=A_{m,n}\mathrm{e}^{\mathrm{i}\theta_{m,n}}=\mathrm{e}^{\mathrm{i}k(r^{\text{T-I}}_{m,n}+r^{\text{I-R}}_{m,n}-d)}$, $m,n=1,2,\cdots,N$, and then, the received signal with maximum power can be obtained whose power P_r can be formulated as

$$P_r\overset{(a)}{\approx}P_t\left(N^2+1\right)^2\left(\frac{1}{4k^2d^2}\right), \tag{2}$$

where P_t is the power of the transmitted signal $x(t)$, and (a) assumes the distance d is large enough, i.e., $d\approx r^{\text{T-I}}_{m,n}+r^{\text{I-R}}_{m,n}$, $m,n=1,2,\cdots,N$[31].

In 6G networks, for further taking advantage of space division multiplexing, the number of antennas equipped on both the transmitter and receiver will be increased[5]. For example, the ultra-massive MIMO (UM-MIMO) technology with the transmit and receive antennas $(M_r,M_t)=(1024,1024)$ is utilized for THz communications in 6G networks[39]. For the LoS UM-MIMO network assisted by IRS, the received baseband signal vector can be written as

$$\boldsymbol{y}(t)=(\boldsymbol{H}_r\boldsymbol{B}\boldsymbol{H}_t+\boldsymbol{H}_{\text{LoS}})\boldsymbol{x}(t)+\boldsymbol{n}(t), \tag{3}$$

where $\boldsymbol{H}_t$ is the $N\times M_t$ channel matrix from the transmitter to IRS, $\boldsymbol{H}_r$ is the $M_r\times N$ channel matrix from IRS to the receiver, $\boldsymbol{H}_{\text{LoS}}$ is the $M_r\times M_t$ channel matrix from the transmitter to the receiver, $\boldsymbol{x}(t)$ and $\boldsymbol{n}(t)$ are the transmitted baseband signal vector and the corresponding noise vector, $\boldsymbol{B}=[\beta_{m,n}]_{N\times N}$ is the programmable reflection coefficient matrix of IRS. In the practical design of $\boldsymbol{B}$, many factors, such as elements' mutual coupling, noise, and hardware imperfections, need to be considered, and their impact on the performance of IRS is still an ongoing research topic.

B. Hardware Architecture

The hardware implementation of IRS is based on the concept of “metasurface”, which is a kind of ultrathin man-made material with sub-wavelength elements. Specifically, the metasurface is a planar array comprising a mass of passive scattering elements whose EM properties depend on their structural parameters, such as the geometry (e.g., square, split-ring or hexagon), size, orientation, and arrangement[3,38]. It is reported in Ref. [40] that a planar metasurface with 0.4 m^2 and 1.5 mm thickness consists of 102 controllable electromagnetic unit cells. Through proper external stimulation, the physical parameters of scattering elements can be altered, leading to the change of signal response of IRS without refabrication[41].

The typical architecture of IRS is shown in Fig. 1, which consists of an intelligent IRS controller and three layers[3]. In the outer layer, plenty of tunable elements embedded with metasurfaces are printed on the dielectric substrate to directly interact with incident signals. In wireless communication networks, the tunable elements are required to be able to reconfigure in real time to cater to dynamic channels arising from the user mobility[3], which can be achieved by some electronic devices. One candidate is a positive-intrinsic negative (PIN) diode that can be switched between “On” and “Off” states by different direct-current (DC) voltage to generate 0 and π phase shifts[42]. Another candidate is a varactor diode that can be adjusted continuously by regulating the reverse bias voltage[43]. Moreover, to avoid signal energy leakage, a copper backplane is set in the middle layer[3]. Last, the inner layer is a control network that is used to adjust the reflection coefficient of tunable elements. The control network can be an integrated network with multiple tiny controllers, in which each controller is only used to control one tunable element[44,45]. Each tiny controller in the integrated network is able to interpret external instructions and adjust the configuration of the tunable element to achieve the EM reconfiguration of IRS. Moreover, the control network can also be made up of a smaller group of controller chips, in which each controller chip serves several tunable elements[46]. All of the controller chips are interconnected locally and communicate wirelessly to the IRS controller. In practice, a field programmable gate array (FPGA) can be employed as not only the IRS controller but also a gateway to communicate and coordinate with other network devices, such as base stations (BSs) and terminals, through separate wireless links for low-rate information exchange with them[3,38].

C. Technology Comparison and Performance Advantages

When new technologies come into the spotlight, there is a responsibility to rigorously examine the potential benefits and limitations that they may offer compared to similar and mature technologies. Therefore, it is advisable to contrast IRS with transmission technologies that are likely to be bound up with them. The two technologies that are often deemed to be equivalent to IRS are relay-aided transmission and backscatter communications[31]. Hence, we will compare and analyze IRS, relay-aided communications, and backscatter communications in the following.

The common relay-aided communications include amplify-and-forward (AF) relay-aided communications and decode-and-forward (DF) relay-aided communications. Both relay-aided communication schemes require relay stations, which need a dedicated power source for operation, to process relay signals. The difference between AF relaying and DF relaying is that the relay signals are amplified and forwarded in the AF relay station[47] but decoded and forwarded in the DF relay station[48]. However, both of signal processing have high complexity, thus leading to high hardware complexity and energy consumption[48,49]. Moreover, the active electronic components used in relay stations are responsible for the presence of additive noise that negatively affects the performance of relaying communications[48]. Especially, the noise is amplified in AF relay stations.

Backscatter communications are a method for low-energy wireless communications using modulating signals scattered from a transponder (RF tag)[47]. Specifically, backscatter communications have no electronics for power harvesting or transmitting and only a switching mechanism or a variable load to modulate the wave reflections, which promises battery less or ultra-low power communications[50]. Besides, compared with the traditional schemes, the signal processing of backscatter communications is relatively simple, thus reducing the energy consumption and hardware complexity. However, the transmitted signal in backscatter communication systems is modulated and transmitted by the transponder, which may introduce additional noise.

It is worth noting that the proposed IRS differs significantly from all the above techniques. Firstly, compared with relaying that assists transmission by actively generating new signals, IRS reflects the incident RF signals by the massive passive reflecting elements without the transmitter module[47], which thus do not incurs additional power consumption and noise. For example, the IRS with 256 elements designed in Ref. [51] consumes only about 0.72 W, significantly lower than that of the active relaying in practice. Meanwhile, IRS usually operates in the full-duplex (FD) mode and thus has higher spectrally efficiency than relaying operating in the half-duplex (HD) mode. Secondly, different from traditional backscatter communications, IRS is utilized mainly to enhance the existing communication link performance instead of delivering its own information by reflection[47]. Therefore, the direct-path in IRS-assisted communications does not need to be suppressed and can also carry the same useful information as the reflect-path to maximize the total received power. Moreover,

Tab. 1 Comparison of IRS with other related technologies

Technology	Role	Duplex	Power budget	Noise	Compatibility	Interference	Hardware complexity	Energy consumption
IRS	Helper	Full duplex	Passive low	No noise	Very high	Very low	Very low	Low
AF relaying	Helper	Half/Full duplex	Active high	Additive noise	Low	High	High	High
DF relaying	Helper	Half/Full duplex	Active high	Additive noise	Low	High	High	High
Backscatter communications	Source	Full duplex	Active very low	Additive noise	Low	High	Low	Very low

IRS possesses other advantages, such as easy deployment, good compatibility with existing networks, and having full-band response[31,52]. A more detailed comparison between the above technologies and IRS is summarized in Tab. 1.

Based on the above advantages, IRS naturally becomes a promising technology for the next 6G networks. In the following, we will mainly discuss the performance advantages of IRS-assisted wireless networks over traditional wireless networks without IRS to predict the performance of IRS-assisted 6G networks. In Ref. [53], an IRS-assisted THz MIMO system is proposed to mitigate blockage vulnerability in indoor scenarios, in which IRS is used to control the propagation direction of the THz beam and enhance the coverage performance by intelligently adjusting the phase shifts of reflecting elements. The simulation results show that the data rate of IRS-assisted THz MIMO system is improved by about 45% over the traditional THz system without IRS. In Ref. [54], a novel feedforward fully connected structure based deep neural network (DNN) scheme is designed and applied in IRS-assisted THz communications, which has the ability to output the optimal phase shift configurations assisted by the estimated channel parameters. The simulation results show that the DNN-based IRS scheme achieves a near-optimal communication rate performance, reaching 190% of that in the non-IRS-assisted network. Besides, the authors in Ref. [55] design an IRS-assisted mobile edge computing (MEC) system that is capable of significantly outperforming the conventional MEC system operating without IRS. Quantitatively, about 20% computational latency reduction is achieved over the conventional MEC system. Moreover, in Ref. [56], a multi-user multiple-input single-output (MISO) communication scheme with a large IRS is proposed, which can provide significant energy efficiency gains compared to conventional relay-assisted communications. Specifically, the energy efficiency of an IRS-assisted system is about 45% higher than that of the relay-assisted system. Meanwhile, the authors in Ref. [29] indicate that, compared with the conventional multi-antenna AF relaying, the IRS-assisted wireless network can provide up to 300% energy efficiency. Moreover, the authors in Ref. [57] indicate deploying large-scale IRS in the point-to-point MISO communication system is more efficient than increasing the antenna array size for enhancing the spectral efficiency. Specifically, the average spectral efficiency of the IRS-assisted system is improved by about 6.7% compared with the traditional system without IRS. In Ref. [58], a new sum-path-gain maximization (SPGM) criterion is proposed and applied in the IRS-assisted point-to-point MIMO system, and the simulation results show that the spectral efficiency of IRS-assisted system with SPGM criterion is improved by nearly 40% compared with the non-IRS-assisted system. In Ref. [59], the authors discuss the main performance gains of IRS-assisted massive MIMO non-orthogonal multiple access (NOMA) networks. Specifically, the achievable rate of the far user in IRS-NOMA system is improved by more than 6 times when compared with that achieved in MIMO-NOMA, and the energy efficiency of IRS-NOMA system is also greatly improved. Based on the above discussion, there are reasons to believe that compared with the existing 5G networks, the performance of IRS-assisted 6G networks, such as data rates, spectrum efficiency, and energy efficiency, will be greatly improved due to the powerful environmental control capacity of IRS, and the main performance advantages of IRS-assisted networks are summarized in Tab. 2.

IV. IRS-Assisted 6G Wireless Networks

With its flexibility in deployment and reconfiguration, low implementation cost, and low power consumption, IRS is expected to improve the transmission performance in the next 6G wireless networks. In this section, we propose a general idea of IRS-assisted 6G wireless networks including intelligent and controllable wireless environment, ubiquitous connectivity supported by IRS, IRS-assisted deep connectivity, and IRS-assisted holographic communications.

Tab. 2 Performance advantages of IRS-assisted wireless network

Performance	IRS-assisted wireless network
Data rate	Up to 190% of the non-IRS-assisted network[55]
Latency	20% lower than the non-IRS-assisted network[55]
Energy efficiency	Up to 300% of the non-IRS-assisted network[29]
Spectrum efficiency	40% higher than the non-IRS-assisted network[58]

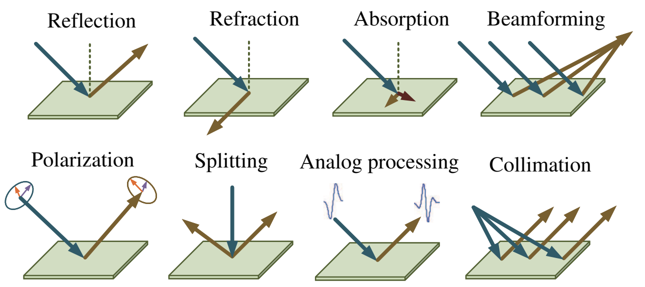

Fig. 4 Electromagnetic-based elementary functions[63]

A. *Intelligent and Controllable Wireless Environment*

The first to the fifth generation wireless communication networks have been designed by assuming that wireless channels between communicating devices are decided by various uncontrollable physical environments, e.g., outdoor urban/suburban environment and indoor environment[60-62]. A number of channel models have been proposed for different environments and frequencies, which are assumed to cannot be modified and reconstructed, and can be only compensated through sophisticated transmission and reception schemes. However, in 6G wireless networks, the improvements that can be expected by operating only on the end-points of the wireless environment are not likely to be sufficient to meet the challenging KPI requirements of ultra-high throughput, ultra-low latency, and ultra-high reliability. Therefore, IRS can be proposed as the breaking technology of turning the wireless environment into an optimization variable, which can be controlled and programmed rather than just adapted to.

The EM control functions of IRS include reflection, refraction, absorption, beamforming, polarization, splitting, analog processing, and collimation as illustrated in Fig. 4. Reflection/refraction is reflecting/refracting incident radio waves to a specified direction that does not necessarily coincide with the incident direction[63]. Absorption means intelligently designing IRS that nulls, for the incident radio waves, the corresponding radio waves that are reflected and refracted. Beamforming is focusing incident radio waves toward a given location, i.e., concentrating the energy of incident radio waves. Polarization refers to modify the polarization modes of incident radio waves, for example, incident radio waves are transverse electric polarized, and reflected radio waves can be modified as transverse magnetic polarized[63]. Splitting means creating multiple reflected or refracted radio waves for the incident radio waves. Analog processing refers to directly perform mathematical operations at the EM level, e.g., the radio waves refracted by IRS can be the first-order derivative or the integral of incident radio waves[63]. Collimation can be regarded as the complementary of beamforming.

Moreover, IRS can also control the output signals through digital processing by the FPGA-based IRS controller. In this case, the IRS-assisted transmitter scheme can realize an IRS-based version of spatial modulation (SM), index modulation (IM)[64-69], and multi-antenna spatial multiplexing (MASM)[25,26,63,70-72]. There is reason to believe that IRS-based MASM is attractive in 6G networks since multiple data streams can be transmitted simultaneously with a single feeder. Based on the above modes, several other IRS-assisted transmitter designs can be realized[63], which can shape radio waves emitted by IRS through a simple RF feeder and an encoder.

Due to the EM and digital control capabilities of IRS, intelligent connectivity of 6G networks can be achieved assisted by IRS. Fig. 5 describes some potential applications of IRS in 6G networks. For example, IRS can be configured to generate adaptive non-line-of-sight (NLoS) links in a dead zone or low coverage areas where LoS communications are impossible or insufficient due to obstructions/shadowing[73-75]. Meanwhile, IRS also can be configured to steer signals towards required directions or locations not only for enhancing the signal quality but also for suppressing unwanted signals that interfere with the wireless network[76]. Besides, IRS can be configured to worsen the signal towards malicious users either by creating destructive interference or by changing the reflection of signals off the locations occupied by malicious users[77-79]. Moreover, IRS can be intelligently configured to shape the wireless environment whose channel matrix has a high rank and a good condition number, to increase the channel capacity[80]. Furthermore, IRS can be configured to transmit wireless information and power to IoT devices at the same time. Other potential applications of IRS in 6G networks are summarized in Ref. [63].

Several potential scenarios in 6G networks can benefit from IRS-assisted intelligent connectivity. For example, in the city, a large amount of the outside walls of high buildings are made of glass. Smart glasses with special IRSs[63] can be deployed to effectively control the propagation of radio waves. Besides, in crowded areas, such as large buildings, university campuses, offices, classrooms, IRS can be deployed to offer the desired high-speed connectivity without the necessity of installing several access points. Most strikingly, the intelligent cloth can be realized by embedding IRSs and smart sensors to create wearable body area networks for monitoring the health of people in real time. These IRS-assisted applications set the foundation for the deployment of the intelligent information society.

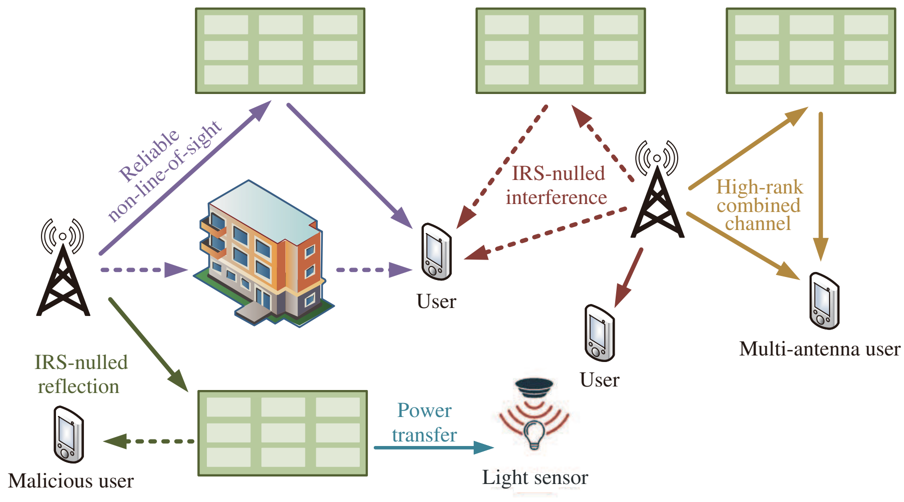

Fig. 5 Potential applications of IRS in intelligent connectivity[63]

B. Ubiquitous Connectivity Supported by IRS

With the rapid development of aerospace and exploration technologies, the scope of human activity is gradually expanding. In the next decade, more people will get a chance to get to space, and the communication requirements between satellites and ground/spacecraft will greatly increase. Meanwhile, the scope of human activity on the earth will be extended to many unfrequented areas including high-seas, desert hinterlands, and polar areas, more and more uninhabited islands will be settled by humans[14]. Therefore, the next 6G wireless networks are required to support ubiquitous connectivity to cover the space-aerial-terrestrial-underwater area.

Due to the relatively simple deployment and low energy consumption of IRS, IRS-assisted communications can be used to significantly enhance the coverage of 6G networks in several potential scenarios[63,81]. For example, in the outdoor urban environment, the outside wall of buildings can be coated with IRS. This offers opportunities for enhancing the coverage and improving the energy efficiency of 6G networks in cities. Especially, IRS can be deployed upon the surface of high buildings, thereby creating a virtual LoS link between the access point and IRS, which is particularly favorable when the direct path is severely shadowed[82]. Besides, due to the large deployment of IRS, the EM radiation caused by network infrastructures in the city could be greatly reduced. In the indoor environment, interior walls can also be coated with IRS for enhancing the local connectivity of several kinds of devices, such as mobile phones and tablets, which rely on wireless connectivity for operation. Especially, IRS can be deployed in ceilings and walls underground to provide the necessary connectivity to a large number of users simultaneously. Besides, the skin of cars/high-speed trains/airplanes can be coated with IRS, which can serve as moving nearly-passive relays for enhancing the coverage of 6G networks in the air and ground moving scenarios. Meanwhile, the interior and glasses of cars/high-speed trains/airplanes also can be coated with IRS that can provide high-speed Internet to passengers while reducing their EM field exposure and decreasing energy consumption. Moreover, IRS-assisted unmanned aerial vehicles (UAVs) communications[83-89] can be employed in 6G networks to effectively enhance the coverage in remote areas, such as remote rural and desert areas. It is worth noting that IRS deployed in UAV networks can harvest energy from the incident signals, thus not requiring a dedicated energy supply[87]. Furthermore, IRS can be employed in satellite communications[90] and offshore communications[91] to provide a cost-effective coverage of high-speed data services. There is reason to believe that by using the IRS, the coverage of 6G networks can be significantly enhanced, thus achieving the goal of covering the space-aerial-terrestrial-underwater area.

C. IRS-Assisted Deep Connectivity

Human production and living space are expanding continuously, and the types and scenarios of information interaction are becoming more and more complex. Internet of everything, starting with 5G networks, promotes rapid growth in IoT communication demand, which is likely to peak in the next decade. Compared with man-machine interaction, the information interaction in IoT will be greatly expanded in both information types and communication range. It can be predicted that in the future, the intelligent IoT will develop rapidly from the following two aspects: 1) the deep expansion of the activity space for connected devices, 2) the ability to deep interactive sensing, deep data mining, and deep mind[14]. Accordingly, 6G networks are required to provide deep connectivity to support the upcoming intelligent IoT service.

To achieve the deep expansion of the activity space for intelligent IoT devices, the primary issue is how to continuously supply the energy to ubiquitous devices. Since IRS with a large aperture can provide continuous and stable EM energy to nearby devices by passive beamforming, IRS can be used in intelligent IoT networks to transmit wireless information and power to IoT devices simultaneously[3]. In Ref. [92], a semidefinite relaxation (SDR)-based algorithm is used in an IRS-assisted IoT network to maximize the weighted sum power harvested by devices. In Ref. [93], an IRS-assisted IoT network is proposed, whose efficiency of both downlink energy beamforming (EB) and uplink over-the-air computation (AirComp) is drastically enhanced by dynamically reconfiguring the propagation environment. Besides, the authors in Ref. [94] indicate the coverage of the IRS-assisted IoT network can be significantly improved due to the wireless energy transfer capability of IRS. These studies set the foundation for the application of IRS in the intelligent IoT network.

Moreover, due to powerful controlling ability, deep learning (DL) technologies[95] are naturally applied in IRS to assist the IRS controller in reconstructing the wireless environment, which also provides a basis for the application of IRS in intelligent IoT networks. The authors in Ref. [96] indicate both IRS and DL are the key to realize the intelligent wireless environment, and DL can be used in IRS-assisted networks to reduce the network complexity[96,97]. In Ref. [98], a neural-network-based approach is used in the IRS controller to configure software-defined elements for creating intelligent wireless environments. In Ref. [99], an artificial neural network is used in the IRS-assisted indoor network to maximize the received power. Besides, a deep reinforcement learning framework (DRLF) is used in the IRS-assisted MISO wireless system to maximize the downlink received signal-to-noise ratio (SNR)[100]. In Ref. [101], a deep convolutional neural network is designed and trained in the IRS controller to restructure the programmable elements in milliseconds for intelligent multi-beam steering. In Ref. [102], a DRLF is used in the IRS-assisted MIMO system to achieve the joint design of transmit beamforming and element phase shifts in real time. In Ref. [103], a two-stage neural network is trained offline in the IRS-assisted MISO system in an unsupervised manner to maximize the system sum-rate with lower complexity. Furthermore, the authors in Ref. [104] propose the DRLF with reduced training overhead can be used in IRS controller to tune the phase shifts of IRS elements without the assistance of base stations or infrastructure nodes, which paves the way to the deployment of the distributed IRS in intelligent IoT networks. In Ref. [105], a fully connected artificial neural network is employed in the IRS-assisted wireless system to directly estimate the channels and phase angles from the reflected signals received by IRS, which enables the IRS-assisted wireless system to perform symbol detection without any dedicated pilot signaling significantly reducing the overhead. Additionally, compressive sensing and DL technologies are used in IRS with sparse channel sensors to reduce the overhead related to IRS control[106]. In Ref. [107], a twin convolutional neural network architecture is designed and used in massive MIMO systems with large IRS to estimate both direct and cascaded channels in the multi-terminal scenario. In Ref. [108], machine learning approaches are used in the IRS-assisted NOMA network to achieve IRS phase shift control, joint network deployment, and power allocation simultaneously for maximizing energy efficiency. Based on the above results, the IRS-assisted wireless network combined with DL technologies is expected to realize deep sensing and intelligent interaction with the wireless environment, and also has many other advantages including real-time beam reconstruction, high energy efficiency, and low overhead. These advantages lay the foundation for the application of DL-based IRS in intelligent IoT networks, making the controllable connection between intelligent devices possible. Therefore, the DL-based IRS can be considered to be a key enabler for realizing the vision of deep connectivity in 6G networks.

D. IRS-Assisted Holographic Communications

It is reported in Ref. [14] that in the next decade, the form of man-machine interaction is developed from the two-dimensional information interaction to high-fidelity VR/AR interaction and even holographic information interaction. VR/AR can create a virtual image in the real world by reconstructing the image of objects, that is, people can see both the virtual world and the real world at the same time. Therefore, 6G networks are required to reconstruct wavefronts of waves in real time to support the high-fidelity VR/AR services without the limitation of location, and even holographic communication and imaging. It can be predicted that people can enjoy immersive holographic interaction services from anywhere at any time in the future, which is the vision of 6G networks "holographic connectivity".

In theory, VR/AR or holographic display devices are required to reconstruct wavefronts of waves in real time to achieve a dynamic holographic display. However, traditional holography has the issue of insufficient reconstruction ability[109]. Recently, many studies on metasurface have proposed a variety of metasurface holography that can completely control the amplitude and phase shift of waves in real time to solve the issue of traditional holography[110-112]. The above studies have laid the foundation for the application of IRS in holographic communication and imaging. Considering the ability to reconstruct the wavefront of waves in real time, IRS naturally becomes a promising technology for holographic communication and imaging in 6G networks. In Ref. [113], the IRS-based hologram is designed and realize for the first time, which can generate different holographic images with high-resolution and low-noise in real time by switching the phase shifts of recoding elements in IRS. Besides, the authors in Ref. [114] also propose and demonstrate an IRS-based hologram that can flexibly image by tunable phase elements of IRS. In Ref. [115], a high-efficiency holographic imaging method for IRS is proposed to achieve more powerful manipulations of EM waves, thus realizing real-time, continuous, and flexible control of holographic images. In Ref. [116], a systematic approach to IRS hologram synthesis is presented, which exploits the rich field transformation capabilities of IRS for creating a variety of virtual images. In Ref. [117], the authors propose and analyze a real-time reconfigurable metasurface that can be used in IRS holography to realize dynamic holographic imaging at optical frequencies. Furthermore, an effective connection approach between IRS holograms and VR users is implemented in the VR network at THz frequency band[118], which lays a foundation for the practical application of IRS holograms. Based on the above discussion, IRS-based holography is key in enabling future interaction devices with reconfigurable image functionality, which can lead to advances in high-fidelity VR/AR services, and holographic communication and imaging.

V. Challenges and Conclusions

A. New Challenges in IRS Application and Deployment

In the implementation of IRS-assisted 6G networks, the first challenge is the design of tunable elements. Undoubtedly, continuously adjusting the reflection coefficients of each element is beneficial for the network performance, however, it is very costly to implement due to the sophisticated design and expensive hardware of massive high-precision elements. Therefore, a more cost-effective solution for IRS-assisted networks is to use tunable elements with discrete amplitude/phase shift levels, for instance, each element can only adjust two-level amplitude (reflecting or absorbing) and phase-shift (0 or π)[119]. Nevertheless, whether IRS with two-level control can meet the requirements of 6G networks needs further verification. Another challenge for IRS-assisted 6G networks is developing an effective control mechanism to connect and communicate with massive tunable elements, and thus agilely and jointly control their EM behaviors on demand. To date, although several control mechanisms have been proposed[120-123], the control mechanism of IRS with ultra-large-scale or ultra-dense tunable elements is still an open issue in 6G networks. Generally, the IRS without any RF chains is not able to perform any baseband processing functionality. Therefore, the channel between the transmitter and IRS and the channel between IRS and receiver cannot be separately estimated through traditional training-based approaches. Recently, there have been several works taking various approaches to efficiently estimate the channels for IRS-assisted communication[3,77,78,124-127]. However, in terms of the IRS reflected channels, its sparsity and other properties in practical environments are still unknown. A channel estimation framework for a more general channel model without assuming any channel property is expected to be proposed. At the same time, since the transmit power and reflection coefficients are highly coupled, the joint optimization of the channel assignment, power allocation, and reflection coefficients for IRS systems is usually quite difficult. Hence, efficient resource allocation is non-trivial to solve for IRS systems[128].

So far, the research on the ubiquitous connectivity supported by IRS is still in the early theoretical stage, and thus more proof-of-concept prototypes are required to validate the IRS's practical efficiency. Moreover, there are a number of key issues in the development of IRS-assisted 6G holographic communications that need to be resolved, such as IRS-assisted 3D holographic imaging, the EM reconstruction mechanism of IRS-based holograms in different 6G scenarios, and the deployment of IRS-based holograms in 6G networks. In addition, the practical deployment of IRS on buildings in the city will involve different units and property managers, as well as the division of interests between operators and equipment providers, which also brings new challenges to the commercialization of IRS.

B. Conclusions

The intelligent information society with highly digitized, intelligence inspired and globally data driven will be deployed in the next decade, which creates core requirements for 6G networks, that is, intelligent connectivity, ubiquitous connectivity, deep connectivity, and holographic connectivity. Due to its powerful wireless environmental control capability, IRS becomes a promising technology for 6G networks. Specifically, IRS is capable of sensing the wireless environment and modulating its reflection coefficients dynamically to realize various functions. In this paper, we present a comprehensive survey on the theory and applications of IRS to the next 6G wireless communication networks. There is reason to believe that integrating IRS into 6G networks will fundamentally change the wireless network paradigm from an uncontrollable wireless environment to an intelligent and controllable wireless environment, thus opening fertile directions for future research. Since IRS-assisted wireless networks are new and remain largely unexplored, it is hoped that this paper could provide a useful and effective guide for future research on them.

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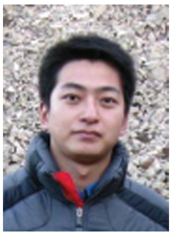

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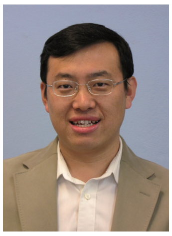

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