Reconfigurable Intelligent Surface Technology White Paper

RIS TECH Alliance

Mar. 2023

Contributors are listed in alphabetical order of company as follows.

Beijing Institute of Technology, Yang Ziyi

Beijing Jiaotong University, Zhang Jiayi, Ai Bo

Beijing Lenovo Software Co.,Ltd. Zhang Yi

Beijing University of Posts and Telecommunications, Zhang Jianhua, Zhang Yuxiang, Wang Ying

Beijing Xiaomi Mobile Software Co., Ltd., Chi Liangang, Duan Gaoming

China Mobile, Yuan Yifei, Su Xin

China Telecom, Sun Zhenqiang, Li Nanxi, Cheng Zhenqiao

China Unicom, Liu Qiuyan, Li Xiaoshuang, Zhang Zhonghao, Li Fuchang

Chongqing University of Posts and Telecommunications, Li Zhidu

CICT Mobile Communications Technology Co., Ltd.,Zhang Xin, Sun Wenlong, Su Xin, Peng Ying

Huazhong University of Science and Technology, Yin Haifan, Pei Xilong

Keysight Technologies, Feng Xiang, Wen Zhu, Cui Yanhua

Nanchang University, Yu Lisu, Wang Yuhao, Wang Zhenghai, Liu Chaoliang, Guo Jichang

Nanjing GloryTelecom Information Technology Co.,Ltd., Yang Yifan

Nanjing University of Aeronautics and Astronautics, Zhou Fuhui, Wu Yuhang, Wu Qihui

Nanjing University of Posts and Telecommunications, Wu Wei, Wang Zi

National and Kapodistrian University of Athens, George C. Alexandropoulos

Northwestern Polytechnical University, Bai Xudong

Paris-Saclay University, Marco Di Renzo

Queen Mary University of London, Liu Yuanwei

Rohde & Schwarz, Wang Lilei, Heinz Mellein

Shanghai Jiao Tong University, Wu Qingqing, Chen Wen, Li Zhendong

Shanghai Normal University, Peng Zhangjie

Shenzhen Research Institute of Big Data, Shen Chao

South China University of Technology, Zheng Beixiong, Chen Zhen

Southeast University, Jin Shi, Cheng Qiang, Pan Cunhua, Tang Wankai, Chen Weicong, Wang Jinghe

Southern University of Science and Technology, You Changsheng

Technology Innovation Institute, He Jiguang, Aymen Fakhreddine, George C. Alexandropoulos

The Chinese University of Hong Kong,Shenzhen, Shen Kaiming, Zhang Zonghui

Tiangong University,Ge Lijun

Tsinghua University, Yang Fan, Dai Linglong, Xu Shenheng

vivo Mobile Communication Co.,Ltd., Yang Kun, Jiang Dajie, Qin Fei

Xidian University, Li Long, Zhang Shun

Università di Bologna, Vittorio Degli Esposti

University of Electronic Science and Technology of China, Yuan Xiaojun, Li Sixian, Cai Chang, Yan Wenjing

University of Glasgow, Qammer H Abbasi, Jalil ur Rehman Kazim, James Rains, Muhammad Ali Imran

Zhejiang University, Huang Chongwen, Yang Zhaohui, Chen Xiaoming, Zhang Zhaoyang

ZTE Corporation, Zhao Yajun, Jian Mengnan, Chen Yijian, Dou Jianwu, Zhang Nan, Zheng Shuang, Xu Hanqing, Zhang Qi, Liu Ruiqi, Wang Shan

Acknowledgement

Thanks to all the members of RISTA.

DOI: 10.12142/RISTA.202302002

Abstract

Reconfigurable Intelligent Surface (RIS) is a foundational and innovative technology, involving meta-materials, electromagnetic information, interface electromagnetism, electromagnetic computing, cybernetics, wireless communication and other multi-disciplinary content. In recent years, a large number of theoretical innovations and prototype tests have demonstrated that RIS has advantages in low cost, low power consumption and easy deployment, which generates many potential opportunities and broad application prospects in the 5G and future 6G networks. Firstly, this white paper discusses the development opportunities of RIS and its potential application in 5G/6G stage based on the development trend and challenges of mobile communication network. Secondly, the technology system of RIS is comprehensively sorted out, including basic theory, hardware structure and regulation, system modeling and key technologies. Then, new types of RISs are discussed, including simultaneously transmitting and reflecting surface, active RIS, new large-scale antennas based on RIS, transceivers based on RIS, and air computing based on RIS. Furthermore, the development status of RIS research and development, test and verification, standard and ecology are analyzed in depth. Finally, the evolution trend of RIS is probed from the perspective of evolution, standard industry and ecological construction.

Contents

1. Introduction

1.1. Challenges of Mobile Communication Networks

The development speed of 5G network far exceeds that of 3G network and 4G network in the same period. Nearly 220 5G commercial networks have been deployed in 86 countries and regions around the world, providing services for 500 million users before June 2022. China has opened a total of more than 2.287 million 5G base stations before Nov. 2022, 5G networks have covered all prefecture-level cities, counties and more than 96% of townships. In terms of the evolution of standard, 3GPP Release 16 and Release 17 have been frozen in June 2020 and June 2022 respectively, focusing on further enhancing basic functions, introducing new features, expanding vertical industries, etc. As an intelligent and comprehensive digital information infrastructure with "high-speed ubiquity, cloud-network services, intelligence and agility, and security and controllability", 5G network construction and operation services directly drive total economic output of more than 1 trillion yuan and indirectly drive total economic output of more than 3 trillion yuan. The 5G network is the main artery of smooth information and a new digital base for economic and social development.

The improvements that 5G brings to society and production will gradually emerge with the progressive pace of 5G implementation. However, the continuous evolution of user needs, better service experience, and the expansion of more vertical industry services will drive the continuous development of mobile communication networks. In the future, new business needs such as digital twins, holographic interaction, and sensory interconnection will put place greater demands on mobile network coverage depth, ubiquitous access capability, air interface transmission rate, end-to-end delay, number of device connections, and endogenous intelligence level. At the same time, in the national green transformation and new development landscape, the harmonious development of man and nature such as carbon peak and carbon neutral has become a new goal for the development of mobile communication networks. Therefore, higher operating frequency bands, larger antenna size, lower equipment energy consumption, and higher level of intelligence are important trends in the development of next-generation future mobile communication networks.

The development of mobile communication networks faces numerous obstacles as well as opportunities.

1) Poor high-frequency channel environment: Compared with low-frequency signals, high-frequency signals have greater propagation loss and penetration loss i.e., high-frequency signals are more easily affected by obstacles, and blind areas or weak coverage areas are prone to appear in network coverage areas, which is not conducive to realizing ubiquitous access and deep coverage of wireless networks.

2) Constrained massive MIMO development: With the increase of the antenna size, the antenna manufacturing process and cost, the difficulty of channel measurement and modeling, the amount of signal processing calculations, and the spending of reference information will all increase significantly, which put higher requirements for the antenna system integration. Therefore, low cost, low power, highly reliable and easy deployment are the prerequisites for the practical application of massive MIMO technology [1].

3) Increasing energy consumption burden: The energy consumption of current 5G base stations is several times higher than that of 4G base stations. In the future, the acceleration of the digital transformation of the whole society will further increase the need for computing power of mobile communication networks. How to effectively reduce equipment energy consumption is one of the key factors affecting the technology selection of the next-generation wireless network.

4) Passive adaption to the wireless environment: Since its birth, the mobile communication system can only passively adapt to the path loss and multipath fading in the wireless environment. The air interface often becomes a major barrier on network performance. Network requirements such as endogenous intelligence and dynamic reconfiguration gradually sink from the core network side to the wireless access side. Building a new paradigm for next-generation mobile communication networks will center on on-demand intelligent dynamic reconfiguration of the wireless environment.

1.2. Concepts and Developments of RIS

RIS has attracted the attention of academia and industry as soon as it appears because it can flexibly manipulate the electromagnetic characteristics of wireless channel, as illustrated in Figure 1. The introduction of RIS makes the wireless propagation environment which previously can only be adapted passively now become controllable, thus building a smart radio environment (SRE) [2]. As a two-dimensional implementation of metamaterials, RIS naturally has the characteristics of low cost, low complexity and easy deployment. It has the potential to address the upcoming demands and difficulties faced by wireless networks.

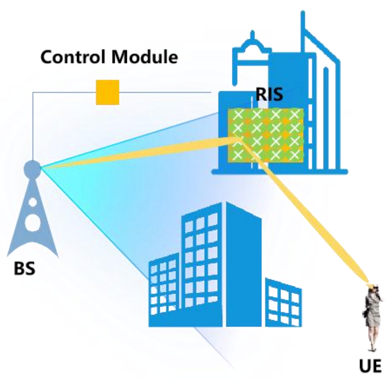


Figure 1 Conceptual illustration of Reconfigurable Intelligent Surfaces

Since 2020, domestic academic and industrial circles have jointly carried out a series of RIS industry promotion activities, which greatly promoted the technological research and industrialization of RIS. In June 2020, China IMT-2030 (6G) Promotion Group established the "RIS Task Force". In September 2020, ZTE Corp. joined hands with more than ten domestic and foreign enterprises and universities such as China Unicom to establish the "RIS Research Project" in CCSA TC 5-WG 6. On September 17th, 2021, IMT-2030 (6G) Promotion Group officially released the industry's first research report on intelligent hypersurface technology in the 6G seminar. On September 24th, 2021, ZTE Corp., Southeast University, China Unicom, and jointly hosted the "1st Reconfigurable Intelligent Surface Technology Forum"[1] [3]. On April 7th, 2022, RIS Technology Alliance (RISTA) was established and the first general meeting of RISTA members was held in Beijing[2] [4]. On February 12, 2023, sponsored by RISTA and others, ZTE and others jointly hosted the "THE 2nd RIS TECH Forum"[3].

At present, China has made significant contributions to the materials, theory, algorithms and experiments of RIS. RIS has a tendency to become one of the key breakthrough technologies. As one of the most potential 5G-Advanced and 6G key technologies, RIS has the potential to be implemented in 5G-Advanced and bring a new communication network paradigm to 6G in the future to meet the needs of future mobile communication [5]. Furthermore, a series of tests and verifications on RIS were undertaken in the current network by the domestic industrial circles. Results verify that the deployment of RIS can effectively improve the throughput and coverage of wireless networks. As a technology for dynamically adjustable electromagnetic parameters, RIS has initially demonstrate powerful performance in a number of areas [6]-[10]. However, RIS still faces many problems and challenges in technical research, engineering application, network deployment and standardization process before being put into large-scale commercial use.

[1] 1st RIS TECH Forum, http://www.risforum.com
[2] RISTA, http://www.risalliance.com
[3] 2nd RIS TECH Forum, http://2022.risforum.com/en/

2. Scenarios of RIS

RIS has the characteristics of decoupling from most of the underlying technologies such as waveform, modulation, coding, and multiple access. It can be applied to the 5G phase of 6G technology. As 5G networks have been deployed widely in commercial settings, it is critical to reduce the transformation need for existing 5G networks of RIS. Therefore, in the 5G-A stage, for the needs of 5G network refinement operation and maintenance, deep coverage, and speed expansion, 5G network coverage supplementation and multi-stream speed increase based on RIS assistance will be the typical application method. For 6G, RIS has the possibility to combine with millimeter wave/terahertz high frequency communication, pass-sense integration, full duplex, and many other frontier technology fields. This white paper expands on the previous research to assess potential RIS applications in 5G and 6G networks based on the RIS technology's stage of development and the trends in the evolution of 5G and 6G networks.

2.1. Potential Scenarios in 5G-A

2.1.1. Coverage Enhancement

There exist coverage holes in the cellular network where signal is blocked by obstacles, including the shadow area of building, the street corner in dense urban area, the edge between indoor and outdoor (or between in-vehicle and out-vehicle). In the above scenarios, RIS can be deployed between the base station and the coverage holes to improve the coverage performance through effectively reflecting/transmitting the transmission signal to reach the blind area of coverage.

(1) Outdoor coverage enhancement

In outdoor macro station coverage scenario, due to obstacles like buildings and vegetation between base stations and terminals, there may not be line-of-sight transmission paths between transceivers and transmitters, resulting in poor received signal quality and blind coverage areas.

For the above scenario, lightweight static RIS devices would be a low-cost, low-power, and easy-to-deploy solution. Virtual LoS transmission can be achieved by constructing a NLoS reflective path on demand and replacing the NLoS direct channel with a LoS reflective channel, as shown in Figure 2.

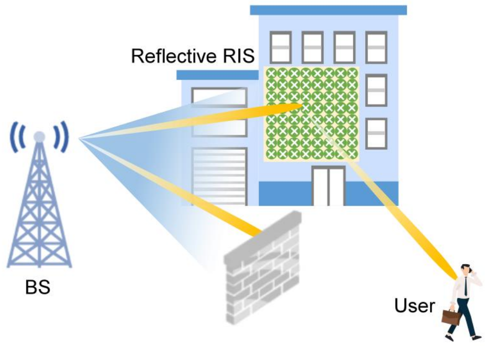


Figure 2 RIS-assisted outdoor macro station coverage enhancement

(2) Outdoor to indoor coverage enhancement

In the outdoor to indoor coverage scenario, transmission signal can be enhanced by deploying refraction RIS on the door and window glass, as shown in Figure 3. By adjusting the transmission characteristics of the RIS on demand through the control units, the desired signal transmission direction can be built, and the performance of outdoor coverage over the interior is enhanced.

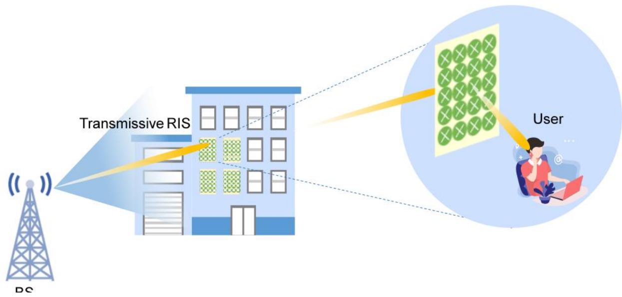


Figure 3 RIS-assisted indoor enhancement of outdoor macro station coverage

(3) Indoor coverage enhancement

Similar to outdoor coverage, there are some weak coverage areas blocked by obstacles, corridor corners in indoor scenario. As shown in Figure 4, RIS is used to build virtual LOS reflection path with dynamic beam direction to replace the indoor NLOS direct channel for indoor coverage enhancement.

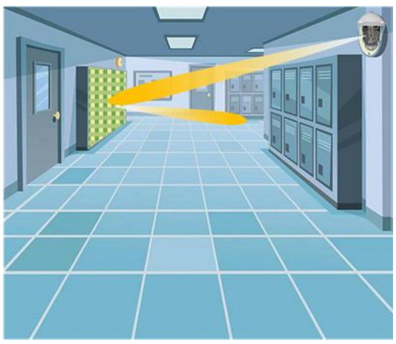


Figure 4 RIS-assisted indoor coverage enhancement

2.1.2. Throughput Enhancement

In hot spots area with intensive traffic, additional paths and channel subspaces can be introduced with RIS deployment. Specifically, the spatial correlation characteristics of the channels between the transceiver antenna arrays can be greatly improved, and the number of subspaces available for data transmission will be increased. This can improve the multiplexing gain of signal transmission and significantly enhance the transmission performance of the system and users.

Cell edge area is lack of multipath environment with weak signal level. Hence, the multi-antenna of the terminals cannot achieve maximum gain. RIS deployment between the transmitter and receiver can create a complex scattering environment for cell edge users on demand, which can effectively utilize the multi-antenna capability of the terminals and improve the transmission performance of cell edge users.

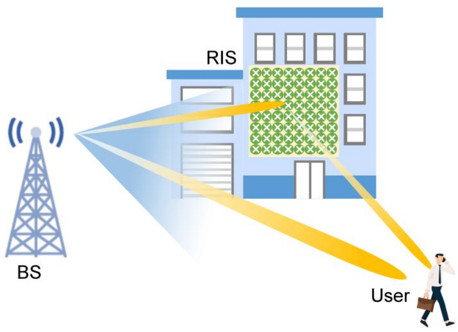


Figure 5 RIS-assisted multi-stream speed increasement

2.1.3. Robustness Enhancement

For high frequency communication system, large beamforming gain is imported to overcome impact from large pathloss. On the other hand, beam is narrower for the beam with larger beamforming gain and this will have impact on the transmission robustness. For example, the received signal quality will be changed remarkable with the coming obstacles, changing of the posture for holding mobile phone. Therefore, transmission robustness is a problem to be paid more attention in the high frequency communication system.

RIS can be used to deal with this problem. In one RIS, there are a large amount of passive reflecting units. They can be divided into several groups and one group generates one reflecting beam. Then, the transmission robustness can be enhanced by multiple beam transmission. As an example shown in Figure 6, 2 reflecting beams can be generated by RIS to point to two different receiving panels of mobile phone. For this case, even if one beam is blocked, the communication can be guaranteed by transmission of another beam.

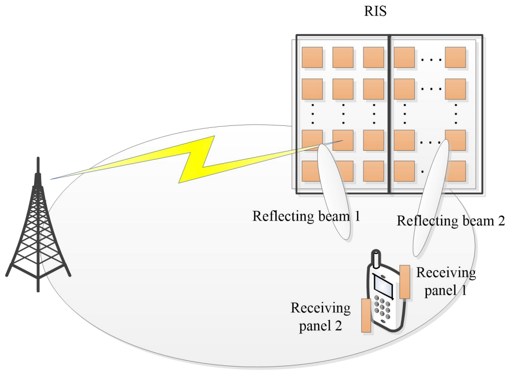


Figure 6 RIS for transmission robustness enhancement

2.2. 6G Potential Scenarios

2.2.1. High-Frequency Communication

2.2.1.1. Millimeter Wave and Terahertz Communication

Millimeter waves and terahertz are potential operating frequency bands of 6G. The most obvious features of high-frequency signal are the severe path loss, the small radius of the coverage, and the susceptibility to obstacles, rain and snow weather, environmental absorption, etc. According to the wireless channel model of 3GPP TR38.901, the path loss of 28 GHz millimeter wave signals is about 18 dB higher than that of 3.5 GHz signals under the same conditions. In terms of penetration loss, the theoretical results in 3GPP and measurement results are presented in Table 1. For low-frequency millimeter waves, obstacles made of concrete and infrared reflective glass can completely obstruct the signal propagation, and the penetration loss to obstacles such as leaves, human bodies, and cars to low-frequency millimeter wave signals is more than 10 dB. The severe penetration loss leads to significant communication quality deterioration in the sheltered area within the coverage range. It is seen that only when obstacles are ordinary glass or wooden doors, the penetration loss of low-frequency millimeter wave can be reduced between 5 dB and 10 dB, however, this penetration loss still results in a serious decline in the communication quality in the covered areas. For higher millimeter wave and terahertz frequency bands, the penetration loss of signals caused by obstacles can be tens of dB.

To overcome the severe path loss of HF communications, base stations and end users are usually equipped with large-scale antenna arrays to achieve high-gain directional transmission. The strongly directional beam and the sparsity of HF channels lead to a rank loss problem in the channel matrix. In extreme strong line-of-sight propagation scenarios, the channel rank even drops to 1, and the spatial multiplexing gain of multi-antenna systems cannot be exploited. In this case, by deploying RISs between the base station and the user, the LoS link can be dynamically established. Utilizing the channel customization capabilities of RISs [11]-[12] the rank of the channel matrix can be flexibly shaped and the multiplexing gain can be improved. With the application and development of metamaterial antennas, RIS will become more diversified. For example, they can be integrated into the facade of buildings. Owing to the characteristics of low-cost, low-power consumption, and flexible deployment, RIS is envisioned to provide effective coverage complements and extensions to base stations.

Table 1 Theoretical penetration loss and measurement of millimeter wave

materials	The 3GPP signal penetration loss model [dB]	Theoretical penetration loss of millimeter waves[dB]	Measured penetration loss of millimeter waves[dB]
Standard glass	L=2+0.2f	8-62	>5
Infrared reflective glass	L =23+0.3f	32-113	——
concrete	L=5+4f	125-1205	Impenetrable
wood	L =4.85+0.12f	8.45-40.85	6
leaf	——	——	16-20
Human	——	——	11-28
Car	——	——	17-23

2.2.1.2. RIS-aided Visible Light Communication

Although the visible light communication technology is developing rapidly, it still faces some critical problems that need to be solved. With RIS technology, the performance of visible light communication network can be effectively improved.

(1) Reflective RIS-assisted large-scale access to visible light communications

As shown in Figure 7, in addition to the line-of-sight link between the transceiver and transmitter, deploying a reconfigurable intelligence surface is able to form a reflective link and achieve dynamic on-demand modulation of the beam, which can improve the received signal quality, increase communication capacity, and lessen signal interference in the visible light communication networks [13].

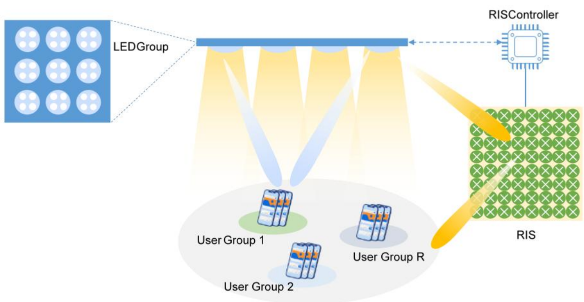


Figure 7 Reflective-RIS assisted massive access VLC

(2) Transmissive RIS-assisted visible light communication

The transmissive RIS can be added to the LED signal transmitter as well as the signal receiver, as shown in Figure 8 and Figure 9. The RIS designed based on liquid crystal or smart lens materials can flexibly regulate the signal direction and reduce the influence of interfering signals [14]-[15]. The RIS array, which supports both transmission and reflection capabilities, can provide favorable conditions for non-orthogonal multiple access technology to better function for visible light communications and effectively improve the total communication capacity.

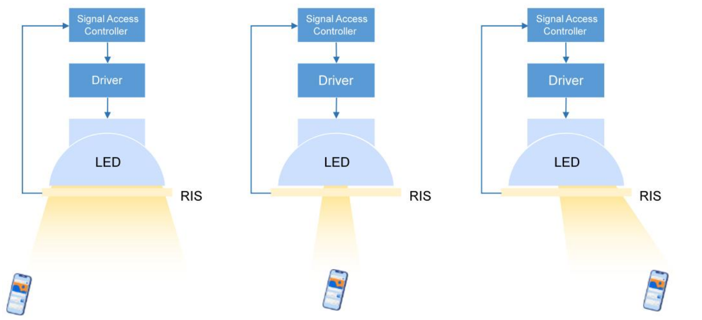


Figure 8 Transmissive RIS-assisted visible light communication

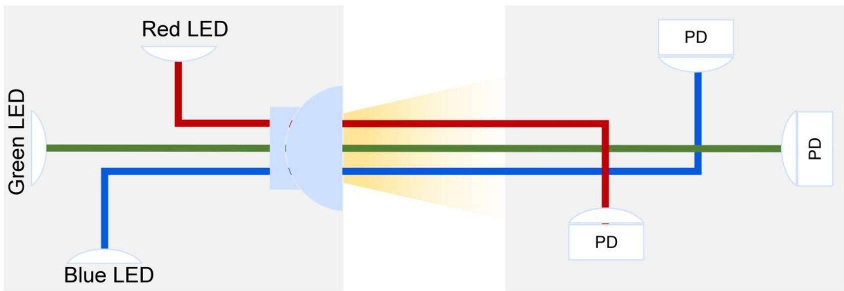


Figure 9 Transmission RIS-assisted WDMA visible light communication

2.2.2. Space Communications

Non Terrestrial Network (NTN) space communication technology is an important complement to terrestrial cellular communication technology. Deeply integrated the satellite communication network and terrestrial 5G and 6G networks can to provide ubiquitous coverage capability regardless of terrain, especially in areas that are extremely difficult to reach by traditional terrestrial networks. It is of great practical significance to achieve integrated network connectivity in air, sky, earth and sea multi-dimensional space [16].

2.2.2.1. Satellite Communication

In satellite communication systems, due to the long transmission distance of the satellite (SAT) link, sufficient transmit power and antenna gain are required to offset the road loss during signal propagation. However, to avoid interference to other areas, it is also required that the signal gain is low enough in areas outside the target area. Applying RIS to satellite communication can replace traditional phased arrays to achieve larger antenna arrays with lighter mass and smaller size. Using RIS with energy storage function, it can also replace solar panels on satellites to store energy from sunlight radiation for signal transmission. In addition, RIS can also be used for enhanced signal coverage in millimeter wave satellite communication systems. In particular, satellites can be equipped with solar panels for harvesting solar energy from the Sun, while the SAT-side RISs can be coated on the reverse side of these solar panels and thus face towards the Earth for assisting the satellite communication [17]. On the other hand, depending on the specific communication scenario on the ground, various RISs can be flexibly mounted on cars, camping tents, house roofs, buildings, ships, etc.

Among various types of satellites operating at different orbital altitudes, the low-earth orbit (LEO) satellite has received the most attention for providing communication services to various ground nodes, due to its low altitude and the resultant advantages such as less propagation loss, shorter transmission delay, and lower cost as compared to other higher orbit satellites. In order to achieve 5G and 6G with low latency LEO satellite communications, it is necessary to build low-orbit satellite mobile communications and space Internet systems such as STARLINK, such a large constellation of low-orbit satellites using traditional space delivery system is obviously difficult to achieve in a short period of time, must use a stacked LEO satellite architecture, generally a single arrow needs to reach 60 stars to maximize the effectiveness of the carrier, a large number of satellite deployment on the demand for low-cost, low surface density and ultra-low-profile phased array systems is growing, as shown in Figure 10. Phased array antennas based on existing RIS systems can greatly reduce the cost and weight of the system by eliminating the T/R components required for cell phase shift in conventional phased arrays, among which, the integrated ultra-low-profile self-excited RIS system with integrated feed and phase adjustment is of great significance to promote the rapid deployment of low-orbit giant constellations [18]. In addition, RIS can also be deployed on the ground to enhance the performance of communication.

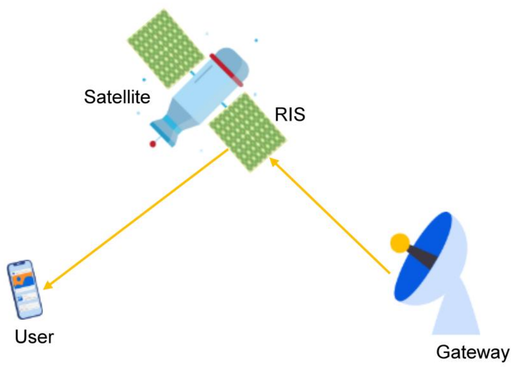


Figure 10 RIS-based satellite communication scenario

2.2.2.2. Unmanned Aerial Vehicle Communication

Unmanned Aerial Vehicles (UAV) plays an important role in wireless communication due to their advantages such as in low cost, high mobility, wide coverage, and short-range line-of-sight link communication with users. UAVs can act as both aerial base stations and relays to sustain information transmissions. However, in the practical scenario, due to the overly complex urban environment, the presence of obstacles as well as eavesdroppers can seriously reduce the communication quality and security rate of the UAV communication networks, resulting in creating security risks. By combining RIS technology with UAVs, the characteristics of RIS reflective information can be used to build new information transmission paths and expand signal coverage in the communication network, greatly simplifying the channel modeling of UAV communication and reducing the complexity of the algorithm; at the same time, by optimizing the signal transmission power, flight trajectory and RIS phase shift of UAVs with the characteristics of passive beam assignment, the transmission performance of UAV communication can be further improved. By optimizing the UAV signal transmission power, flight trajectory, and RIS phase shift, the transmission performance of UAV communication can be further improved, or the signal superposition and signal weakening can be achieved by sub-users, thus realizing safe communication [19]-[20].

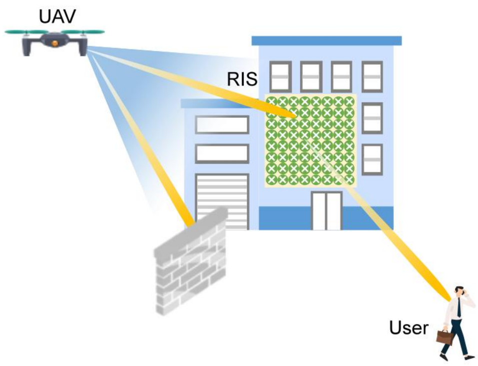


Figure 11 RIS-assisted UAV-based communication scenario

2.2.3. Integrated Sensing and Communication

The integrated sensing and communication (ISAC) has been recently proposed as a new concept for reusing the same spectrum of sensing and communication [21]. To support simultaneous target detection and high data rate transmission, RIS was deployed in ISAC system to provide virtual LoS paths to achieve accurate target feature information (such as the target's location, distance and velocity), especially to three-dimensional positioning. For example, in autonomous driving, as shown in Figure 12, RIS can ensure uninterrupted localization and communication services even if the LoS path is temporarily blocked, while a large RIS can provide near-field localization by using the radar wavefront signal. The phase shifts of RIS can be reconfigured in real time according to sensing information, thus improving the accuracy of the positioning system. In addition, the accuracy and robustness of 3D positioning can be improved by pre-configuring the base station or RIS position information and reference signals [21]-[27].

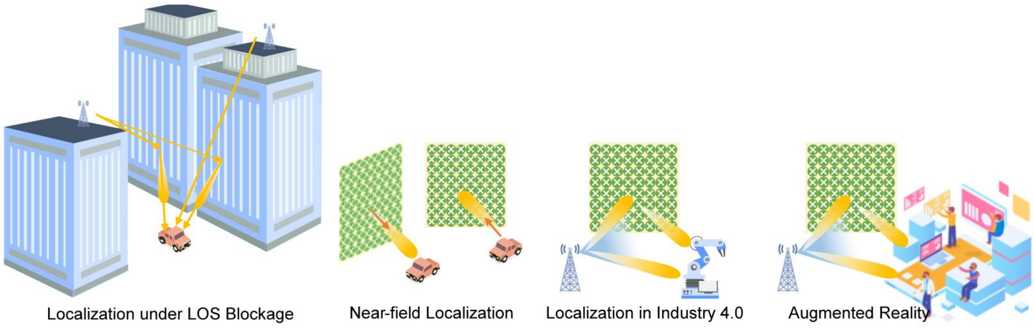


Figure 12 Application scenarios based on RIS positioning [23]

In addition, the RIS also provides additional degrees of freedom (DoFs) and mitigate mutual interference of the ISAC systems when facing severe channel degradations. As shown in Figure 13, the transmit waveform and the reflection coefficients are jointly designed to minimize the multi-user interference (MUI) for better communication QoS under the requirement of radar sensing in terms of beampattern similarity.

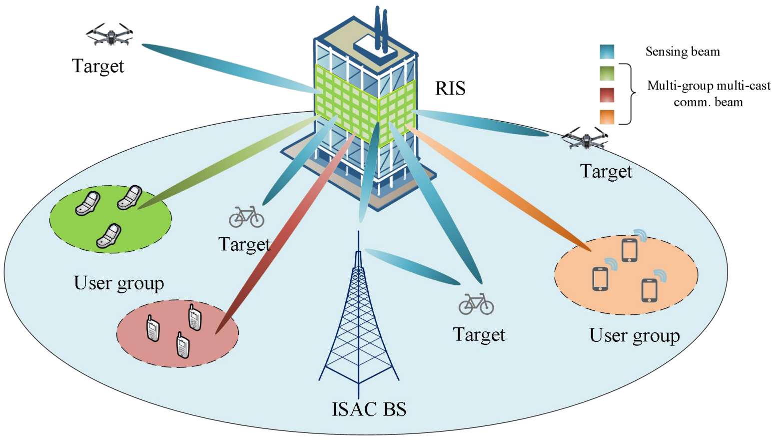


Figure 13 Schematic of RIS-assisted interagted sensing and communication

2.2.4. RIS-Aided Internet of Things

RIS has many promising applications on the Internet of Things (IoT) network environment. For example, using RIS to establish virtual offload links can increase the offload link channel gain, thus offloading more data to the edge servers, allowing data to be processed more efficiently.

In addition, RIS can simultaneously enhance the signals collected by the serving base stations in a multi-cell IoT to reduce inter-cell interference between large-scale IoT devices. Integrating RIS into 6G IoT applications, such as smart buildings, can help establish interfaces between indoor and outdoor entities and facilitate access to private homes in smart buildings. Integrating RIS into human posture recognition systems for surveillance and remote health monitoring allows the system to obtain optimal propagation links by periodically modulating the state of the RIS relative to randomly configured and non-configurable environments, thus creating multiple independent paths to accumulate useful information about human posture for better estimation of human posture.

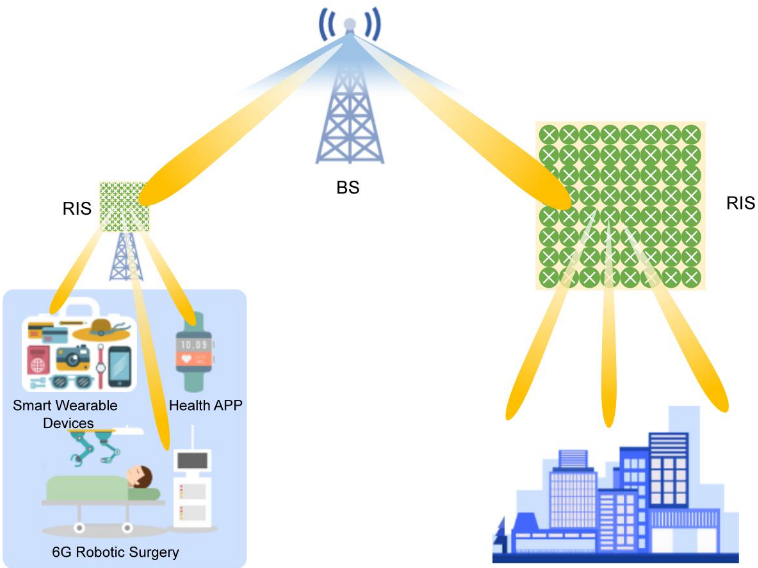


Figure 14 RIS-assisted IoT application scenarios based on

2.2.5. Wireless Edge Computing

In future new applications such as Virtual Reality (VR), computationally demanding image or video processing tasks need to be processed in real time. Due to the limited power and hardware support capabilities of VR devices, these tasks are generally difficult to perform locally. To solve this problem, VR devices can offload these computationally intensive tasks to the edge computing nodes of the network to assist their computation. However, for some special scenarios, poor channel quality of the passthrough link between VR devices and edge nodes can occur, resulting in a slow task upload rate and thus a large offload delay. To solve this problem, the RIS can be installed at a suitable location between the VR device and the edge node [28], thus improving the offload channel quality and reducing the offload latency.

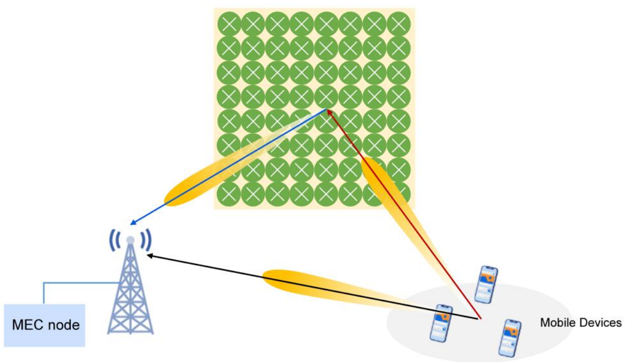


Figure 15 RIS-enabled wireless edge computing

2.2.6. Physical Layer Security

Due to the broadcast nature of wireless transmission, wireless transmission is vulnerable to security threats, such as malicious attacks or security information leakage. Traditional secure communication technology uses an upper layer of encrypted communication protocol to secure the transmission. However, this scheme requires more complex security secret key exchange and management protocols, which increases the communication latency and system complexity. In contrast, physical layer security techniques can avoid complex key exchange protocols and have received extensive research attention. To maximize the security rate, the techniques of artificial noise or beam assignment are generally used. However, system performance using only the above two techniques is limited when legitimate users and eavesdropping users are in the same propagation direction. To solve this problem, RIS can be deployed in the network [29]-[30]. By reasonably optimizing the reflection coefficients of the base station precoding and RIS, the reflected signal passing through the RIS can be enhanced at the legitimate user's end and attenuated at the eavesdropping user at the same time. Moreover, RIS-assisted transmission can effectively improve the system's covert communication performance.

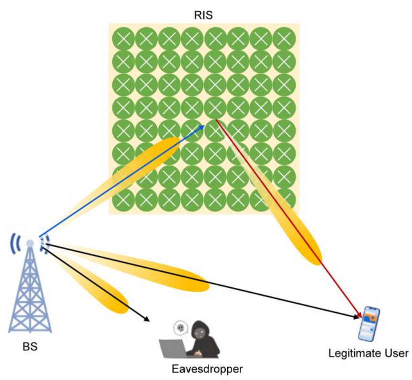


Figure 16 RIS-enabled physical layer security

2.2.7. Information-Power Simultaneous Transmission

Electromagnetic waves can transmit both information and energy, and the theory and technology of efficient wireless energy transmission and collection is a current hot area of applied fundamental research at the intersection of electromagnetic fields, microwaves, circuits and systems, power electronics, energy conversion, and other disciplines [31]. Currently, energy and information for data transmission are handled in a discrete manner, and a unified design for digital-energy homologation will make full use of the RF/microwave spectrum and network infrastructure for communication and power supply [32]-[35]. The system solutions for digital energy co-location can be divided into three main categories, namely, wireless portable communication (Simultaneously Wireless Information and Power Transfer, SWIPT), wireless powered communication (WPC) and WPC- SWIPT systems.

The RIS-based SWIPT system is shown in Figure 17, in which the RIS acts as a multi-array transmitter to achieve simultaneous information and energy signal transmission. Specifically, the electromagnetic unit of RIS regulates the phase, amplitude and polarization direction of the energy signal and information signal sent from the base station in real time and reflects the regulated signals to the corresponding energy receiver and information receiver respectively. The energy receiver and information receiver use the received signals for energy reception and information demodulation, respectively. Compared with the traditional SWIPT system, the RIS-based SWIPT system does not require RF chain, which can greatly reduce the design complexity, hardware cost and power consumption of the array system wireless communication transmitter.

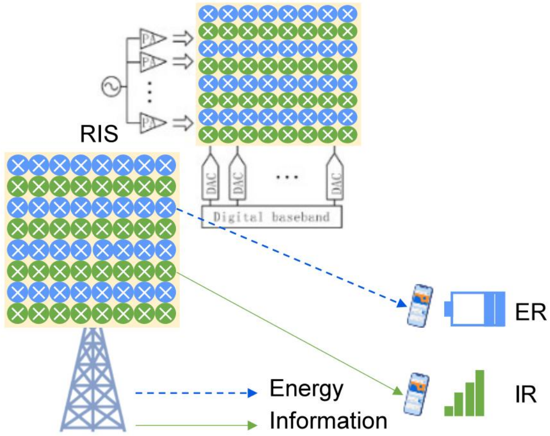


Figure 17 RIS-based SWIPT system

The RIS-based WPC system, shown in Figure 18, deploys RIS equipped with large-scale array units on Hybrid Access Point (HAP) for downlink radio energy beamforming and uplink information reception. It works by dividing the unit time into downlink wireless energy transmission phase and uplink wireless information transmission phase. In the downlink wireless energy transmission phase, the energy-limited device collects the RF energy signal modulated by the RIS and stores it; in the uplink wireless information transmission phase, the energy-limited device uses the collected energy to send information to the RIS, which processes the received signal by beamforming and feeds it back to the HAP. Beam alignment and enhanced uplink received signal strength; (2) helps to extend the operational life of energy-constrained devices with real-time and rapid information feedback.

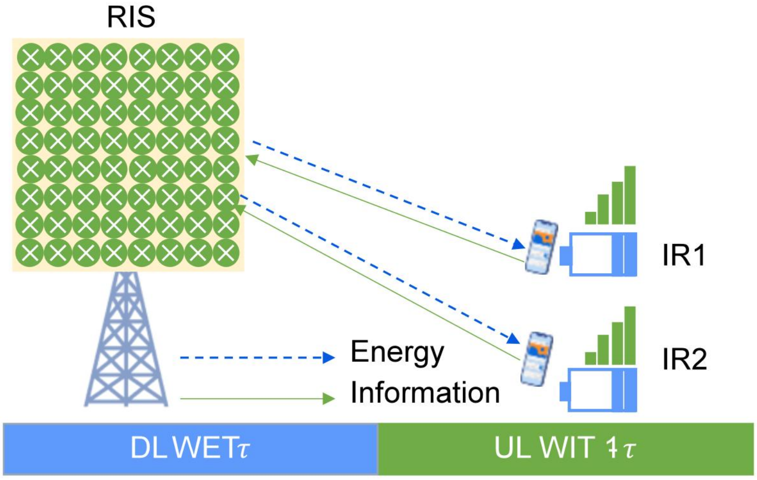


Figure 18 RIS-based WPC system

As is shown in Figure 19, the RIS-based WPC-SWIPT system, divides a unit time slot into two transmission phases: the wireless energy transmission phase and the FF phase of the wireless information and power. In the first phase (wireless energy transmission phase), the power station and RIS transmit energy signals to the wireless energy user, who performs energy harvesting and stores the harvested energy in the battery. In the second stage (cotransmission phase of the wireless information and power), the wireless energy user stops energy collection and uses the energy collected in the first stage to transmit information for the remote information receiver. Based on the power shunt protocol, the information receiver divides the received signal into two parts i.e., the energy harvesting part and the information decoding part. The system has the following advantages: (1) the deployment of RIS enhances the transmission of wireless energy signals and provides the possibility of WPC network implementation; (2) it expands the network coverage area and provides high quality communication services for cellular edge users; (3) energy harvesting technology is used in both transmission phases to promote low-power devices that can communicate and power up anytime and anywhere on the move.

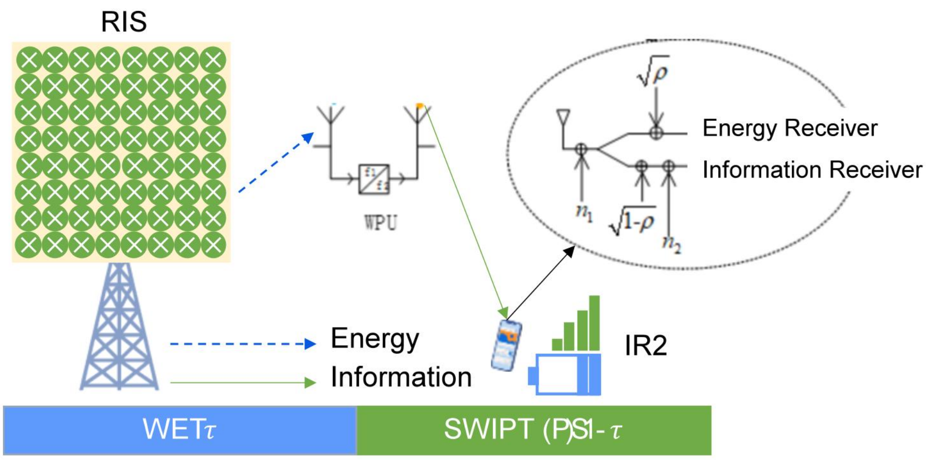


Figure 19 RIS-based WPC-SWIPT system

2.2.8. Spectrum Sensing and Sharing

Spectrum-aware technology refers to the technology of detecting and collecting data of the target authorized band by secondary users in the spectrum sharing network based on opportunity access or sensory enhancement and using different detection techniques to judge whether there is signal occupation in the authorized band, so as to realize the detection of spectrum voids and share the spectrum of primary users in real time. The main spectrum sensing techniques are energy detection, matched filter detection, eigenvalue detection, cyclic smooth feature detection, etc. In the RIS-assisted spectrum sharing network, there are three access mechanisms that enable multiple spectra sharing users to coexist, namely, power control-based spectrum sharing, opportunity access-based spectrum sharing, and sensory enhancement-based spectrum sharing. Among them, it is difficult to guarantee the quality of service of the main network due to the lack of spectrum-awareness process within the power-controlled spectrum sharing-based network. Therefore, the other two access mechanisms based on spectrum sensing become the preferred choice for RIS-assisted spectrum sharing networks.

In RIS-assisted spectrum sensing, the signal from the primary user can be enhanced by dynamically adjusting the RIS phase, thus improving the received signal-to-noise ratio of secondary users and achieving high accuracy spectrum sensing. It was demonstrated in [36] that RIS-assisted spectrum sensing can effectively improve the average detection probability of single-user spectrum sensing, multi-user spectrum sensing, and diversity reception under the energy detection algorithm. In addition, RIS-assisted spectrum sensing can be organically combined with spectrum sharing networks to achieve the synergistic improvement of spectrum sensing accuracy and information transmission performance, further enhancing the spectrum efficiency of RIS-assisted spectrum sharing networks [37].

Spectrum sharing networks usually refer to the coexistence of multiple communication networks in the same frequency band, including primary user communication networks authorized by (spectrum management boards, telecom operators, etc.) and secondary user networks with lower access rights. The reconfigurable channel feature of RIS helps to mitigate the interference problem between primary and secondary user transceivers, thus improving the spectrum efficiency of the whole system. A typical RIS-assisted spectrum sharing network is shown in Figure 18. In the downlink communication of primary and secondary users, for the primary user receiver, the reflected channel introduced by RIS can both enhance the useful signal from the primary user transmitter and suppress the interference signal from the secondary user transmitter; while for the secondary user receiver, the reflected channel introduced by RIS can both enhance the useful signal from the secondary user transmitter and suppress the interference signal from the primary user transmitter. For secondary user receivers, the reflection channel introduced by RIS can both enhance the useful signals from secondary user transmitters and suppress the interfering signals from primary user transmitters.

RIS-assisted spectrum sharing networks can be applied to a variety of scenarios, such as the U.S. 3.5 GHz Citizens Broadband Radio Service (CBRS) band, and 3GPP's LTE-U, NR-U, and other spectrum sharing technology standards. The U.S. 3.5GHz CBRS band allows multi-operator coexistence, which is equivalent to the coexistence of multiple primary user networks with secondary networks, increasing the access requirements for secondary users, i.e., the need to not interfere with the normal communication of multiple primary user networks. In this scenario, the RIS reflection coefficient as well as the deployment location can be designed to effectively reduce the interference of secondary user transmitters to multiple primary user receivers, while also increasing the communication rate of secondary users [38]-[42]. the 3GPP proposed LTE-U or NR-U usually compete with Wi-Fi technologies for access opportunities with the same priority in the 5 GHz and 60 GHz authentication-free bands. Equivalently, multiple sub-networks coexist in the same frequency band, and the adjustment of parameters such as RIS reflection coefficient and deployment location can improve the overall spectrum efficiency of multiple sub-networks [39]-[41].Both RIS and spectrum sharing technologies have deployment flexibility, which is beneficial to the low-cost and highly resilient application of RIS-assisted spectrum sharing networks in practical systems to adapt to future complex and changing communication scenarios.

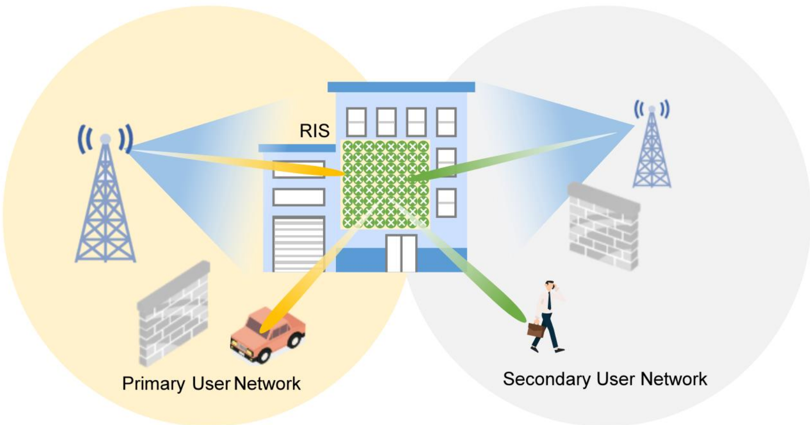


Figure 20 Schematic diagram of the spectrum sharing network assisted by RIS

2.2.9. Full Duplex Communication

Full-duplex technology lifts the limitation of traditional duplex mechanism on the spectrum resource utilization of transceiver and helps to further improve the spectrum efficiency and system flexibility, and theoretically simultaneous co-channel full-duplex can improve the spectrum efficiency by double. However, based on the traditional base station design concept of simultaneous co-channel transmission of signals in the uplink and downlink, there will be serious self-interference and cross-interference problems, requiring certain means of interference suppression and cancellation during equipment and network deployment. Compared with conventional base stations or relay devices, RIS-based wireless devices can transmit in full duplex mode without introducing self-interference [43]-[44].

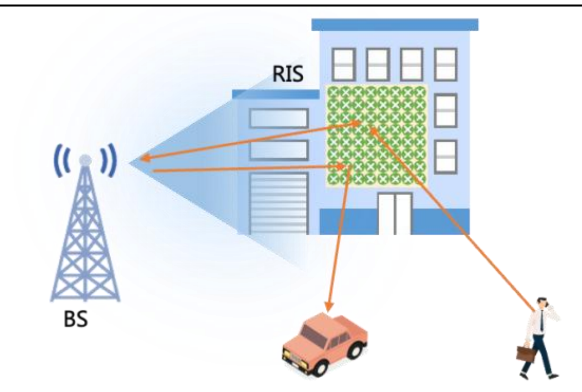


Figure 21 RIS-assisted full-duplex communication scenario

2.2.10.Multicell Communication System

To maximize the spectrum efficiency of the communication system, multiple base stations in a multi-cell generally multiplex the same spectrum resources, which will bring about a multi-cell interference problem, which is especially obvious for the cell edge users. To solve this problem, the RIS can be installed at the cell edge [45], and by reasonably optimizing the RIS reflected phase value and multi-base station precoding, the RIS can not only increase the received useful signal power value, but also effectively eliminate the interfering signals from neighboring cells.

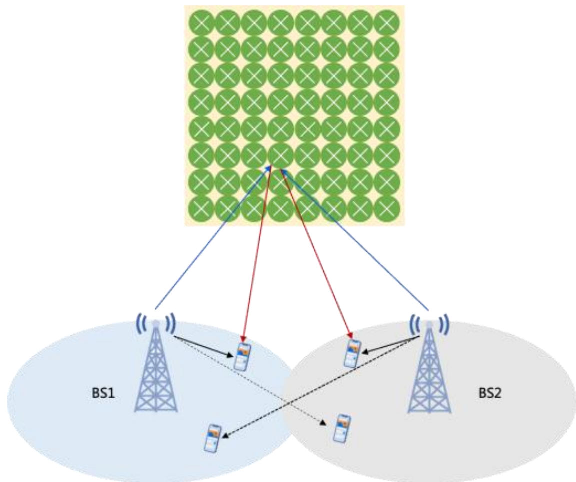


Figure 22 RIS-aided multicell networks

2.2.11.Multigroup Multicast Transmission

Multicast applications are an important part of communication systems that can effectively reduce the pressure of high data stream transmission in traditional unicast transmission systems. Typical multicast applications include video conferencing, video games, and broadcasting of major sports events. In a multi-group multicast communication transmission system, users in each group share the same transmission content, so the transmission rate of each group will be constrained by the users with the worst channel quality within the group. To solve this problem, RIS can be installed in this system, and by reasonably optimizing the design of the reflection coefficient of RIS, the channel quality of the bottleneck users can be improved at the expense of the user channels with good channel quality within the group, thus increasing the overall transmission rate within the group [46].

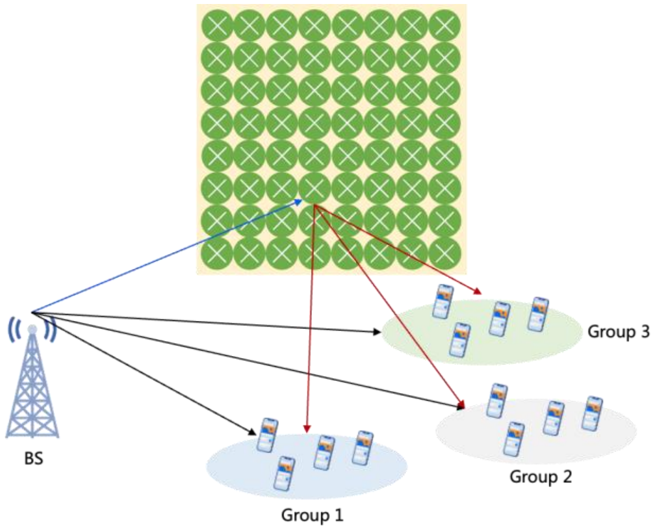


Figure 23 RIS-assisted multi-group multicast transmission system

2.2.12.Orbital Angular Momentum

There are various ways to generate OAM vortex electromagnetic fields. One of the typical methods is the generation of vortex EMF based on reconfigurable intelligence surface. The reflective and transmissive reconfigurable intelligence surface can generate dual-polarized dual-band multimodal OAM vortex EMFs, and can also realize the flexible conversion of OAM vortex EMFs between linear polarization and circular polarization [47]-[52].

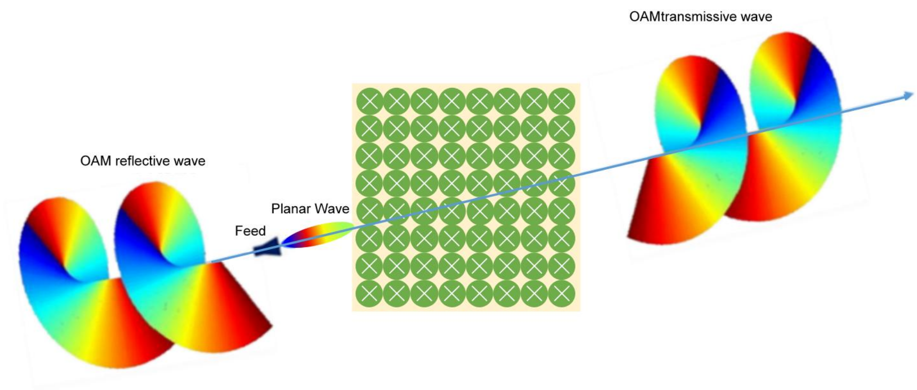


Figure 24 Schematic of RIS-assisted orbital angular momentum (OAM)-based vortex generation

2.2.13.Semantic Communication

Semantic communication is one of the potential communication methods in the future. By sharing part of the knowledge base between the transmitting and receiving ends, artificial intelligence is usually used to mine the relationship between the transmitted information, so that redundant information can be removed, and important information can be extracted, and the purpose of information compression can be achieved. To further improve the communication efficiency, RIS can be installed in the semantic communication system, and the efficiency of the semantic communication system can be better adaptively improved by reasonably and optimally designing the RIS reflection angle and the compression ratio of the semantic information extracted from the transmitter [53].

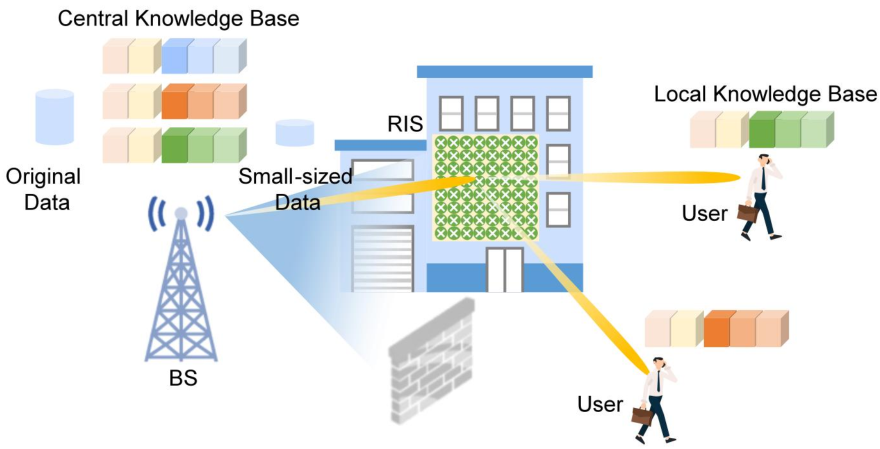


Figure 25 RIS-assisted semantic communication system

3. Fundamental Theories

RIS is a multidisciplinary fusion technology. Before the inception birth of RIS, some related fundamental relative basic theories represented by the metamaterial theory and the surface surface electromagneticss theory have been well developed, laying a solid foundation for the establishment of the theoretical framework of RIS. In terms of key technologies, the phased array, programmable logic gate and other technologies those related to RIS, such as phased arrays and programmable logic gates, have also been applied in other fields. Therefore, the existing theoretical and technical foundations basis support the rapid development of RIS research, although its concept, regarded as a potential 6G key technology, has only been proposed in the past decade.

3.1. Metamaterial Theory

Broadly speaking, RIS is a branch of metamaterials (or electromagnetic metamaterials). Metamaterials can be categorized as three-dimensional metamaterials and two-dimensional metasurfaces, and the latter includes fixed-parameter metasurfaces and tunable metasurfaces. RIS is generally regarded as a tunable metasurface. Of course, fixed-parameter metasurfaces are sometimes considered as a special case of RIS research. Metamaterials were originally known as “left-handed materials” and “double negative medium”. In 1967, Prof. Viktor Veselago published a paper in Russian, which was translated into English in 1968 [54], and proposed the concept of left-handed materials, i.e., the materials with negative permittivity ε and permeability μ. The author analyzed the propagation characteristics of electromagnetic waves in double negative medium systematically, and predicted theoretically many novel anomalous phenomena. In 1996, Sir John B. Pendry realized the negative permittivity with periodically arranged split resonant rings [55], and verified the negative permeability through the periodic arrangement in 1999 [56]. The earliest research on artificial electromagnetic surfaces (i.e., metasurfaces) was the mushroom-shaped high-impedance surface proposed by Prof. Daniel F. Sievenpiper in 1999 [57]. In 2000, based on the work of Sir Pendry, Prof. David R. Smith implemented a composite left-handed material with both negative permittivity and negative permeability.

Three-dimensional metamaterials can use traditional equivalent medium parameters (permittivity and permeability) to describe the electromagnetic properties of materials, but they are no longer suitable for analyzing metasurfaces [58]. For the structural properties of two-dimensional metasurfaces, researchers have proposed a variety of theories for analysis and modeling, the most representative of which is the generalized Snell’s law proposed by Prof. Federico Capasso’s team in 2011 [59]. It well describes the physical properties of electromagnetic metasurface, as shown in equations (1) and (2)

$$n_t sin\theta_t - n_i sin\theta_i dx = \frac{\lambda_0 d\varphi}{2\pi dx} \quad (1)$$

$$sin\theta_t - sin\theta_i dx = \frac{\lambda_0 d\varphi}{2\pi n_i dx} \quad (2)$$

Among them, (1) is the generalized Snell's law of refraction, and (2) is the generalized Snell's law of reflection, λ_0 is the signal wavelength, n_i and n_t are the refractive indices of the incidence and exit surfaces, θ_i and θ_t are the incidence and exit angles.

3.2. Electromagnetic Information Theory

Early electromagnetic metasurfaces usually use continuous or quasi-continuous parameters such as surface polarizability, surface impedance, amplitude, and phase to characterize the electromagnetic properties on the metasurface. All these methods study metasurfaces from the physical perspective, and thus are called "analog metasurfaces". In 2014, Prof. Cui Tiejun's team from Southeast University proposed the concept of "digital coding and programmable metamaterials/metasurfaces", which innovatively uses the form of binary codes to characterize metasurfaces [60], marking the advent of metasurfaces into the digital era from the analog era. After digitally coding the adjustable physical properties of the tunable metasurfaces, the well-developed coding theory and software algorithms in computer science can be used to optimize the physical parameters of metasurfaces. It is also convenient to better use the artificial intelligence (AI) algorithms for intelligent modulation [61]. In 2017, Prof. Cui Tiejun's team published a paper summarizing the existing researches and proposed the concept of "information metamaterials/metasurfaces" [62].

In 2008, Prof. F. K. Gruber proposed the concept of electromagnetic information theory for analyzing the performance of massive MIMO systems [63]. In 2021, Prof. Linglong Dai's team from Tsinghua University proposed to use Electromagnetic Information Theory (EIT) to reveal the fundamental physical limits of the capacity of RIS-based wireless communication systems. It is pointed out that EIT can establish a new analytical framework for deriving degrees of freedom, channel capacity, and other critical performance of communication systems [64].

In 2020, Prof. Cui Tiejun's team established the relationship between the geometric information entropy I_1 of the codebook and the physical information entropy I_2 of the scattering far-field pattern from the perspective of information theory [65]

$$I_1 + I_2 \leq ln\,(4\pi S/e^2\lambda^2) \quad (3)$$

3.3. Surface Electromagnetics Theory

As a new research direction of electromagnetics, the surface electromagnetics (SEM) theory aims to guide the design and optimization of various electromagnetic surfaces by analyzing and explaining different types of electromagnetic phenomena on two-dimensional surfaces.

Electromagnetics is well known to be a fundamental science that describes the law of electromagnetic fields changing with time and space. Therefore, the spatial dimension of electromagnetic field oscillations can be used to distinguish different electromagnetic phenomena and corresponding theoretical methods, as shown in Figure 26. As an extreme simplification of three-dimensional (3-D) phenomena, when the spatial variation of the device or the electromagnetic phenomenon is much smaller than the wavelength in all three spatial dimensions, the circuit theory turns out to be an accurate and efficient method for analyzing 0-D phenomena. Resistors (R), inductors (L) and capacitors (C) are typical components in circuits with voltage and current sources. For 1-D microwave circuits and optical waveguides, the transmission line theory is developed and has become the cornerstone of microwave engineering [66]. The characteristic impedance and the propagation constant are key parameters describing these 1-D phenomena. The SEM theory dealing with 2-D phenomena has not yet been fully developed. The characteristic parameters of the general surface need to be defined and the simplified theorems of Maxwell's equations need to be derived. Moreover, it remains a challenge to utilize appropriate SEM theory to analyze and design cutting-edge electromagnetic surfaces.

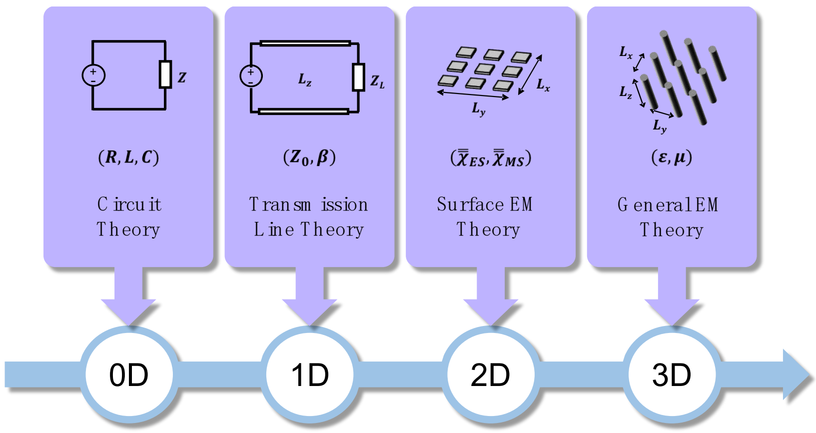


Figure 26 Subject position of surface electromagnetics.

The electromagnetic surface can be classified according to different electromagnetic field properties. Among them, the following three catagories have received extensive attentions:

(1) Space wave control.

As the most basic form of space electromagnetic waves, the plane wave includes five basic properties: frequency, propagation direction, polarization direction, amplitude, and phase. When a plane wave illuminates an electromagnetic surface, the scattered wave can have different characteristics through the specific surface design to realize effective electromagnetic wave control. Representative examples of amplitude-frequency control are frequency selective surfaces [67]-[68] and absorbing surfaces [69]-[72]. The working principle is that when a periodic electromagnetic surface resonates, it causes a total reflection or transmission in a specific frequency band and incident direction.

Phase-frequency controlled electromagnetic surfaces, also known as phase shift surfaces, are usually designed using phase synthesis methods for quasi-periodic or reconfigurable electromagnetic surfaces. The surface phase distribution is used to compensate the spatial phase difference of the incident or scattered wave and to realize beam focusing, shaping, scanning, and other functions.

Polarization control is an additional degree of freedom for electromagnetic waves compared to circuit signals, including polarization selection and polarization conversion. Classic structures include grids, linear-to-circular polarization converters, etc. The design of different polarization control electromagnetic surfaces is roughly based on the methods of polarization decomposition and synthesis.

(2) Surface wave control

In addition to controlling space waves, electromagnetic surfaces can also be employed to manipulate surface waves. The manipulation of surface waves is mainly divided into three aspects: filtering, altering the propagation path, and transforming into space waves. Specific periodic surfaces like HIS [73] and EBG [74] exhibit bandgap behaviors in a frequency range and thus can be considered as bandstop filters for surface waves. Based on the concept of transformation optics, metalenses can design the propagation direction of guided waves. Leaky wave antennas can make surface waves propagating along the surface radiate outwards and generate space waves [75]-[76].

(3) Active and nonlinear functions

Active and nonlinear functions provide an efficient way to achieve reconfigurable properties. PIN diodes, varactor diodes and Micro Electromechanical System (MEMS) are the most popular control devices in reconfigurable electromagnetic surfaces to achieve space-time modulation. In addition, electromagnetic surfaces can be used as spatial circuits, such as spatial power combiners [77]-[79], grid mixers [80] , amplifying reflector arrays [81]-[82], and grid oscillators [77]. The microwave amplifier grid proposed can combine up to 25 identical signal sources without transmission loss. On the other hand, electromagnetic surfaces have more nonlinear properties in optics. Some representative nonlinear optical properties include second harmonics, third harmonics, spontaneous parametric down-conversion, sum and difference frequency generation, four-wave mixing, nonlinear phase control, nonlinear switching and routing, etc. [83].

4. Hardware Structure and Modulation

4.1. System Architecture

The Reconfigurable Intelligence Surface hardware architecture consists of three main components, namely, the feeder module, the reconfigurable electromagnetic surface, and the control module.

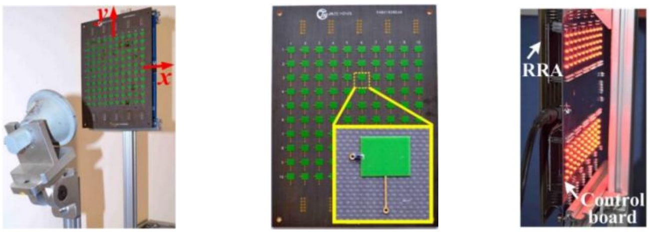


Figure 27 Feed modules, reconfigurable electromagnetic surfaces and control modules

The feed module is the signal input source of the whole system, and its main function is to feed the electromagnetic signal to be emitted to the reconfigurable electromagnetic surface. At present, according to the different feed-in and output modes of the feed module, it can be divided into far-field reflective, far-field transmissive, near-field transmissive, active, and passive integrated, and other modes. Among them, the far-field reflective and far-field transmissive feed modules can adopt either the active transmission mode of the feed antenna in the same system, or the passive reception of remote electromagnetic waves from other signal sources. In this case, although the feed module does not exist as a physical entity, it is still an important part of the entire system.

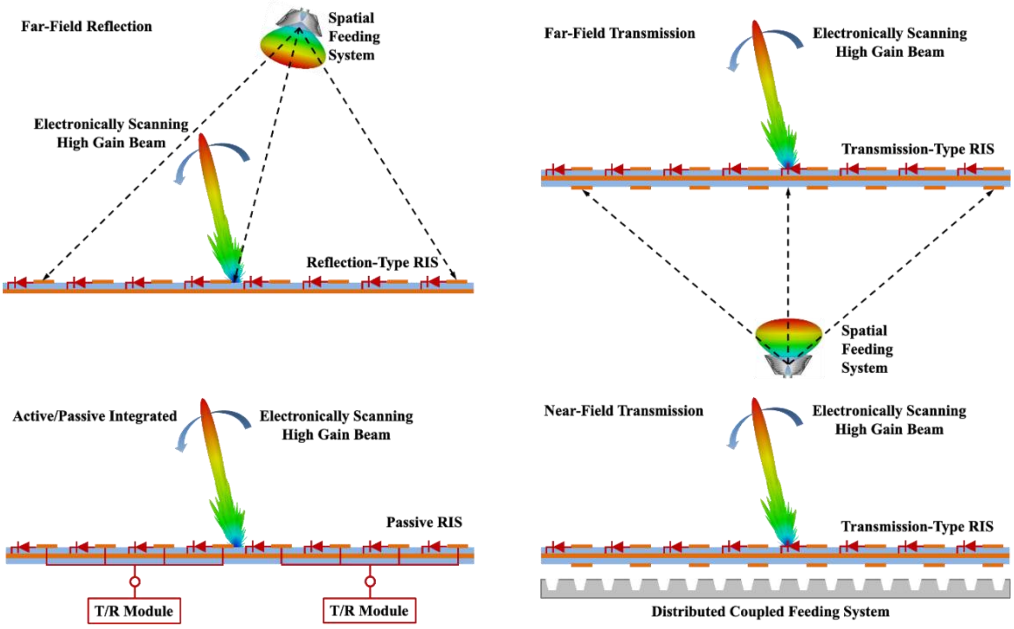


Figure 28 Four Types of Different Feeding Systems

Reconfigurable electromagnetic surface is the main body of the system to regulate electromagnetic waves, usually consists of periodic or quasi-periodic arrangement of electromagnetic units, each electromagnetic unit through the integration of PIN diodes, varactor diodes and other nonlinear devices can respond to the low-frequency control signal given by the control module, change the electromagnetic characteristics of the local unit, and then regulate the high-frequency communication signal from the feeder module.

The main function of the control module is to control the reconfigurable electromagnetic surface, which is usually implemented on a programmable logic gate (Field Programmable Gate Array, FPGA) or a similar programmable platform. According to the control decisions given by the upper system, the control module generates low-frequency control signals and driving voltages and loads them on the nonlinear devices on the electromagnetic surface, thereby realizing real-time control of the functions of the electromagnetic surface.

4.2. Types of RIS

With the evolution of RIS industrial application research, many different types of Reconfigurable Intelligence Surface hardware have emerged in the industry. Table 2 summarizes the types of RIS and their technical characteristics in some public documents.

Table 2 Types of Reconfigurable Intelligence Surface

Technical features	Types
Transmissive or reflective	Reflective, transmissive, reflective-transmissive integrated type[4]
Modulation functions	Information modulation (e.g., Transmitter [4] or backscatter), channel modulation (e.g., beam assignment), new RIS-based phased-array antennas, simultaneous information, and energy transmission (e.g., digital-energy simultaneous transmission), RIS-based airborne computing[4].
Modulation method (device/material)	PIN tubes, varactor diodes, MEMS, liquid crystals, graphene, etc.
Frequency bands	Low frequency (Sub-6GHz), millimetre wave, terahertz and optical bands
Is power amplification available	Passive RIS, Active RIS [4]
Regulatory dynamics	RIS Passive static regulated RIS, Semi-static regulated RIS, Dynamic regulated RIS
Measurement/perception capabilities	Only passive units are available, some active units can perform measurement/sensing
Deployment models	Network control, stand-alone deployment

Different types of Reconfigurable Intelligence Surface can be used in different scenarios according to different actual needs. Taking the dynamic regulation of Reconfigurable Intelligence Surface as an example, the passive static regulation of RIS keeps the beam fixed. It is used for rapid deployment, expansion of weak coverage scenarios, network coverage and blind filling. The RIS is controlled semi-statically, the beam changes semi-statically, and the phase is adjusted at intervals of a

[4] Details in Chapter 6

long period of time. It is used to expand beam coverage and improve cell capacity and speed. Passive static control RIS and semi-static control RIS have the advantages of simple control and rapid deployment. However, since the coverage direction is fixed within a certain period, beamforming cannot be performed for users, and an optimal beam response cannot be made for real-time channel changes. Therefore, a further intelligent RIS should be able to adjust dynamically. The RIS is dynamically adjusted, and the beam changes dynamically in real time. It is used to dynamically track users, match channel environment, and intelligently regulate electromagnetic waves. The dynamic control RIS is further divided into a dynamic control RIS based on beam scanning and a dynamic control RIS based on channel state information (Channel State Information, CSI). The dynamic control RIS based on beam scanning does not require small-scale channel information during the phase adjustment process. RIS scans multiple beam directions and selects the best beam direction based on the channel measurement information fed back by the terminal. Although the dynamic regulation of RIS based on beam scanning has advantages such as no need for small-scale channel information and low control instruction overhead, multiple beam adjustments will also bring large system overhead. The CSI-based dynamic control RIS performs channel estimation through reference signals and configures the codebook according to the channel estimation results. Although CSI-based dynamic regulation of RIS can achieve better performance, the current cascaded channel estimation algorithm and process have high complexity and high system overhead.

4.3. Array Design

Before designing an intelligent surface, a suitable system architecture must be determined based on the actual application scenario. First, consider the system's feeding method, which needs to be selected based on the operating mode, performance metrics, space size and other requirements. For scenarios with high beam gain requirements, reflective smart super-surfaces with low loss are usually used; for scenarios with smaller space dimensions, near-field coupled smart super-surfaces can be used. Secondly, the appropriate control method is selected, including three types of mechanical control, analogue signal control and digital signal control. Mechanical control is now less commonly used due to its slow response time. Analogue signal control generally consists of a control module that generates continuously distributed levels to control devices with continuously varying parameters, such as varactor diodes, to produce different responses. Digital signal control, on the other hand, consists of the control module generating different levels to control different responses from switching devices such as PIN diodes, which can usually be classified as 1-bit or multi-bit control depending on the number of controllable states. Increasing the number of digital signal control bits leads to an increase in the complexity of the surface structure and a decrease in the marginal gain in performance, therefore most of the RIS prototypes at this stage use 1-bit and 2-bit control, with a few prototypes using 3-bit or even more control bits.

4.3.1. Electromagnetic Unit Design and Optimization

Electromagnetic cell design and optimization is the core of intelligent super-surface array design. It is necessary to first determine the cell design objectives according to the actual application requirements, and then optimize the design of the electromagnetic cell body, bias lines, etc.

Firstly, electromagnetic simulation software, such as HFSS and CST, is used to establish an equivalent model of the cell body and non-linear components, configure the periodic boundary conditions and Floquet port excitation. Subsequently, suitable cell geometries are selected and optimized to meet pre-defined design requirements in the operating frequency band, e.g., 1-bit reflective cells requiring a reflection amplitude close to 0 dB and a reflection phase difference of 180°. Finally, structures such as bias lines for connection to the control system need to be considered to verify their effect on the performance of the unit.

Taking a 1-bit digital phase control unit as an example [84] , the design goal is to achieve 1-bit digital phase modulation near 14.5 GHz. For the specific implementation, a classical rectangular resonant cell is chosen, and the resonant length of the cell is changed by the on and off the PIN diode, resulting in two states with different phase frequency responses, making the phase difference between the two states at the center frequency point 180°. By adding bias lines for the control of the PIN diode and fan branches for cross-direct isolation, it can be verified that their effect on the electrical characteristics in the operating band of the cell is small.

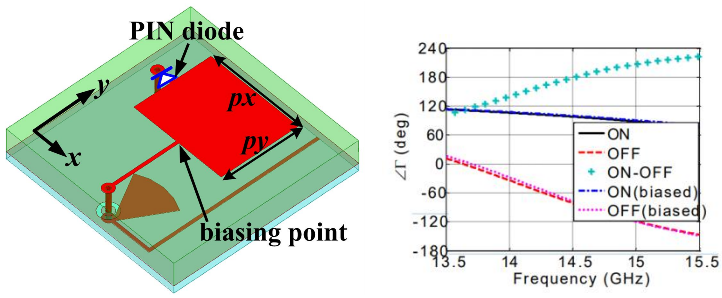


Figure 29 1-bit digital phase-control unit and its phase response

4.3.2. Array Full-Wave Simulation and Processing Test

After completing the cell design, theoretically it has been possible to expand the cell structure periodically to obtain the final RIS model, but generally due to high sub-mode and mutual coupling, there will be some gap between the actual RIS electromagnetic performance and the cell design results under the period boundary, and full-wave simulation is needed for the whole intelligent surface array to guide the actual processing, testing and verification of RIS.

Array full-wave simulation is to model and simulate the whole array and feeder in the simulation software, which has high requirements on computing resources, and the simulation time usually takes several hours or even days. Usually, the array full-wave simulation results are more credible than the cell results, but still cannot replace the actual measurement results.

Real-world testing usually includes waveguide testing, Radar Cross Section (RCS) testing, and far-field testing. Waveguide testing generally requires the design of a suitable waveguide and placing two cells across the waveguide to measure the actual cell characteristics, while RCS testing includes single- or dual-station RCS testing methods, in which all cells on the surface are regulated to the same state and "all-on, all-off" testing is performed to compare and determine the phase difference between the different operating states of the surface cells. The phase difference between the different operating states of the surface units is determined by comparison. The far-field test is based on the actual application scenario and is conducted in a large far-field darkroom or outside field.

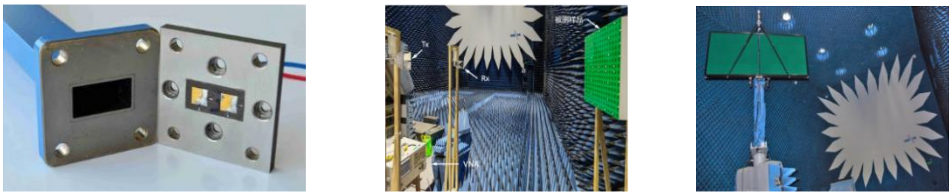


Figure 30 waveguide test, RCS test and far field test

4.4. Design of Control Module

The main function of the control module is to provide RIS units with different phase distributions according to the incident direction and outgoing direction of the RIS beam. The quantized phase distribution of each unit is also called a code table. Use the α-incident and β-exit beam code table to phase the incident beam with an angle of α° with the normal, and then emit in the direction of the angle β° with the normal. The control module is mainly composed of a host computer, a control chip, and a drive circuit, as shown in Figure 31. Among them, the upper computer can be connected to the communication system to provide the control chip with the output direction in real time. The control chip, taking the implementation of the FPGA chip as an example, assigns the code table to the output pin according to the outgoing direction, and the pin is connected to the RIS through the driving circuit and the cable. Since the unit of RIS usually realizes the phase reconfigurable function by PIN, high electron mobility transistor (High Electron Mobility Transistor, HEMT) or varactor diode and other components. Therefore, the drive circuit of the control board only needs to output the corresponding voltage or current according to the digital logic of the pins to complete the phase arrangement of the RIS, thereby completing the control of the RIS.

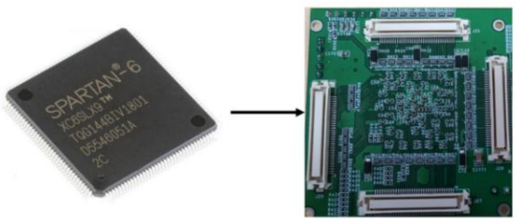


Figure 31 RIS control module diagram

4.4.1. Code Table Extraction of Control Module

Taking the control module based on FPGA as an example, the control code table of RIS can be calculated according to the incident direction. At present, there are two ideas for extracting the code table: one is to calculate the code table in each direction in advance and store it in the FPGA memory or integrated storage, and extract the corresponding code table according to the address according to the instruction of the host computer during work and complete the pin assignment; The other is to implant the code table calculation program into the FPGA chip, and complete the calculation of the code table on the FPGA side. The former has greater requirements on the memory space of the control board, especially positively related to the size of the RIS, but the corresponding Verilog program on the FPGA side is relatively simple; The latter requires the FPGA side to support the code table calculation program, and it is best to execute various code table optimization algorithms, but this can reduce storage requirements, and if a targeted FPGA design is carried out, the FPGA performance utilization rate can be improved.

4.4.2. Response Speed of Control Module

In the RIS auxiliary communication system, the switching speed of the RIS outgoing beam is determined by the response speed from the host computer to the control module and the RIS beam forming speed. The latter depends on the design of RIS and the characteristics of integrated switching devices, while the former depends on the communication code rate of the host computer and communication chip, as well as the program structure and system clock inside the control chip.

In the practical application of RIS, it is necessary to formulate a standard of RIS beam switching time. The bottleneck of the beam switching speed lies in the response speed from the upper computer to the control module. Therefore, in the design of the control module, it is necessary to improve the response speed as much as possible, that is, the time from the host computer to issue the command to the drive circuit to complete the voltage or current bias should be as short as possible.

4.4.3. Potential Functional Requirements of Control Module

In addition to direct control of the outgoing beam by the host computer, the control module may also require adaptive beam switching and network configuration in potential future application scenarios. If the host computer does not know the exact location of the receiver, it can let the RIS perform beam scanning to find the receiver user, end the beam switching and keep the beam stable outgoing or tracking after the handshake with the receiver. The corresponding control module needs to set up automatic beam switching and real-time communication with the host computer to ensure stable tracking of the receiver. On the other hand, the network configuration function is applied to some super large-scale RIS scenarios, due to the limited resources of the control chip, there will be less than the total number of output pins, then the need for multiple control chips to control the same RIS partition, then the control module needs to configure the network, each chip is a network node, so as to achieve synchronous operation of the chip or block operation.

5. System Model and Key Technologies

5.1. RIS-Aided Transmission Signal Model

In addition to the traditional communication link between the transmitter and the receiver, the equivalent cascaded communication link introduced by RIS is added to the communication system. Hence, the received signal $\mathbf{y}$ at the receiver is:

$$\mathbf{y} = \sqrt{P_t}\left(\mathbf{H}_{RU}{}^{\mathrm{T}}\boldsymbol{\Phi}\mathbf{H}_{TR} + \mathbf{H}_{TU}\right)\mathbf{s} + \boldsymbol{\omega}, \tag{4}$$

The equivalent cascaded channel between the receiver and the transmitter is the product of the channel $\mathbf{H}_{RU}$ between RIS and the receiver, the adjustable phase shift diagonal matrix $\boldsymbol{\Phi}$ of the RIS, and the channel $\mathbf{H}_{TR}$ between the transmitter and RIS. $\mathbf{H}_{TU}$ is the direct link between the receiver and the transmitter. Besides, P_t is the transmit power, $\mathbf{s}$ is the signal sent by the transmitter and $\boldsymbol{\omega}$ is the Gaussian white noise.

5.2. RIS Channel Modeling Method

The main channel modeling methods include statistical modeling based on geometry, deterministic modeling based on ray tracing and map-based hybrid channel model. The statistical modeling method based on geometry can well restore the statistical characteristics of the channel in a certain kind of scene. At the same time, its low complexity and convenient implementation make the model become the existing 5G standardized channel model [85]. The deterministic channel modeling method based on ray tracing can identify all multipaths from the transmitter to the receiver through electromagnetic propagation theory, which greatly improves the modeling accuracy. Besides, this model is gradually accepted by the industry and becomes an alternative model of standardized channel Model [86].

5.2.1. Geometry-Based Statistical Modeling Method

The basic principle of geometry-based statistical modeling (GBSM) is to obtain the statistical distribution of the channel characteristics in the scene by a large number of channel measurements. In the process of channel simulation, the complete channel information can be restored by randomly sampling these statistical distributions to generate channel features. Considering the increasing resolution of wireless communication system in time domain, frequency domain and space domain, and the more obvious clustering effect of multipath, GBSM model is based on cluster structure, whose model structure is shown in Figure 32.

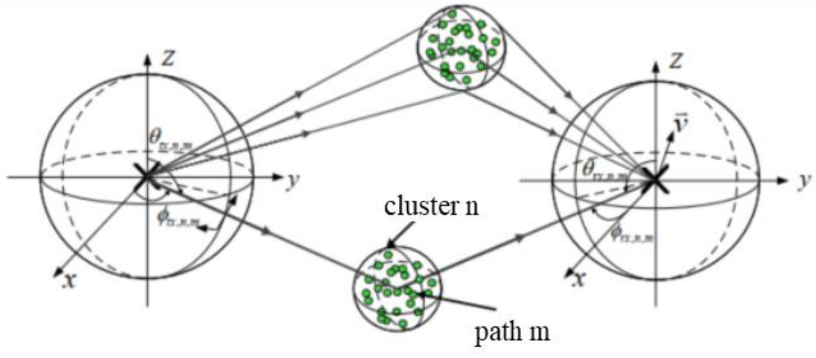


Figure 32 Geometry-Based Statistical Modeling [86]

We focus on the multiple antennas scene that the transmitter has S transmitting antennas and the receiver has U receiving antennas, so that the channel can be represented by a U×S complex matrix. Each unit in the matrix represents the channel impulse response of the corresponding sub-channel, which can be expressed as [86]:

$$h_{u,s}^{3D}(t,\tau)=\sum_{n=1}^{N}\sum_{m=1}^{M}\sqrt{P_{n,m}}\begin{bmatrix}\gamma_{rx,u,p_1}^{3D}\left(\phi_{rx,n,m},\theta_{rx,n,m}\right)\\ \gamma_{rx,u,p_2}^{3D}\left(\phi_{rx,n,m},\theta_{rx,n,m}\right)\end{bmatrix}^T\begin{bmatrix}e^{j\Phi_{n,m}^{p_1,p_1}} & \sqrt{\kappa_{n,m}^{-1}}e^{j\Phi_{n,m}^{p_1,p_2}}\\ \sqrt{\kappa_{n,m}^{-1}}e^{j\Phi_{n,m}^{p_2,p_1}} & e^{j\Phi_{n,m}^{p_2,p_2}}\end{bmatrix}$$
$$\begin{bmatrix}\gamma_{tx,u,p_1}^{3D}\left(\phi_{tx,n,m},\theta_{tx,n,m}\right)\\ \gamma_{tx,u,p_2}^{3D}\left(\phi_{tx,n,m},\theta_{tx,n,m}\right)\end{bmatrix}\cdot e^{j2\pi\lambda^{-1}\mathbf{r}_{rx}^T\mathbf{d}_{rx,u}}\cdot e^{j2\pi\lambda^{-1}\mathbf{r}_{tx}^T\mathbf{d}_{tx,s}}\cdot e^{j2\pi f_{n,m}t}\cdot\delta\left(\tau-\tau_{n,m}\right)\# \quad (5)$$

N, M represents the number of clusters and corresponding links; $P_{n,m}$ represents the power of the m-th link in the n-th cluster; The polarization is introduced in the matrix part, in which there are p_1 and p_2 two orthogonal polarization directions, and γ^{3D} corresponds to the antenna pattern in the polarization direction, $\phi_{rx,n,m}$, $\theta_{rx,n,m}$, $\phi_{tx,n,m}$, $\theta_{tx,n,m}$ are respectively the azimuth angle of arrival (AOA), the zenith angle of arrival (ZOA), the azimuth angle of departure (AOD) and the zenith angle of departure (ZOD) of the m-th path in the n-th cluster, $\Phi_{n,m}$ represents the the initial phase of the multipath and $\kappa_{n,,m}$ represents the cross-polarized power ratio of the corresponding sub link, λ is the center carrier wavelength. $\mathbf{r}_{Tx}$, $\mathbf{r}_{Rx}$ are respectively the direction vector in spherical coordinates for the arrival and departure angles and $\mathbf{d}_{Rx,u}$, $\mathbf{d}_{Tx,s}$ represents the position vector of the antenna corresponding to the transceiver, $f_{n,m}$ means the Doppler effect and $\tau_{n,m}$ means the delay of the corresponding sub link.

The RIS is introduced into the model framework, whose channel model is shown in Figure 33:

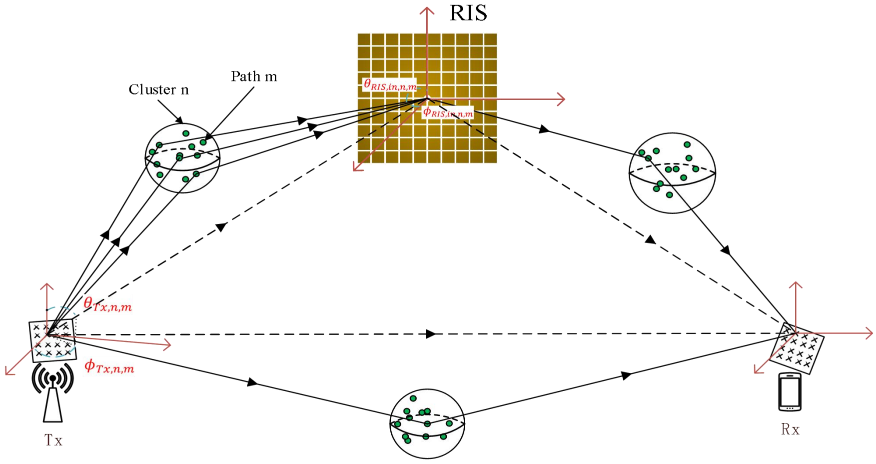


Figure 33 RIS-assisted communication channel model

The basic idea of this model is to divide the original Tx-Rx channel into the RIS-assisted Tx-RIS-Rx communication channel and Tx-Rx direct communication channel, as shown in (6):

$$\mathbf{H} = \frac{1}{\sqrt{PL_{RU}}}\mathbf{H}_{RU}^{\mathrm{T}}\mathbf{\Phi}\frac{1}{\sqrt{PL_{TR}}}\mathbf{H}_{TR} + \frac{1}{\sqrt{PL_{TU}}}\mathbf{H}_{TU}, \tag{6}$$

The first part of (6) is RIS-assisted communication channel, in which H_{TR}、H_{RU} are the channel response matrix from the transmitter to the RIS and the RIS to the receiver, and PL_{TR}、PL_{RU} are the path loss for the corresponding link. The second part is the direct link channel from the transmitter to the receiver, in which H_{TU} the channel impulse response is and PL_{TU} is the path loss. As the electromagnetic properties of RIS can be represented digitally [87], the phased (amplitude-controlled) diagonal array $\Phi = \mathrm{diag}(\alpha_1 e^{j\theta_1}, \ldots, \alpha_k e^{j\theta_k}, \ldots, \alpha_{n\times n} e^{j\theta_{n\times n}})$ is used in the model in which α_k、θ_k is the amplitude control coefficient and phase control coefficient of the k-th RIS unit.

RIS in the RIS-assisted channel model is independent of the cascaded channels whose CIR are H_{TR} and H_{RU}. Take H_{RU} as an example:

$$\mathbf{H}_{RU} = (h_{u,1}^{3D}(t,\tau),\ldots,h_{u,k}^{3D}(t,\tau),\ldots,h_{u,n\times n}^{3D}(t,\tau)), \tag{7}$$

The number of RIS unit is $n \times n$. Taking each electromagnetic unit of RIS as a transmitting unit, the channel response from the k-th electromagnetic unit on RIS to the u-th antenna at the receiving end is expressed in a method similar to (6). It should be noted that the radiation pattern of the transmitting antenna $\gamma_{tx}^{3D}(\phi_{tx,n,m}, \theta_{tx,n,m})$ should be modified to the radiation pattern of the corresponding RIS unit. In the same way, the Tx-RIS channel response matrix H_{TR} can be written.

Based on the above description, the RIS-assisted communication channel modeling process is shown in Figure 34.

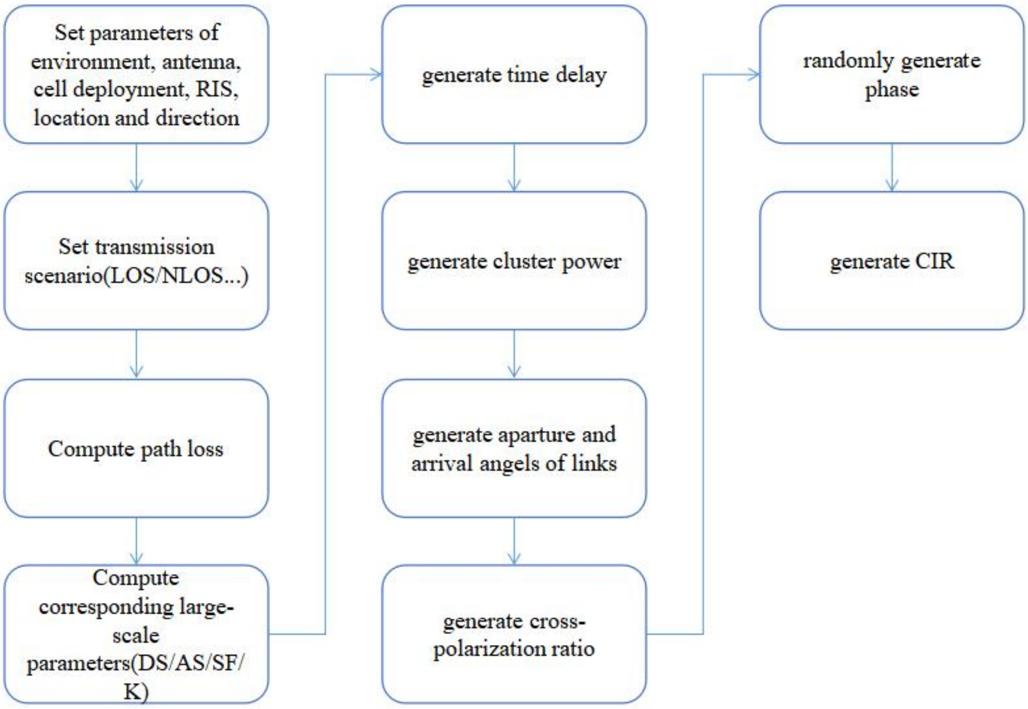


Figure 34 RIS-assisted channel modeling flow chart

The main part of the modeling process is similar to the standard channel modeling process, but some of the work will be different with the introduction of RIS. RIS parameters include the number of RIS units, operating frequency band and minimum electromagnetic unit spacing. RIS position and angle information are expressed as three-dimensional coordinates (x, y, z) of RIS center and normal vector $\mathbf{n}(\theta, \varphi)$. Then the LOS angle information can be calculated. For different RIS deployment scenarios, the path loss generation formula is different, referring to the path loss formula in the 3GPP standard. It should be noted that this model divides the channel into two parts, and the path loss generation is also divided into two parts PL_{RU}、PL_{TR}, in order to decouple the influence of RIS itself from the channel. Channel large-scale parameters include shadow fading (SF), Rician K factor, time-delay spread, and angular spread (ASA/ASD/ZSA/ZSD). Due to different RIS deployment scenarios and locations, the cross-correlation matrix of large-scale parameters will change and adequate measurement data to support it is needed. After obtaining the large-scale parameters, the related small-scale parameters can be generated, including the power, time delay and angle information of the cluster (AOA/AOD/ZOD/ZOA). If you're interested, the generation method can be found in the Step 5 in the section 7.5 of [88]. Because of the introduction of RIS, some generation process of parameters is changed, such as the range of azimuth angle of RIS, the mean and variance of different scene delay, etc. In a word, the influence of RIS on the channel is mainly embodied in the RIS deployment scenario and the location. However, the current RIS-related measurement work is not enough, for example, the empirical path loss formula, large-scale parameter correlation matrix and small-scale parameter generation are still to be studied.

5.2.2. Deterministic Modeling based on Ray Tracing

Different from the statistical channel modeling method, the deterministic channel modeling method is for high-precision restoration modeling of real communication scenes. It reconstructs the real wireless propagation environment, extracts the geometric description and electromagnetic parameters of objects in the environment, and accurately describes the wireless channel based on the electromagnetic wave propagation theory. In the deterministic channel modeling system, there are mainly two kinds of methods: full wave analysis method based on Maxwell equations and ray tracing method based on geometric optics approximation. The ray tracing method is widely used and will be discussed in the chapter.

The ray tracing modeling method can realize the prediction of all ray (path) propagation processes between the transmitter and receiver based on geometric optics theory and uniform theory of diffraction. After accurately simulating the propagation path, parameters such as AOD, AOA and optical path of the ray can be determined. Then, the energy propagation of electromagnetic wave is regarded as the propagation of ray (light). According to the electromagnetic theory and the corresponding reflection coefficient, diffraction coefficient and penetration coefficient, the electromagnetic calculation is carried out to predict the electromagnetic parameters of all paths, and then the channel parameters such as the power of each ray can be obtained. Finally, the propagation characteristics of the channel are calculated, including path loss, angle spread, delay spread, etc., and the channel model corresponding to the specific environment is established.

The process of ray tracing to predict the ray propagation path is called geometric calculation, and the process of calculating the power of each ray based on the geometric calculation results is called electromagnetic calculation, in which geometric calculation is the core part of ray tracing. Geometric calculation includes geometric calculation of reflected rays and geometric calculation of diffracted rays. Its principle is briefly explained below.

For the geometric calculation of reflected rays, a common method is the mirror image method. Suppose Tx represents the transmitting point, Rx represents the receiving point, and O is the reflection point on the plane P_1. According to the mirror image method, find the mirror symmetry point Tx' of Tx about P_1, and connect Tx' with Rx, and the intersection of the line and plane P_1 is the reflection point O. The path starting from Tx, passing through O, and finally arriving at Rx is the desired reflected ray. It is worth noting that the computation of higher-order reflected rays is expensive, and the higher-order reflected rays have little impact on the channel due to their low power, so it is reasonable to ignore the higher-order reflected rays. Reference [89] pointed out that in indoor scenes, when the reflection order of a ray is higher than two, its impact on the channel is almost negligible.

In single RIS-assisted communication systems, the rays arriving at the receiver consists of two parts. The first part is the rays starting from the transmitter, reflected by RIS, and then arriving at the receiver. The second part is the rays directly arriving at the receiver from the transmitter without RIS reflection. Geometric calculation and electromagnetic calculation can be performed on the rays in the two parts respectively, and then the overall channel response can be synthesized.

For the rays in the first part, their geometric calculation is special. This is because when the rays travel to RIS, their reflection behavior can not be simply described as specular reflection, but should be regarded as secondary radiation produced by RIS in accordance with specific direction gain. Moreover, this direction gain is closely related to the phase regulation codebook of RIS. One way to deal with this specificity is to divide these rays into two segments bounded by RIS, the first from Tx to RIS and the second from RIS to Rx, and then perform geometric calculations for each segment. Finally, we spliced the two segments into one segment to complete the geometric calculation of the rays in the first part.

Then, electromagnetic calculation is required for each ray to obtain its power. Similar to the geometric calculation, we once again divide all rays into two segments bounded by RIS [90]. Taking one of the paths as an example, its electromagnetic calculation is done by the following steps. Firstly, complete the electromagnetic calculation of the first segment. This can be done by geometric optics and uniform theory of diffraction, and the calculation results include the path amplitude, phase, etc. Secondly, model the receiving and radiation direction gain of RIS. Some mathematical or electromagnetic methods can be used to model the receiving and radiation direction gain of RIS. Finally, complete the electromagnetic calculation of the second segment. By combining the receiving direction gain of RIS with the electromagnetic calculation results of the first segment, the receiving power of RIS can be calculated. Then, RIS is regarded as an antenna that radiates signals outward according to its radiation direction gain, and the radiation power is its received power. Thus, by combining the radiation direction gain and radiation power, the electromagnetic calculation of the second segments can be completed.

It is worth noting that during the electromagnetic calculation of the rays in the first part, the emphasis is on modeling the receiving and radiation direction gain of RIS. For the receiving direction gain of RIS, a modeling method is given in [91], which can be expressed as:

$$\mathrm{F}\left(\theta_{\mathrm{ZOA}}\right)=\begin{cases}\sqrt{\cos\left(\theta_{\mathrm{ZOA}}\right)}, & \theta_{\mathrm{ZOA}}<\dfrac{\pi}{2}\\[2mm] 0, & \theta_{\mathrm{ZOA}}>=\dfrac{\pi}{2}\end{cases}, \tag{8}$$

Where, F represents the receiving direction gain, θ_{ZOA} represents the zenith angle of arrival of the ray. Here, the local coordinate system takes the direction of RIS normal vector as the positive direction of z-axis. In this method, the RIS area is not included, this is because the effect of RIS area is included in the RIS radiation direction gain in this literature.

As for the receiver direction gain of RIS, it can be obtained by coherently superpose the radiation direction gain of each unit, after considering RIS codebook and RIS array steering vector. A superposition formula is given in reference [91]. Further, the radiation direction gain of each RIS unit can be obtained from electromagnetic scattering theory such as physical optics method or full wave method, and some simplified methods of mathematical fitting. In reference [92], the authors fit the receiving and radiation direction gain of RIS units with a cos^q mode.

For the rays in second part i.e., rays that are not reflected by RIS but directly arrive at the Rx from the Tx, the geometric calculation and electromagnetic calculation conform to the standard process of ray tracing, which is not different from the communication system without RIS.

Finally, a deterministic channel model of a single RIS assisted system is obtained by combining the above two parts rays and extracting the power, delay, AOA, AOD and other information of each ray.

5.2.3. Hybrid Channel Modeling Methodology and RIS Physical Model

Map-based Hybrid Channel Model (MHCM) has been adopted by 3GPP and ITU for scheme selection and performance evaluation of mobile communication systems. The relevant model provides large-scale and small-scale 3D channel characteristics between base station and user equipment. It supports modeling of 0.5 GHz ~ 100 GHz band, large bandwidth, large-scale Multiple-Input Multiple-Output (MIMO), spatial consistency, blocking, oxygen loss, time varying, Doppler, absolute time of arrival, dual movement, deterministic ground reflection and other characteristics. MHCM balances the accuracy of the channel model and the amount of computation. It is composed of deterministic part and stochastic part. The deterministic part is calculated by ray tracing technology to reflect the deterministic component of the channel. The influence of map inaccuracy, configuration simplification and rough surface scattering is supplemented by stochastic part to reflect the random component of the channel.

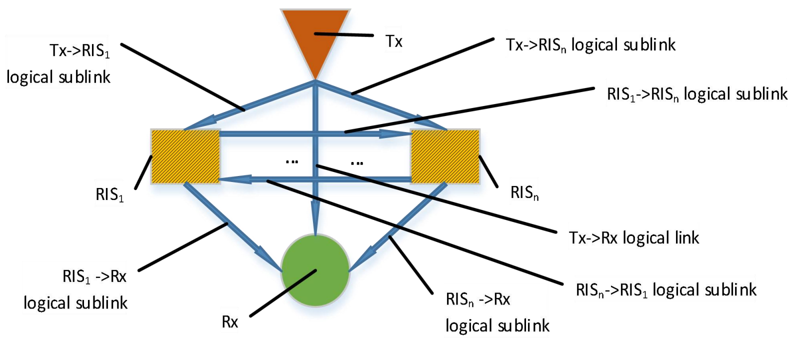


Figure 35 Channel logical links digraph between Tx and Rx

On the basis of MHCM [92], when the base station is the transmitting signal source Tx, the user equipment is the receiving device Rx, and multiple RISs are the passive controllable reflection nodes, the channel model between the Tx and the Rx shall consider the wireless channel link between the Tx and the Rx in existing model, as well as the link between Tx-RIS-Rx. The key lies in 1) Tx-RIS channel model; 2) RIS response model to the polarization incident signal excitation with different incoming wave directions under the specific codebook of RIS; 3) RIS-RIS channel model; 4) RIS-Rx channel model.

In order to balance complexity, precision and usability, possible logical links combinations can be specifically determined based on the deployment principles and regulatory objectives of RIS, since only the signals received by RIS have sufficient strength, can RIS have a significant impact on the final channel response, which is also based on the consideration of the balance between model efficiency and model precision. Figure 35 shows the channel modeling process of RIS based on MHCM model [92].

The RIS panel can be modeled as multiple virtual logic base stations excited by multiple incident polarization electromagnetic waves. The transmitted power of each logic base station is determined by the power density of incoming waves, direction of wave vector, RIS panel area and insertion loss based on the principle of energy conservation. The polarization radiation pattern of each logical base station is determined by the array factor pattern determined by the codebook of RIS panel and the polarization radiation pattern of RIS unit. Based on the theory of electromagnetic scattering and the Stratton-chu equation, a method for determining the polarization radiation pattern of RIS unit is proposed under the assumption that RIS units are perfect electrical conductors. The effectiveness of the method is verified by comparing the measured results and the simulated models.

For a perfect electric conductor, the surface electric current units is excited by the magnetic field, which needs to be decomposed into two polarization directions combined with the polarization configuration of RIS units. Then, based on the codebooks of RIS units in different polarization directions, the synthetic radiation pattern of RIS units or field intensity at a specified field point is calculated. The scattered electric and magnetic fields stimulated by different polarization feed electromagnetic waves can be further simplified and decomposed into:

$$\begin{aligned}
\vec{E}^{s}_{pol_x}\left(\vec{r}\right) &= \frac{-jkZ_0}{4\pi}\iint_S \hat{r}\times\left[\hat{r}\times\left[(\hat{n}\times\vec{H}^{t})^{T}\bullet\vec{V}_{pol_x}\right]\vec{V}_{pol_x}\right]\cdot\frac{e^{-jk|\hat{r}|}}{|\hat{r}|}ds' \\
\vec{H}^{s}_{pol_x}\left(\vec{r}\right) &= \frac{jk}{4\pi}\iint_S \hat{r}\times\left[\left[(\hat{n}\times\vec{H}^{t})^{T}\bullet\vec{V}_{pol_x}\right]\vec{V}_{pol_x}\right]\cdot\frac{e^{-jk|\hat{r}|}}{|\hat{r}|}ds' \\
\vec{E}^{s}_{pol_y}\left(\vec{r}\right) &= \frac{-jkZ_0}{4\pi}\iint_S \hat{r}\times\left[\hat{r}\times\left[(\hat{n}\times\vec{H}^{t})^{T}\bullet\vec{V}_{pol_y}\right]\vec{V}_{pol_y}\right]\cdot\frac{e^{-jk|\hat{r}|}}{|\hat{r}|}ds' \\
\vec{H}^{s}_{pol_y}\left(\vec{r}\right) &= \frac{jk}{4\pi}\iint_S \hat{r}\times\left[\left[(\hat{n}\times\vec{H}^{t})^{T}\bullet\vec{V}_{pol_y}\right]\vec{V}_{pol_y}\right]\cdot\frac{e^{-jk|\hat{r}|}}{|\hat{r}|}ds'
\end{aligned} \tag{9}$$

Where, $\vec{V}_{pol\_x}$ and $\vec{V}_{pol\_y}$ are the unit vectors of RIS in two orthogonal polarization directions,

Z_0 is the free space wave impedance, $\vec{E}^s$ and $\vec{H}^s$ are the electric field intensity and magnetic field intensity of the field point, respectively. $\vec{H}^t$ is the total field intensity of the surface magnetic field at the source point of RIS units, $\vec{n}$ is the unit normal vector of the source point position in RIS uints, $\hat{r} = \vec{r} - \vec{r}^{'}$, $\vec{r}^{'}$ is the source point position vector, $\vec{r}$ is the field point position vector, S is the RIS units region. $\vec{k}$ corresponds to the wave vector at the carrier frequency.

When the polarization direction and incidence angle of the feed-in electromagnetic wave vector are given, in the case of far field, the polarization radiation patterns corresponding to the two orthogonal polarization components of RIS units can be obtained through comprehensive normalization on the basis of equation (9), considering energy conservation and far field conditions of RIS units.

The phase regulation of each unit of the RIS panel can be regulated independently or synchronously along two polarization directions, or the phase of only one polarization direction can be adjusted, depending on the specific RIS panel configuration or implementation. For the single-polarized RIS panel, the codebook of non-controllable direction can be configured as a fixed value π. For the dual-polarized codebook homology RIS panel, RIS units can be configured with the same codebook or codebook with fixed phase deviation.

For the linear polarization fed electromagnetic wave with a given incidence angle, two independent polarization radiation patterns can be excited based on RIS panel polarization configuration and codebook configuration, which is the basis for RIS panel to be equivalent to virtual base stations.

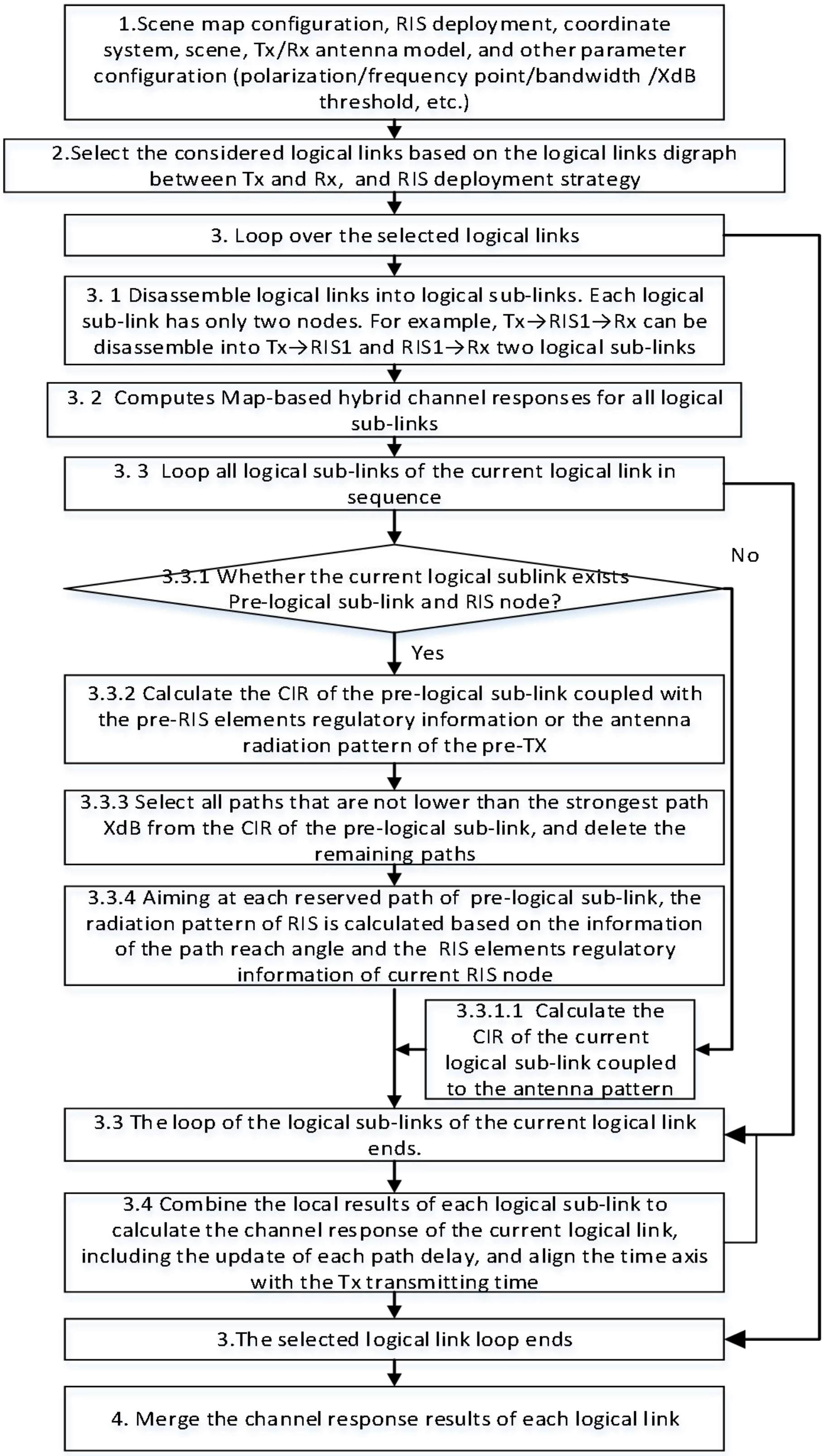


Figure 36 RIS wireless channel modeling process

5.3. Key Technologies of RIS-assisted Communication Network

5.3.1. Channel Estimation and Feedback

In the RIS-assisted wireless communication system, in addition to the direct channel between the BS and the terminal, the reflection channel components include "BS-RIS" and "RIS-terminal", which are called cascaded channels. Cascaded channel state information (CSI) acquisition is one of the basic problems to be solved in the quasi passive RIS system [92]-[100]. In order to enhance the performance of RIS and achieve intelligent control of the electromagnetic environment, accurate CSI acquisition is indispensable. Channel information acquisition includes channel estimation, beam training, codebook feedback and other technologies. The acquisition of RIS channel information faces many challenges. For example, the increasing number of RIS units results in the much higher dimension for channel estimation; passive channel estimation makes it difficult to acquire segmented channels; the increasing RIS surface size causes near-field channel estimation problems; the hardware errors affect the accuracy of channel estimation; and beam offset occurs in broadband channels and so on.

Design based on binary reflection [101]: the whole channel estimation time is divided into several sub stages. In the first sub phase, all the reflection units in the RIS are closed. The BS only needs to estimate the direct channel from the BS to the user. Therefore, the wireless communication system based on RIS can be simplified into a traditional wireless communication system without RIS. Furthermore, the estimation of the direct channel can be realized through classical solutions, such as least square method or least mean square error algorithm. In each subsequent sub stage, the individual reflection units of the RIS are opened in turn, and the remaining reflection units are kept closed. The BS successively estimates the cascaded channels from the BS to the reflection unit and from the reflection unit to the user. Finally, the channel estimation of the whole system is completed through the estimation results of all sub stages by least square method or least mean square error algorithm.

Design based on minimum variance unbiased [102]: during the whole training phase, all reflective units of RIS are turned on. First of all, the estimation time of the whole cascade channel is still divided into several sub stages. In each sub stage, the optimal phase shift matrix of RIS is represented as discrete Fourier transform matrix[103]. Therefore, the cascaded channel is estimated based on all received pilot signals of all sub stages.

Two timescale-based design [104]: consider two different timing. The location from the BS to the RIS is usually fixed. Therefore, the channel status remains unchanged for a long time, which is represented by large-scale timing attributes. Because of the mobility of the user, the channel state between the user and the BS and the RIS will change frequently. Therefore, it is a small-scale timing attribute. Among them, the high-dimensional channel matrix in large-scale time series can be estimated by the dual link pilot transmission strategy. In the long run, the pilot overhead caused by high dimensions can be ignored. In small-scale time series, although channel information needs to be estimated frequently, due to its low dimensionality, its pilot overhead is very low. Therefore, the average pilot overhead will be reduced.

Design based on multi-user correlation [105]-[107]: First, the cascaded channel of the first user is estimated by the channel estimation method based on minimum variance unbiased. Then, the cascaded channels of other users are estimated based on the correlation between multiple users to reduce pilot overhead. Note that the correlation between multiple users is due to the fact that all the users share the same (common) RIS-BS channel, As such, by exploiting the common RIS-BS channel property, the training efficiency can be substantially improved and more users can be accommodated concurrently for channel estimation in the RIS-aided multi-user system

Compressive sensing-based design [103]: Compressive sensing can compress sparse cascaded channels to reduce pilot overhead. However, traditional compressed sensing algorithms, such as orthogonal matching pursuit, can not achieve enough accuracy of channel estimation, especially in the case of low SNR. Therefore, the joint sparse matrix recovery method based on channel estimation is proposed to solve the problem of accuracy, but its pilot cost is still high. Furthermore, the whole RIS is divided into several sub planes, where all RIS reflection units in the sub planes have the same channel coefficients. Therefore, in this way, the estimated channel coefficients will be greatly reduced. If these two technologies are combined, the pilot overhead will be greatly reduced.

Channel estimation based on RIS discrete phase shifts [108]: In practice, RIS phase shifters can only operate with a finite number of discrete phase-shift values due to the hardware constraint, thus rendering the DFT based RIS training reflection design inapplicable. To address this issue, one efficient method is to construct near-orthogonal reflection coefficients using proper quantization techniques (e.g., DFT/Hadamard-matrix quantization) for general cases; while in some special cases, it can be shown that the simple DFT/Hadamard matrix is still an optimal training relfection.

Design based on full-ON reflection [103], [109]: Apart from binary reflection design, full-ON RIS training reflection design based on some special matrices (e.g., the DFT matrix, Hadamard matrix, and circulant matrix generated by Zadoff-Chu sequence) has been developed for the cascaded channel estimation. The channel estimation accuracy can be significantly improved by exploiting the full RIS aper-ture gain with the full-ON RIS training reflection pattern. Furthermore, the training reflection pattern at the RIS can be jointly designed with the pilot sequence at the transmitter, so as to achieve perfect orthogonality over the RIS-reflected signals for minimizing the channel estimation error.

Low overhead codebook feedback design [111]: For RIS assisted MIMO systems, the downlink channel feedback of frequency division duplex becomes a huge challenge due to the expansion of cascade channel dimensions. To solve this problem, part of the research design is based on the transmission scheme design of limited parameter feedback. One direction is to design an analog phase shifter at RIS based on layered analog codebook and limited feedback message overhead to indicate the optimal beam index. In addition, we can further analyze the characteristics of RIS channel to reduce the dimension of the cascade channel feedback more efficiently and use low dimension codebook for feedback.

Adaptive cascade feedback codebook design [112]: For the BS-RIS-user channel cascaded by RIS, the BS-RIS subchannel and RIS-user subchannel have different channel distribution characteristics due to different mobile states of the BS, RIS and user. In order to better quantify segmented subchannels and improve channel feedback accuracy, adaptive cascaded feedback codebooks can be designed according to the distribution characteristics of subchannels. Under limited feedback overhead, quantized codewords conforming to channel characteristics can be dynamically generated through reasonable allocation of feedback bits, which can reduce the performance loss caused by limited feedback.

Design for passive reflection characteristics [114]-[115]: RIS has passive reflection characteristics. It does not need to configure a large number of RF links, and has a large number of arrays, which makes it difficult to obtain its CSI. To solve this problem, part of the research adopts the RIS hardware structure design of active units with a small number of sensing and signal processing functions. This is to deploy a small number of active components connected to baseband on the passive RIS surface, estimate and reconstruct the RIS channel with significantly reduced pilot number through compression sensing tools, and use deep learning to study the reflection matrix design to achieve the performance close to the upper limit of the rate. For pure passive RIS, in the first stage, AOD and UE of BS are estimated first, and then other channel compositions are estimated; For hybrid active sensor RIS, it is assumed that alternate uplink and downlink training is used to estimate segmented channels, which can achieve channel estimation at lower channel path loss.

Assume that the complete CSI of the current communication system can be obtained at the BS. The existing transmission design work can be divided into perfect CSI and imperfect CSI. Perfect CSI considers transmission design based on the assumption that instantaneous CSI is fully available. Considering that the channel estimation error is inevitable, if the estimated CSI is considered perfect in the transmission design, the solution may not meet the QoS requirements. In the RIS-aided communication system, this problem is further aggravated due to the need to estimate additional channels related to RIS. Therefore, it is necessary to consider the robust transmission design of channel estimation error. Among the early contributions in this field, most of them studied the imperfect channel from the RIS to the user and believed that the channel from BS to RIS was perfect. This method needs to estimate the BS-RIS and RIS-UE channels respectively, which is difficult to implement in practice. The existing research proposes a robust transmission design framework for RIS assisted multi-user system based on cascaded channel imperfect CSI, which uses bounded CSI error model and statistical CSI error model to characterize the cascade channel estimation error.

5.3.2. Beamforming

The principle of RIS beamforming is to change the phase response of the reflection unit to the incident electromagnetic wave, so that the reflection waves of all the reflection units on the panel in a specific direction are superposed in the same phase, so that the reflected energy is concentrated in a small solid angle. Beamforming can not only obtain higher directional gain, but also reduce the interference of reflected signals to adjacent areas. Through the joint optimization of precoding beamforming on the BS side and the RIS side, more secure wireless communication can also be achieved.

As the phase shift design of the RIS is fully coupled with the beamforming design at the base station (BS), it needs to adjust a large number of reflecting elements frequently in high-speed moving scenes, which makes it difficult to obtain the accurate beam direction [116]-[117]. To address this challenge, one direction is to jointly optimize the beamforming strategy at the BS and the phase shifts at the RIS. In addition, recent research shows that sensing-enhanced wireless communication can be considered to reduce reflecting elements adjustment frequently. It is a brand-new technique that combines the characteristic of radar, navigation and communication to track the target's location, distance and velocity. According to the diversification of users' demands, the phase shift design of the RIS can be designed based on the location of target, which can reduce the running time of beam scanning. The distance and velocity can be also used to improve beam tracking and so on. During this processing, the RIS can not only provide the line-of-sight (LOS) path for radar sensing, but also improve the quality of communications by concentrating signal power on the target.

5.3.2.1. Beamforming Algorithm

For scenarios where RIS is used to improve coverage, there is usually no direct link between the BS and the terminal due to the presence of blocking. It is necessary to rely on RIS to generate artificial reflection paths to form a virtual direct link. If there are only direct paths between the BS and the RIS, or between the RIS and the terminal, or multipath paths other than the direct path can be ignored, the beamforming design is relatively simple. However, the actual application scenarios are generally more complex, which increases the complexity of joint optimization of precoding beamforming on the BS side and the RIS side. For example, there may only be NLOS paths between the BS and the RIS, or between the RIS and the terminal, or there may be LOS and NLOS paths at the same time, which will complicate the channel. Another example is that a single RIS serves multiple users, multiple RIS serves a single user, multiple RIS serves multiple users, or even multiple BTSs and multiple RIS work together to serve multiple users, and multiple RIS work together to achieve multi-hop transmission. For these complex scenarios, from the perspective of interference suppression, channel capacity, energy efficiency, spectral efficiency, etc., a joint beamforming design is required for the BS and RIS. At this point, the problem to be solved is no longer a simple problem of regulating beam reflected by RIS, but a problem of optimizing the performance of RIS assisted communication systems under certain constraints.

Based on the Alternative Optimization (AO) algorithm: joint beamforming design is usually difficult to obtain a closed solution due to multiple constraints, which can only be solved by numerical methods. However, the non-convex nature of its optimization model makes it difficult to solve by conventional methods, which usually requires iterative solution in the form of alternative optimization. However, there are differences in the constraints, optimization objectives or research scenarios used. The optimization objectives include: "maximizing spectral and energy efficiency", "maximizing the minimum signal-to-noise ratio of multiple users", "minimizing the symbol error probability", "maximizing the sum rate of multiple users", etc. Constraints include "maximum power constraint of BS", "minimum SNR constraint", " outage probability constraint", etc. The main problem of the alternative optimization algorithm is that it needs to deal with the delay, and the complexity is relatively high. The convergence efficiency of the iterative solution and avoiding falling into the local optimum are issues that need special attention in practical applications, especially in ultra-low delay transmission or ultra-high speed mobile scenes. In addition, accurate high-dimensional concatenated channel information is very difficult to obtain, and the algorithm performance is very dependent on it.

Based on the Semidefinite Relaxation (SDR) optimization algorithm: a conventional method to deal with the constraint conditions of non-convex unit modulus is to convert the passive beamforming vector of RIS into a semi positive definite matrix with rank 1. By using the Semidefinite Relaxation method and ignoring the constraint condition of nonconvex rank 1, the original nonconvex problem is transformed into a convex positive semi-definite programming (SDP) problem. This problem can be solved by many effective convex optimization tools (CVX). However, if the rank of the obtained matrix is not 1, the Gaussian random method is usually used to solve this problem. However, in general, the solution obtained by the constructed rank 1 solution is suboptimal. This solution may not be valid for the design of the original RIS passive beamforming. It will not only reduce the overall performance, but also cannot guarantee the convergence of the AO based iterative algorithm. Therefore, two other effective algorithms, including fixed-point iteration method and manifold optimization method (MO), are used to design the RIS passive beamforming. Compared with SDR, these two algorithms can achieve relatively high system performance and low computational complexity.

Based on branch and bound (BnB) optimization algorithm: due to the nonconvex characteristics of the RIS passive beamforming, it is difficult to obtain the optimal solution through standard convex optimization. The branch and bound method can solve the NP hard discrete and combinatorial optimization problems, as well as some specific continuous function optimization problems. Therefore, for the problem of the RIS passive beamforming, the branch and bound method can obtain the global optimal solution, although this method requires higher computational complexity. However, this method can be used as one of the performance benchmarks to verify the effectiveness of the algorithms related to sub-optimal solutions.

Iterative-based optimization algorithm: its main idea is to obtain local optimal solution or sub-optimal solution with acceptable computational complexity. These algorithms include not limited to continuous thinning algorithm, conjugate gradient algorithm, fixed-point iteration algorithm and manifold optimization algorithm (MO). These algorithms can better balance performance and computational complexity.

Optimization algorithm based on quantization: under the assumption of limited phase shift, the quantization method can relax each discrete phase shift variable into a continuous variable. By relaxation, the obtained continuous variable is quantized to the nearest discrete value. However, the quantization method may lead to the degradation of system performance. In addition, after continuous relaxation, the constraint condition of non-convex unit modulus still exists.

Feedback-based greedy algorithm: In an RIS-aided communication system, it is necessary to obtain the phase shift matrix of the RIS elements in order to adjust the electromagnetic characteristics of the RIS and properly aim the reflected beam toward the desired users. The feedback-based greedy algorithm is a low-complexity searching scheme that can efficiently adjust the array states to enhance the SNR on the receiving side, avoiding the extremely high time complexity of the exhaustive search method. By continuously altering the states of the RIS array and maximizing the received power, a local optimal solution with high performance gain can be attained in a short period, which is validated in practice [110].

5.3.2.2. Beam Training

Codebook based design can effectively reduce the feedback overhead, which plays an important role in reducing system costs and improving communication efficiency. Due to the cascade channel characteristics brought by RIS, its corresponding training codebook is usually a hierarchical codebook, which makes its codebook training different from traditional MIMO. Therefore, it is necessary to reasonably design RIS codebook and beam training scheme.

The fast beam training scheme of RIS based on codebook [111]:In order to reduce the pilot cost of RIS-assisted uplink communication, the fast beam training scheme proposed in the document divides the beam training into two stages. In the first stage, the user uses omni-directional transmission, and RIS carries out beam training to obtain the optimal passive beam; In the second stage, RIS uses the optimal passive beam and is fixed, and the user carries out beam training to obtain the optimal active beam. In addition, in the beam training at the RIS end, the multi-beam scanning scheme is proposed to further reduce the pilot overhead required for beam training.

RIS phase-shift optimization based on layered codebook [112]: First of all, layered analog precoding codebook and layered hybrid precoding codebook applicable to RIS based on least square method are proposed, and the codebook design needs to meet the power constraints and hardware constraints. Based on the proposed layered codebook, the beam training is divided into multiple stages. Each stage tests the codewords to be tested in different layers of codebooks, and the codewords to be tested in each layer are determined by the optimal codewords in the upper layer. With the beam training, the range of optimal codewords is continuously reduced until the optimal codewords of RIS and mobile terminal are found. In addition, the author also locates the mobile terminal based on the optimal codewords obtained from beam training to obtain higher transmission rate.

RIS beam training based on concatenated codebook: The concatenated codebook consists of two sub-codebooks, and the codewords in the two sub-codebooks are applicable to the LOS path and non-LOS path respectively. Therefore, the codebook can change its structure according to different scenarios and capture different distribution characteristics of path gain. On the basis of the proposed cascade codebook, the theoretical upper bound of the BER in the case of finite feedback bits is derived, and the finite channel feedback scheme of dividing the feedback bits into four parts to generate the sub-codebook is proposed to minimize the upper bound of the BER.

Multi-beam RIS beam training [113]: Multi-beam training method is an effective approach to reduce the RIS beam training overhead by the exhaustive search. To be specific, RIS reflecting elements can be divided into multiple sub-arrays to steer different beam directions simultaneously. By simply comparing the received signal power over time, each user can detect its optimal RIS beam direction with a high probability, even without searching over all possible beam directions as the single-beam training. This multi-beam training method needs neither user feedback as in the hierarchical beam training, nor the exhaustive search as in the sequential beam training, thus significantly reducing the training overhead for RIS-aided multi-user systems.

5.3.2.3. Joint beamforming and information transmission

Joint beamforming and information transmission aims to further improve the information transmission speed of RIS-aided system. In this scheme, RIS, on the one hand, reflects electromagnetic waves directionally through beamforming to enhance communication between transceivers. At the same time, by adjusting the electromagnetic wave response of the reflection unit, RIS modulates additional information on the reflection signal to passively upload its information [38].

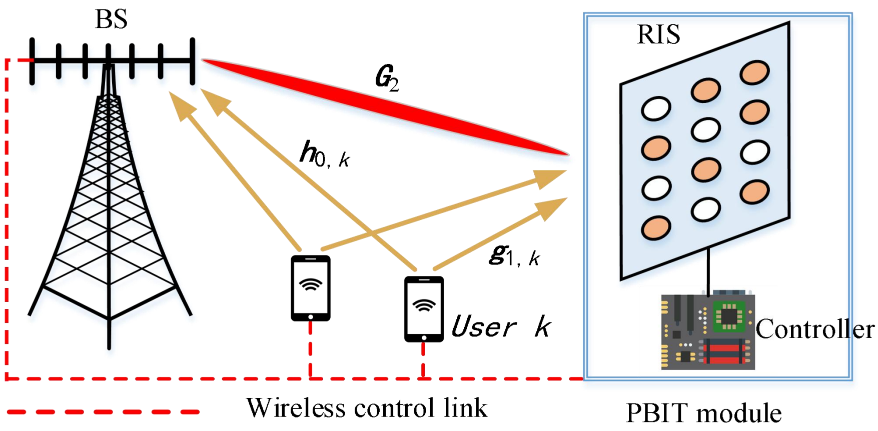


Figure 37 Joint beamforming and information transmission system based on RIS

On the one hand, the information transmission capability of RIS can meet its own communication needs. First, in a communication system, RIS needs to upload handshake information during link establishment and report confirmation information during transceiver synchronization. Secondly, a certain amount of information needs to be uploaded during the configuration and maintenance of the RIS-aided communication system. For example, real-time monitoring of RIS working environment (such as temperature, humidity, pressure, etc.) is required to avoid damage to RIS components and report fault information when damage occurs. On the other hand, RIS's passive information transmission capability can assist other small devices around it, such as sensors, to transmit information, thus helping to build a green Internet of Things system. Compared with uploading information through a dedicated RF link, the RIS based joint beamforming and information transmission mechanism has the following three main advantages: 1) no additional hardware costs and energy consumption are required to generate or retransmit RF signals; 2) No additional time/frequency resources are consumed, because RIS information is modulated on the reflected signal from the RF transmitter; 3) The joint beamforming and information transmission of RIS have the potential to improve the multiplexing gain of RIS-aided systems.

There are still many open issues with respect to the joint design of beamforming and information transmission in RIS systems. The first is the design of RIS reflection mode. That is, how to design the information modulation mode of RIS (such as switch modulation, amplitude modulation, phase modulation, frequency modulation) to simplify the design of RIS assignment communication system, so that the system has greater capacity, higher degree of freedom, etc. The second is beamforming design. Since the electromagnetic wave response of RIS unit carries additional information, the state of its reflection unit has certain randomness. This makes the beamforming design of RIS a random optimization problem. It is usually more difficult to solve the stochastic optimization problem than to solve the deterministic optimization problem involved in traditional beamforming design. Thirdly, since the information from RIS is modulated on the signal from the RF transmitter, the two channels of information are multiplied together. It is a bi-linear signal recovery problem for the receiver to recover the two channels of information simultaneously based on the observed signal. This is more complex than the single linear signal recovery in traditional communication systems. In addition, the joint beamforming based on RIS and the channel capacity characterization of information transmission system, the joint beamforming of transmitter and RIS, and the integrated design of transceiver and RIS are also worthy of further study.

To solve the problem of high complexity of RIS beamforming, literature [118] proposed a low complexity design scheme based on RIS zoning. The design of RIS zoning no longer optimizes reflection elements unit by unit, but considers each block as a design entity, thus reducing the complexity of RIS beamforming problem. Specifically, RIS zoning design explores the reflection characteristics of each block to the incident electromagnetic wave, optimizes only the reflection direction and wave front phase of each block to the incident electromagnetic wave, and realizes the macro-control of the RIS at the block level to greatly reduce the system optimization cost.

5.3.3. AI-Empowered Technologies

The key idea of artificial intelligence (AI) enabling RIS communication is to solve the key signal processing problems in RIS communication using AI-based technology, such as channel acquisition, beamforming design and resource scheduling, so as to obtain higher system efficiency than traditional technology. By training massive data sets, channel acquisition can be more accurate. In addition, AI can also help overcome the nonlinear problems caused by hardware damage and pilot pollution. In addition, by formulating different AI learning strategies, beamforming design can be configured for different purposes, and resource scheduling can be realized to build a better network topology. Therefore, AI will help to enhance the robustness of the overall design for beamforming design and resource scheduling.

5.3.3.1. AI-enabled Cascaded CSI Acquisition

In order to make full use of the collected data or solve the problem of channel estimation when the channel model is unknown, a new method of artificial intelligence can be used for channel estimation. The rapid development of AI in recent years has provided a new processing paradigm for traditional wireless communication and brought a new solution for RIS channel estimation [119]. The inherent characteristics of AI real data, processing signals in a data-driven manner, are applicable to non-ideal RIS scenarios such as model mismatch, insufficient resources, hardware damage, and dynamic transmission.

For the acquisition of direct channel, literature [120] proposes to directly estimate the cascading channel of RIS communication, and describes the channel estimation problem as a de-noising process. Then the deep residual learning (DReL) method is used to implicitly learn the residual noise to recover the channel coefficients from the observation based on noise pilots. Next, the minimum mean square error (MMSE) estimator based on the deep residual network is derived with the help of the Bayesian principle. However, in the case of multiple users, since the channel training of all users are always implemented in the base station, all training data sets should be transmitted to the BS. Therefore, its transmission cost will be very high. Literature [121] adopts the Federated Learning (FL) framework, in which the neural network will be trained at the user rather than at the BS. In this case, only updated parameters need to be transmitted between the base station and the user.

Due to the large scale of the BS antenna array and RIS unit, direct estimation of the RIS channel will lead to huge training costs. One solution is to reconstruct the channel matrix from a limited number of measurements through compression sensing technology. However, the compressed sensing method requires complex mathematical operations and is not robust to noise measurement. Recent research shows that the whole channel can be deduced from part of the channel by using artificial intelligence. For all passive RIS, the extrapolation of all cascaded channels can be realized at the terminal (i.e., BS or user). The literature [122] adopts the ordinary differential equation ODE and establishes the connection between different data layers in the convolutional neural network (CNN), which can better fit the mapping between the sampling channel and the full channel than the ordinary CNN. At the same time, in the recently designed hybrid active/passive RIS architecture, some RIS units have signal processing capabilities [123]. Therefore, the estimation of the unilateral channel can be directly realized at the RIS [124]. In [125], a part of the RIS cells have been activated to restore the single channel at the active cell, and then infers the complete unilateral channel information from the part of the channel, in which CNN is used. In addition, the author also proposes an antenna selection network based on the probability sampling theory to select the best pattern of these active RIS cells. In addition, in [126], a unit grouping strategy is proposed to reduce the cost of cascading channel estimation. In this scheme, each RIS unit in each group remains open state, shares the same reflection coefficient, with the same CSI. In fact, the channels in a group are different. In the RIS grouping scheme, only some but not all channel information can be observed. In addition, the realized channels associated with different RIS units in each group will interfere with each other. Inspired by the idea of antenna extrapolation, a neural network can be designed to eliminate the interference in each group and obtain accurate partial cascade channels. Using these partial channels, we can further use other Deep Learning (DL) schemes to extrapolate the full cascade channels.

RIS channel estimation should also include high-mobility scenarios, and the idea of channel extrapolation in the antenna domain can be transplanted to the time domain. Channel extrapolation in the time domain is essentially a problem of time series reconstruction and prediction, which can be applied to the Recurrent Neural Network (RNN). However, when the time-varying RIS channel has a long-term dependence, the RNN model will face the problem of gradient disappearance or explosion. Another solution is to design a scheme based on Long Short Term Memory (LSTM) to separate its memory from the time continuous state. However, due to hardware damage and environmental interference, some regular sampling points may fail and only irregular sampling channels can be obtained. Inspired by the ODE structure, a continuous time-varying channel model can be built by adding connections and linear calculations between irregular sampling points with coefficients. In this case, the recently proposed potential ODE can be used to obtain the highest channel extrapolation performance in the time domain. Different from the traditional the ODE model, in the potential ODE, the potential variable framework can explicitly decouple the system change, observation possibility, and identification model [127]. Therefore, the time domain prediction problem based on the random sub-sampling measurement will become easier to deal with. Compared with RNN and conventional ODE, the channel prediction based on potential ODE has significant improvement in its prediction of MSE.

5.3.3.2. AI-enabled Beamforming for RIS Systems

The existing research on RIS mostly follows the traditional model-driven beamforming design scheme, and highly depends on the accuracy and real timing channel information. However, in the actual project deployment, it is quite difficult to obtain the channel of the RIS auxiliary communication system from the perspective of complexity, cost and compatibility with the protocol. In order to avoid the difficulties of channel estimation, a blind beamforming scheme independent of channel information has been proposed. Based on some research on the application of neural networks to channel estimation or beamforming of RIS, some studies have proposed to combine the two directly to learn how to perform beamforming based on the received signal. This method combined with depth learning can extract more relevant information from the original data. There are also studies on the design of beamforming algorithms using the statistical characteristics of received signals, whose basic idea is to design beamforming algorithms using the conditional sample average value of received signal power by giving enough random samples of reflection phases. This method has been proved to be applicable to the cooperative deployment of multiple RISs and long-term large-scale fading channels. This kind of scheme is applicable to the blind plot where the channel estimation is difficult and RIS only performs simple operations offline.

The most important gain of RIS communication comes from beamforming, which can control the reflection of signals in the desired direction and improve the transmission quality. This can be achieved by continuously tuning the phase shift and reflection amplitude of the RIS units. However, the high-precision adjustment will lead to huge hardware costs and huge challenges to the realization of control circuits. Here, we will introduce typical AI-based beamforming design strategies in three scenarios, namely, all-passive RIS, hybrid passive/active RIS, and high mobility scenarios, as shown in Figure 38.

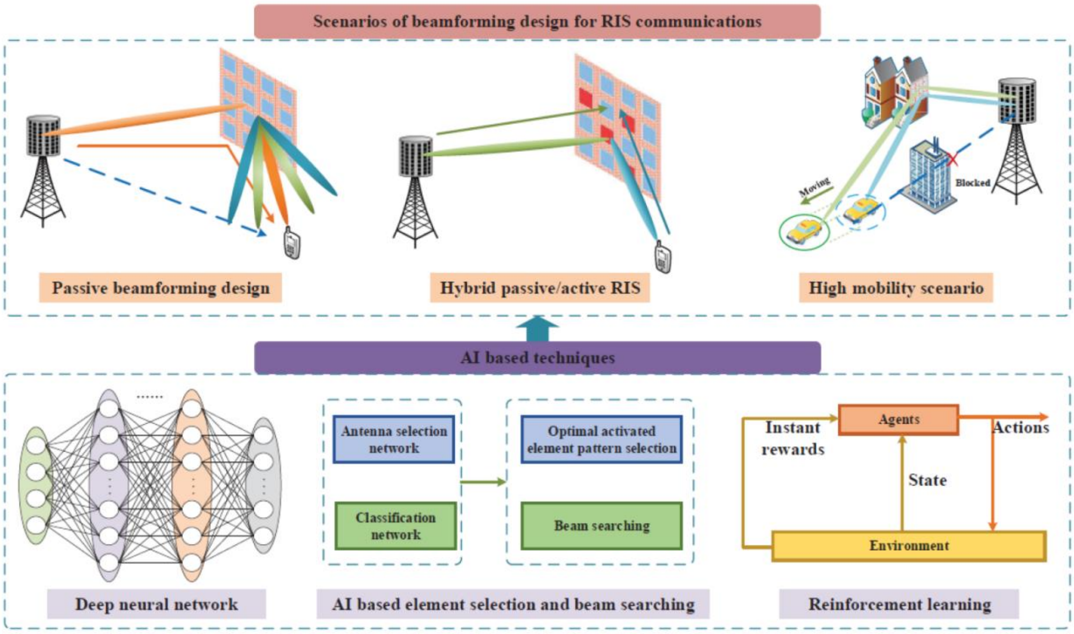


Figure 38 AI-empowered beamforming design for RIS systems.

For the beamforming design of passive RIS, literature [128] proposes a DL-based method to realize RIS configuration for indoor communication scenarios, in which the deep neural network (DNN) It is trained to accurately map the user's location and the configuration of RIS units. Then, the optimal RIS beamforming matrix can be obtained by maximizing the received signal strength on the user side. However, this supervised learning method requires a large number of data sets and requires a long training time. A method based on deep reinforcement learning (DRL) has been developed in [129], in which one of the agents will gradually get its best behavior through trial-and-error interaction with the environment over time, and then generate the best beamforming matrix. This algorithm can not only learn from the environment and gradually adjust its behavior, but also obtain a performance comparable to that of weighted MMSE and fractional programming based on zero-forcing beamforming. There is also some work on the hybrid precoding architecture based on RIS, in which the analog precoding based on a phased array at BS is replaced by RIS beamforming. Due to the non-convex constraint of discrete phase shift, it is difficult to solve the problem of system and rate maximization. Literature [130] proposed a classification problem based on parallel DNN, and proposed a DL-based multiple discrete classification (DL-MDC) hybrid precoding scheme. In this structure, multiple DNNs are used, and the output of each DNN corresponds to the diagonal elements of the RIS-based analog beamforming matrix. Compared with cross-entropy optimization [131], the scheme based on DL-MDC can significantly reduce the running time, and the performance loss can be negligible. It works well in the Saleh Valenzuela channel model and the actual 3GPP channel model.

For hybrid passive/active RIS, RIS can only obtain and process the sampled subchannel information from the active unit. Compared with passive beamforming design, since RIS can only obtain effective signals from limited active reflection units, the input data of NN for beamforming design will be limited, which will damage the performance of the scheme based on continuous optimization in [129]. In [132], the finite beam-forming codebook is constructed with the help of the DFT matrix. Selecting the best beam-forming from the codebook can be regarded as a classification problem. Then, the author designed a fully connected neural network (FNN) The classification network of hybrid passive active RIS is used to jointly obtain the optimal active reflection cell mode and the search beamforming matrix.

For high mobility scenarios, the main challenge of RIS beamforming design is to accurately match time-varying characteristics. Literature [133] considers the THz UAV network, in which mobile users are served by BS and flight RIS. Based on the prior observation of the beam path, a DL algorithm is proposed to actively predict the optimal RIS beamforming. Due to the mobility of UAV, the network structure based on Gated Recurrent Unit (GRU) is used to capture the time correlation in spectrum data and learn the sequence correlation. Inspired by the ODE structure and LSTM framework in [122], another feasible scheme combining channel and beam tracking can be introduced. First, the auxiliary channel of the RIS can be sampled by turning on/off the active part of the RIS unit. Similar to the time-domain channel extrapolation based on LSTM, the time-varying channel model based on ODE can be constructed to obtain the time-domain sampled subchannel, and then the channel tracking can be realized through LSTM. With antenna-domain sampled, and the optimal beamforming matrix of the corresponding time can be selected through the classification network.

In order to achieve the upper limit of the communication rate given by Shannon's theorem in the new generation of electromagnetic wireless communication, it is first necessary to carry out baseband digital coding for the information entropy of communication big data; Then it is necessary to intelligently adjust the degree of freedom of the electromagnetic channel according to the actual electromagnetic environment to achieve the dynamic optimal MIMO/RIS beamforming. In order to optimize the compression coding of communication big data, it is necessary to carry out data feature mining, feature extraction, and de-correlation. Since 2020, the team from Sun Yat-sen University and Liao Shaolin from the Illinois University of Technology in the United States has developed the efficient Dictionary Learning based Compressed Sensing Neural Network (DL-CSNet), which organically combines the dictionary learning of big data with the compression sensing technology, thus improving the signal-to-noise ratio of image restoration by more than three orders of magnitude.

For the problem of the sharp increase in the number of pilots needed for the training of the codebook of the RIS in the near field, a near-field RIS beam training scheme based on deep learning is proposed in [134]. First, the RIS codebook applicable to the near-field channel is designed, and each codeword is determined by the angle and distance of the user relative to the RIS. During the beam training, only part of the near-field codewords are tested, and the received signal from the test is used as the input of the neural network. The trained neural network outputs the index of the optimal codeword in the near-field RIS codebook according to the received signal, thus effectively reducing the pilot cost.

5.3.3.3. AI-empowered Resource Schedule

The optimization objectives of AI-assisted resource scheduling include the following aspects: spectrum and energy efficiency, environmental awareness range, system deployment cost, and network topology, etc., joint beamforming design of multiple BS, and RIS and joint power allocation. In addition, in the high mobility scenarios, since the channel link is closely related to the scheduling on RIS and BS, user mobility will further affect the optimal network topology of RIS communication. Therefore, network topology optimization in mobility scenarios should also be discussed.

In order to maximize the sum rate of downlink non-orthogonal multiple access (NOMA) networks, literature [135] calls a modified object migration automation algorithm to divide users into several clusters of the same size, and uses the Deep Deterministic Policy Gradient (DDPG) algorithm to jointly control reflection elements in RIS. Unlike the process of training before testing, literature employs [135] a long-term self-adjusting learning scheme. Through iterative exploration and development, search for the best action in each given environment, namely user partition and RIS beamforming. This RIS-assisted NOMA downlink network achieves better performance than traditional orthgonal multiple access (OMA).

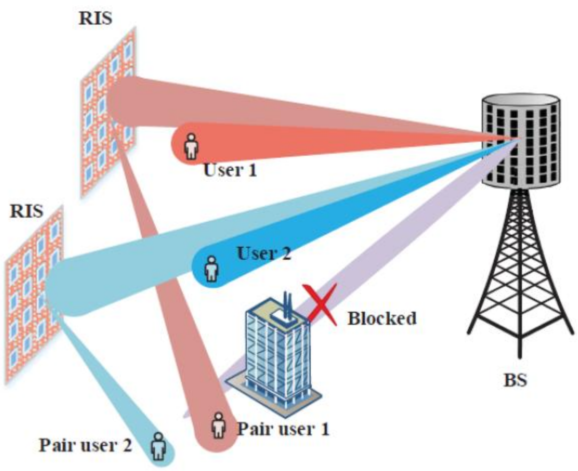


Figure 39 RIS-aided NOMA systems.

In order to improve the performance of RIS-assisted millimeter wave communication, a beam management framework for machine learning authorization is proposed in [136] to accurately align the beam between BS and user terminals. In this framework, DNN is used to identify complex network environments, which can help each BS select its best RIS. In addition, online learning method is used to predict terminal mobility. Through integrated environment and mobility awareness, active waves beam switching scheme can be realized by mapping the user's position to its best RIS. In addition to many works focusing on a single RIS, there are also many works that discuss the collaboration of multiple RISs. For example, the channel link in RIS communication can also be scheduled in a multi-hop manner, which can effectively combat severe propagation attenuation and improve the coverage of environmental sensing. However, due to multi-user interference, multi-hop signals that are difficult to deal with mathematically, and nonlinear constraints, the formula for optimizing the sum rate of the maximum multi-RIS system is non-convex. A DRL-based algorithm is proposed in [132], which uses the DDPG algorithm to expand the sensing range of RIS communication. In order to overcome the unrealistic search complexity of the super large Q table in the DRL framework, the DNN-based Q learning method is used. In addition, the core of the DDPG structure is a network of reviewers and actors composed of fully connected DNNs. After the input of the the beamforming matrix and channel information, the DDPG algorithm will output the current iterative beamforming design.

Using the DRL method, the average energy efficiency is maximized in [137] by jointly optimizing the transmission power allocation, RIS beamforming matrix, and the switching state of the RIS elements. Although predefined rewards may be affected by various unknown aspects, such as the uncertainty of the user channel, the difference between the expected reward and the actual reward can be used by DNN in the DRL framework, where the feedback comes from the uncertain environment. The resource scheduling of FL involves training the NN of multiple users, but the FL framework is also a feasible method to deal with the resource scheduling problem. FL is applied in [138] to RIS-assisted millimeter wave system and privacy protection design is implemented. FL is applied to training DNN model for mapping between the user channel and its optimal RIS beamforming. In addition, FL can help optimize multiple RIS in parallel while protecting private CSI. However, since all local parameters are transmitted on shared wireless channels, unexpected propagation errors will inevitably worsen the global situation performance of polymerization. Literature [139] proposes an alternative optimization algorithm to minimize the aggregation error and accelerate the convergence rate of FL. By calling the semi-definite relaxation method, the nonlinear and non-convex problems of joint optimization of transmit power, receive scalar, and phase shift are solved. In addition, the location information of base stations, RIS, and users can also assist in resource scheduling. Using the knowledge of location information, we can easily obtain the location relationship between different objects through geometric methods, that is, base-station RIS or RIS-users. Using the predefined set for beamforming selection, the mapping between the position information and the best beamforming index can be searched by using the appropriately designed NN.

In the mobile scenarios, since the user's location is changing, it is necessary to adapt to the changing environment for resource scheduling. In order to maximize the uplink and rate of the multi-cell network assisted by multiple RIS in the mobility scenarios, A dynamic control scheme based on multi-agent DRL is proposed in [140], in which BS is regarded as an independent agent. In particular, each BS adaptively configures its local UE power, local RIS beamforming, and its combiner. In view of the nonstationarity caused by the action coupling of multiple base stations, an effective message transmission scheme is proposed, which requires only limited information exchange between adjacent base stations. For vehicle communication, the RoadSide Unit (RSU) can use RIS to provide indirect wireless transmission in the uncovered area. Because the vehicle moves in different directions and speeds, and has different dwell time in the blind area. If the same business volume is provided to all vehicles in the blind area, the low-mobility vehicles will obtain poorer service quality than the high-mobility vehicles. Therefore, literature [141] has studied joint vehicle scheduling and passive beamforming in RIS-enabled vehicle communication to maximize the minimum achievable rate of vehicles in the blind area. This problem is divided into two sub-problems: wireless scheduling and RIS phase shift optimization. The former is solved by DRL to obtain the optimal RSU scheduling scheme under various road conditions and RIS selection, and the latter is solved by block coordinate descent (BCD) to maximize the instantaneous and speed of the current service vehicle.

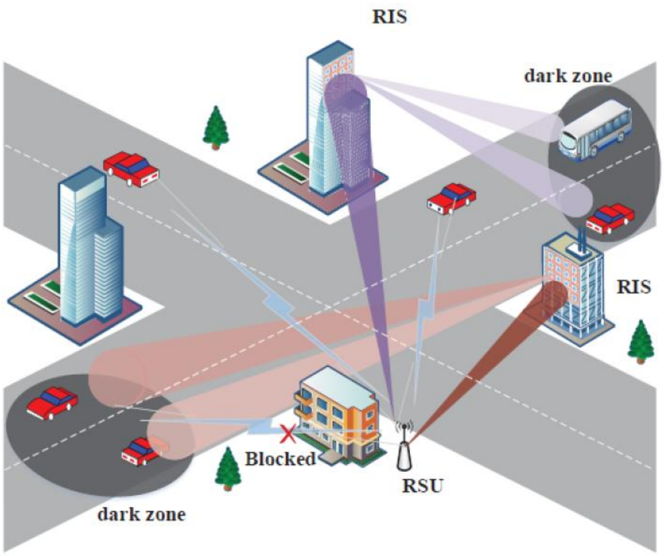


Figure 40 RIS scheduling in vehicular communications.

5.4. RIS-Enhanced Multiple Access

Multiple access (MA) techniques are the most important enabling technology for supporting multi-user communications. MA can be broadly classified into two categories, namely orthogonal multiple access (OMA) and non-orthogonal multiple access (NOMA).

5.4.1. RIS-Assisted TDMA

Time division multiple access (TDMA), as a typical representative of OMA, is mainly implemented by allocating orthogonal time resources for multiple users to avoid inter-user interference. For conventional communication systems, the channel conditions of each user remain constant within each channel coherence time, and the spectral efficiency of TDMA is usually lower than that of NOMA.

For RIS-assisted multi-user communication systems, a time-varying channel can be artificially created by dynamically adjusting the phase shift matrix of the RIS in the coherence time of each channel to obtain the time diversity. In the RIS-assisted TDMA system, each user is sequentially scheduled in the time domain. Therefore, a specific RIS phase shift matrix can be designed for each user when being served, i.e., the TDMA system performance can be significantly enhanced. However, in the NOMA system, since all users are scheduled at the same time, the dynamic configuration of RIS cannot improve the system performance significantly. In RIS-assisted two-user downlink communication systems, it has been found that under specific conditions of user location distribution, TDMA consumes less transmit power than NOMA to guarantee user quality of service[142]. In addition, for energy-constrained uplink transmission systems or wireless power transfer scenarios, existing work [143] has demonstrated that the dynamic configuration of the RIS phase shift matrix enables TDMA to achieve higher throughput than NOMA. Considering other performance indicators or factors such as end-to-end transmission delay and user fairness, NOMA has inherent advantages over TDMA, while the performance comparison between RIS-assisted TDMA and NOMA may have different results.

5.4.2. RIS-Assisted NOMA

The number of wireless communication services and wireless devices will explode in the future. OMA employed in current mobile communication systems is limited by the freedom of wireless resources in the time, frequency, code, and space domains. This not only makes it difficult to fully utilize the limited wireless resources, but also greatly limits the number of users served in the network. In order to improve the spectrum efficiency and the number of connected users in RIS-assisted communication systems, RIS-assisted NOMA is a promising solution [144]-[145]. The core idea of NOMA is to accommodate multiple users over the same wireless resource blocks such as time slots, subcarriers, and spatial beams, and distinguish each user in the power domain or codeword domain, thus enhancing the spectral efficiency and user connectivity. It is worth mentioning that the achievable communication performance gain in traditional NOMA depends heavily on the variability of channel conditions among users. By reconfiguring (enhancing or weakening) the user channel conditions via employing the RIS, a more flexible NOMA can be achieved, thus further improving the performance gain of NOMA over OMA [146]. Thus, RIS-assisted NOMA can be considered as a "win-win" integration.

In order to fully reap the gains of RIS-assisted NOMA, many challenges have to be overcome. For example, for multi-antenna NOMA communications, the successive interference cancellation (SIC) decoding order among users is no longer merely determined by the user channel gain, but also requires additional decoding rate conditions to be satisfied. A preliminary RIS-enhanced multi-antenna NOMA transmission framework has been proposed in [147], where different RIS types are considered and a convex optimization-based algorithm was proposed to obtain a locally optimal solution for maximizing the system throughput. In this case, the active beamforming at the BS and the passive beamforming at the RIS will be highly coupled with the SIC decoding order and the user clustering schemes. When the number of users is large, the corresponding low complexity and efficient optimization design algorithms should be further studied.

Another typical feature of power domain NOMA is that it can be combined with traditional orthogonal multiple access schemes, thus compromising system performance and the complexity of SIC implementation. It is worth noting that, benefiting from RIS dynamic beamforming, the RIS-assisted TDMA communication system can obtain a time-varying channel that is beneficial to the communication of each user, thereby bringing about a significant increase in system throughput. Considering the influence of RIS, combining the advantages of TDMA and NOMA to balance the performance and implementation complexity of the system is a problem worth considering. By combining TDMA with NOMA, the users are grouped, in which the users in the group transmit in the power domain NOMA mode and share the same RIS beamforming vector. The users in one group occupy orthogonal time resources and provide a unique RIS beamforming vector, forming a NOMA-TDMA hybrid multiple access technology. Setting the number of user groups reasonably, the RIS-assisted NOMA-TDMA system can balance the system complexity and throughput performance flexibly and efficiently [148]-[149]. However, the RIS-assisted NOMA-TDMA system also brings new challenges to performance optimization. The user grouping criterion is no longer directly determined by the user's channel, and it is necessary to consider the influence of the equivalent channel combined with the RIS phase, which makes the RIS phase highly coupled with the user group design. For the uplink communication scenario, early studies carried out research on throughput maximization in passive and active RIS-assisted TDMA-NOMA scenarios [150]-[152].

5.4.3. RIS-Assisted OTFS

There are many high-mobility communication environments in future wireless communications, including self-organizing Internet of Vehicles, UAV networks, etc. In these communication scenarios, there will be a large-scale Doppler frequency shift, and the channel correlation time will be greatly compressed, causing OFDM to suffer from severe inter-subcarrier interference, which will bring serious challenges to the acquisition of large-scale RIS channel parameters. In recent years, Orthogonal Time Frequency Space Modulation (OTFS), as a new two-dimensional modulation method (delay domain and Doppler domain), provides a new option for 6G. By simply adding the inverse symplectic Fourier transform and symplectic Fourier transform at the receiving end of the OFDM system, it can effectively resist the intersymbol interference caused by the Doppler frequency shift in the OFDM system, and open up a new signal representation domain. It opens up new signal characterization domain quantification identification communication resources, remaining higher stability and reliability in high-speed motion scenes and providing a new perspective for high-speed mobile communication research.

OTFS provides a new two-dimensional signal space, that is, the signal space in the delay-Doppler domain, which can effectively convert the highly dynamic time-varying channel into a nearly static sparse two-dimensional channel in the delay-Doppler domain. The main problem of the OTFS system is that the signal processing at the receiving end, including channel estimation, especially the complexity of channel equalization is too high, while the RIS transceiver can reduce the complexity of channel equalization at the receiving end while realizing a large-scale array. Thus, the large-scale array hardware implemented by RIS can be adapted to the OTFS system very well. Exploring the fusion mechanism of RIS-assisted communication and OTFS waveform and digging into the strong channel representation capability of OTFS in the delay-Doppler domain will help to further expand the application range of RIS.

However, there are still some challenges for RIS-assisted OTFS communication in a mobile environment. First of all, the complex channel estimation and equalization process of OTFS itself makes it difficult to apply it to the classic multi-antenna system. In addition, RIS is a passive device and there are at least two cascaded channels, which leads to its inefficiency in channel estimation. Secondly, the frequency-selective phase shift and other properties of RIS will cause unwanted distortion of the modulated wider-band signal, and introduce additional interference of RIS. RIS hardware with stable broadband performance is an urgent need not only for OFDM systems, but also for OTFS systems. In addition, unlike OFDM symbols, OTFS symbols last longer. If several OTFS symbols are used exclusively for partial virtual channel estimation, it will severely restrict the system spectrum efficiency. In addition, due to the double cyclic shift receiving model structure of OTFS modulation in the delay-Doppler domain, the pilot and data sent by the terminal in the delay-Doppler domain will generate aliasing when passing through a highly dynamic concatenated channel. In theory, guard bands can be placed in the delay-Doppler domain to avoid potential interference between the pilot and data. Since the size of the guard band is proportional to the maximum Doppler frequency shift and the maximum delay of the RIS concatenated channel, it will also greatly reduce the system spectrum efficiency in high mobility scenarios. The pilot frequency design and guard interval selection of the OTFS system supported by RIS are also problems to be solved. Finally, it is necessary to design the RIS phase shift matrix for the new transceiver signal model under OTFS, design an efficient OTFS-based transmission system and the corresponding delayed Doppler domain signal processing algorithm in the RIS system, and improve the RIS communication performance in the high mobile environment.

5.4.4. RIS-Assisted Block Multiple Access System

When using RIS to serve multiple users, the beams of different users may be incident on one RIS at the same time. Since the RIS has only one control state at the same time, it will make it difficult for the beamforming control of the RIS to optimize and adapt channels of multiple users at the same time. To serve multiple users at the same time, in addition to adopting the NOMA scheme, another promising scheme is to divide a piece of RIS into multiple sub-blocks. The base station will send beams for different users to different sub-blocks, and by setting the adjustment phases of different sub-blocks reasonably, it can optimize and match the channels of different users at the same time, so as to realize multi-user access [153]. Compared with the NOMA technology, the block multiple access can well eliminate the interference among multiple users, thus achieving good performance. Compared with TDMA, block multiple access can realize simultaneous transmission and has higher spectral efficiency. The block multiple access mechanism based on RIS can be used in single-cell multi-user access scenarios, and can also be used in multi-cell multi-user access scenarios [154].

5.5. Networking Deployment

From the perspective of communication environment complexity and RIS deployment and control complexity, RIS deployment scenarios can be divided into two categories: small controllable restricted areas and large complex environments. There are great differences between these two scenarios in the deployment principles, and requirements of the RIS network [155]. A small controllable restricted area has the opportunity to deploy RIS with sufficient density to achieve accurate electromagnetic ambient intelligence control, such as a typical indoor hotspot coverage area. In a large complex environment, the distribution of services is relatively sparse, and it is inconvenient or unnecessary to realize accurate control of the wireless propagation environment. In this environment, we can concentrate on adjusting the large-scale characteristics of wireless propagation channels, including shadow fading, free space propagation path loss and other large-scale characteristics.

Based on the above two cases, the deployment of RIS can be further considered from four aspects: deployment mode, coexistence and sharing, increasing rank and coverage, and covering area. (1) From the perspective of network deployment mode, RIS deployment scenarios can include network-controlled mode and standalone mode. These two modes are different in control link requirements between network and RIS, measurement/control signaling interaction, network deployment complexity and so on, and each mode has its own advantages and disadvantages. (2) From the point of view of coexistence and sharing, RIS deployment scenarios can include multi-operator network coexistence, single-user access and multi-user access, multi-RIS deployment, and spectrum attributes (such as licensed spectrum and unlicensed spectrum). (3) From the point of view of increasing rank and enhancing coverage, the deployment scenarios of RIS can include deployment near the base station, deployment at the edge of the cell, deployment in the middle of the cell, or ubiquitous deployment. Among them, ubiquitous deployment may really bring changes to the wireless network architecture. (4) From the point of view of the coverage area, RIS deployment scenarios can include remote areas, urban indoor/outdoor, NTN and so on.

5.5.1. Comparison of RIS network deployment modes

- Network-controlled Mode and Standalone Mode

In term of whether it is controlled by the network or not, the deployment methods of RIS can be divided into two categories. Among them, the deployment mode of RIS controlled by network is called "network-controlled mode", and the deployment mode of RIS self-control is called "standalone mode" [156]. Table 3 compares the advantages and challenges of the networked-controlled mode and the standalone mode.

Table 3 Comparison between network-controlled mode and standalone mode

Type	Advantages	Challenges
Network-Controlled Mode	① Supports multi-network collaboration. ② Supports multi-user access. ③ Better meet the coexistence requirements of wireless networks deployed on licensed spectrum.	① Network deployment is relatively complicated. ② Network control link needs to be deployed. ③ It is necessary to design an interactive flow of control and measurement signaling.
Standalone Mode	① No network control link is required; ② The network is simple and easy to deploy; ③ Suitable for unlicensed spectrum with low coexistence requirements.	① Hard to overcome the interference of multiple networks. ② May cause serious inter-cell interference. ③ Cannot support multi-user access well.

Through the comparative analysis of the above two tables and combing with the characteristics of licensed spectrum and unlicensed spectrum, the following conclusions can be drawn.

① Network-Controlled mode: suitable for scenarios such as complex networks and licensed spectrum with high coexistence requirements (i.e., cellular networks).

② Standalone Mode: suitable for scenarios such as simple networks, unlicensed spectrum technology with local coverage, and so on (e.g., Wi-Fi).

- Centralization and Distribution

Consider the deployment of RIS in a multi-user network. A base station in the network communicates with $K > 1$ users (or K groups of adjacent users), and users are far enough away from each other. In this case, there are two different strategies to deploy N RIS elements in the network: 1) distributed deployment, where elements form multiple distributed RIS, each of which is located near a user; 2) centralized deployment, where all elements form a large RIS near the base station. Note that the above two deployment strategies are equivalent for the single-user situation ($K = 1$), because all

RIS elements will be utilized to achieve the maximum received signal power at the base station. However, for $K > 1$ these two deployment strategies usually result in different channels between users and base stations. In a centralized deployment, all users can use the N reflecting elements to serve. In a distributed deployment, each user only uses a small portion of N elements to obtain the service of the nearest RIS, because the signal reflected by the farther RIS is too weak due to the large path loss.

In terms of system capacity, the centralized RIS deployment usually has advantages over the distributed RIS deployment, but it is worth noting that other practical factors may need to be considered when deploying RIS. Firstly, the distributed deployment needs more RIS, so more backhaul links are needed between the base station and the RIS controller to exchange information, which increases the network overhead [157]. Secondly, due to site/space constraints, it is not always feasible to deploy large centralized RISs near the base station, while deploying multiple distributed RISs at the user end is usually more flexible [158]. Thirdly, the RIS performance gain of the centralized deployment versus the distributed deployment is based on the assumption of cascade channel conditions. For example, the great potential of the cooperative passive beamforming over inter-RIS channels has been unveiled in the distributed double-/multi-RIS aided communication system [161], which was shown to achieve a much higher-order passive beamforming gain than its centralized counterpart. In practical applications, there may be great differences in LoS probability, NLoS fading distribution and channel correlation between the two deployment strategies, which leads to different comparison results in different scenarios.

5.5.2. RIS Network Deployment Challenges

The existing research on RIS mainly focuses on the challenges faced by classical communication problems after the introduction of RIS, such as channel estimation and beamforming, and is aimed at the problems under the assumption of a single network system model. In the actual wireless mobile communication network, the coexistence of multiple networks is a traditional problem. The introduction of RIS may bring new challenges to network coexistence. In the current network, the wireless signal incident on the RIS panel includes both the "target signal" optimized by RIS and other "non-target signals", and RIS will control both types of signals simultaneously. Under uncontrolled conditions, RIS performs unexpected abnormal regulation on "non-target signals" from other networks, which will lead to network coexistence problems. Literature [155] preliminarily analyzed the coexistence of RIS networks, and put forward possible solutions. On the basis of reference [155] and reference [159], the coexistence of RIS networks is further analyzed and modeled, and the new multi-layer RIS structure with out-of-band filtering and RIS blocking mechanism is further analyzed and evaluated. The paper [160] analyzed the deployment challenges of RIS networks in high-speed railway communication scenarios and provided solutions.

RIS technology can be deployed in a user-centered cell-free networks, forming a heterogeneous network consisting of TRP nodes and passive RIS nodes. In a cell-free network, RIS can cooperate with multiple TRP stations in the network to further improve the coverage quality of the wireless network. At the same time, the "many-to-many" cooperation mode between RIS and TRP stations in the cell-free network poses new challenges to channel measurement, beamforming, and resource scheduling. For example, the cell-free network needs to measure not only the channel state between each TRP station and the terminal, but also the channel state of the cascade channels from each TRP station to the terminal through RIS, which increases the pilot cost and computational complexity of RIS cascade channel estimation. Literature [161] provides a dual-time scale channel information acquisition and precoding scheme, which reduces the channel information acquisition cost and precoding optimization complexity through local matching between end users and RIS elements.

6. New Types of RIS

6.1. Simultaneously Transmitting and Reflecting Surfaces

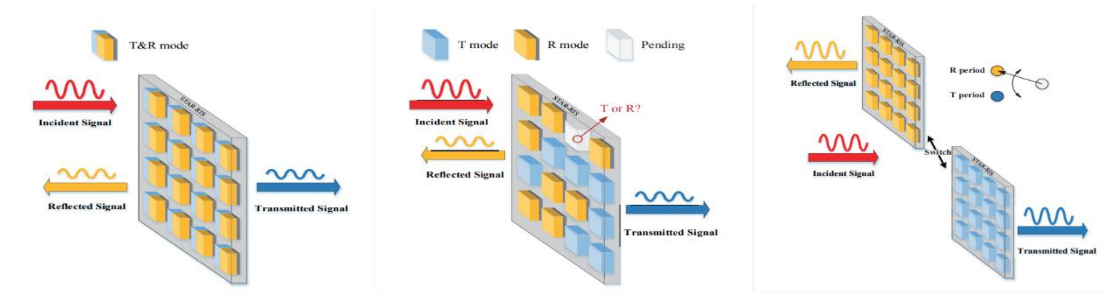
This section introduces a new RIS variant that emphasizes its ability to simultaneously transmit and reflect the incident wireless signal. In contrast to the reflecting-only or transmitting-only RISs, the Simultaneously Transmitting and Reflecting Surfaces (STARS) can achieve full-space coverage and they have higher tunable degrees-of-freedom [162]-[164]. In the meantime, they require more complex hardware design and implementation.

Having presented practical protocols for operating STARS, this section discusses several attractive applications of STAS in next-generation networks for both outdoor and indoor environments. One of the most promising applications of STARS is to improve the coverage area/quality of wireless networks, especially when the links between the base stations (BSs) or access points (APs) and users are severely blocked by obstacles (e.g., trees along roads, buildings, and metallic shells of vehicles). Secondly, exploiting STARS enables a novel communication framework, namely transmission-reflection NOMA, where a pair of users at the transmission-oriented side can be grouped together for facilitating NOMA. Thirdly, by overcoming signal blockages and providing full-space coverage, STARS are capable of improving both the localization and sensing capability of wireless networks, especially in indoor environments. Other than the above-mentioned applications, there are more promising application scenarios for STARS in future-generation wireless networks, including STARS-aided full-space physical layer security (PLS), STARS-aided simultaneous wireless information and power transfer (SWIPT), STARS-assisted visible light communications (VLCs), STARS-aided mmWave/THz communications, and STARS-augmented robotic communications. These applications constitute interesting future research directions.

6.1.1. Operating Principles and Implementations of STARS

Similar to conventional RISs, the tunning of STARS relies on the adjustment of their surface electric and magnetic impedances, i.e., Z_e and Z_m. Upon illumination by an incident EM wave, multiple currents are induced in each STAR element. It is sufficient to consider only two types of currents, namely the electric current and the (equivalent) magnetic current. The hardware implementations of STARS can be loosely classified into two categories, namely the patch-array based implementations and the metasurface based implementations [165]. The patch-array based implementations consist of periodic cells having sizes on the order of a few centimetres. Because of their relatively large sizes, each cell (patch) can be made tunable by incorporating either PIN diodes or delay lines. By contrast, the metasurface based implementations have periodic cells on the order of a few millimetres, possibly micrometres, or even molecular sizes. Hence, they require more sophisticated controls of their EM properties, such as the conductivity and permittivity.

By properly adjusting the amplitude coefficients for transmission and reflection, a given element of a STARS can be operated in the full transmission mode (T mode), the full reflection mode (R mode), and the general simultaneous transmission and reflection mode (T&R mode). Inspired by these observations, this subsection proposes three practical protocols for operating STARS in wireless communication systems, namely energy splitting (ES), mode switching (MS), and time switching (TS) [166], as illustrated in Figure 41.



(a) Energy splitting (ES). (b) Mode switching (MS). (c) Time switching (TS).

Figure 41 Practical operating protocols for STARS

1) Energy Splitting: For ES, all elements of the STARS are assumed to operate in the T&R mode, where the energy of the signal incident on each element is generally split into the energies of the transmitted and reflected signals. For ES, since both the transmission and reflection coefficients of each element can be optimized, a high degree of flexibility for communication system design is enabled. However, the large number of design variables also causes a relatively high overhead for configuration information exchange between the BS and the STARS.

2) Mode Switching: For MS, all elements of the STARS are divided into two groups. Specifically, one group contains elements that operate in the T mode, while the other group contains elements operating in the R mode. Note that MS STARS can be regarded as a special case of ES STARS, where the amplitude coefficients for transmission and reflection are restricted to binary values. Therefore, MS generally cannot achieve the same full-dimension transmission and reflection beamforming gain as ES, since only a subset of the elements is selected for transmission and reflection, respectively. Nevertheless, MS is still appealing in practice, since such an “on-off” type operating protocol is much easier to implement compared to the ES protocol.

3) Time Switching: Different from ES and MS, the TS STARS exploits the time domain and periodically switches all elements between the T mode and the R mode in different orthogonal time slots (referred to as T and R period). Different from the ES and MS protocols, due to the exploitation of the time domain, the design of the transmission and reflection coefficients for TS is not coupled, and thus, easier to handle. However, the periodical switching of the elements introduces stringent

requirements for time synchronization, which entails a higher hardware implementation complexity.

6.1.2. STAR-RIS for 3D Localization

For the previously introduced RISs, they can only support the users on the front side of them for both communication and localization. Namely, the users located in their back side cannot be supported and served. With the introduction of STAR-RIS, this becomes a reality. Namely, STAR-RIS can support 360-degree coverage, beneficial from its dual mode operation, i.e., transmission and refraction. It is a brand-new technique that combines the use of simultaneous transmission and refraction to improve the accuracy of localization systems, making it well-suited for both indoor and outdoor localization. As shown in Figure 42, the cellular BS can localize the outdoor MS and the indoor MS with the aid of STAR-RIS simultaneously. In the system, there exist two paths between the outdoor MS and the BS, i.e., one direct LoS path and one reflection path via STAR-RIS. With respect to the indoor user, there exists only one refraction path via the STAR-RIS. By controlling the reflection and refraction control matrices and power splitting among the two modes, the QoS requirements of the two MSs can be concurrently met. The fundamental performance limits in terms of position error bounds can be found in [167]. The optimization of the two control matrices under the assumption of high-sounding overhead is also conducted in [167]. A brief summary of 3D localization with different types of RISs is provided in Table 4.

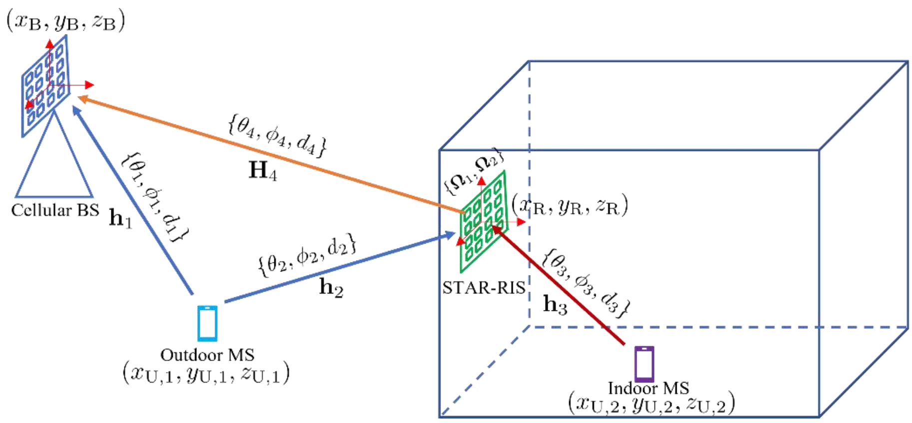


Figure 42 STAR-RIS enabled simultaneous indoor and outdoor localization [167]

Table 4 Summary of 3D Localization with Different Types of RISs

Type of RISs	Number of RISs	Localization approach	Coverage	Accuracy
Passive RISs [168]	≥ 2	Angle based	180 degrees	Medium
Distributed receiving RISs [169]	≥ 3	Angle based	180 degrees	High
Co-located receiving RIS [170]	≥ 1	Angle based	180 degrees	High
STAR-RIS[171][172]	≥ 1	Mixture	360 degrees	Medium

6.2. Active RIS

By integrating the active power amplifiers in RIS unit cells, the RIS is made capable of secondary field enhancement of space electromagnetic waves. The digital coding technique is also used for digitally discrete modulation of the state of the power amplifier, thus realizing the reconfigurable capability of the radiated far-field beam of the RIS. The unit cell structure is shown in Figure 43 [173]. The enhancement modulation function provides the necessary fundamental support for RIS in terms of link channel enhancement, coverage radius improvement, miniaturization, and system conversion efficiency improvement.

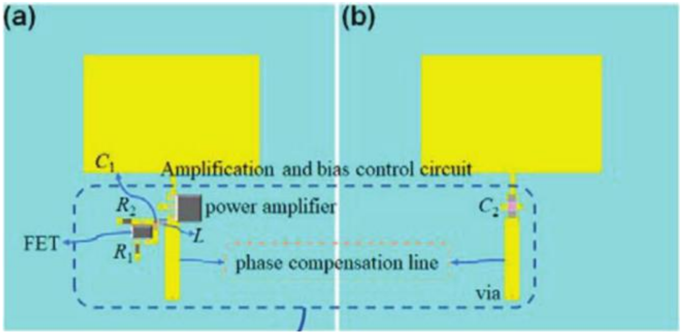


Figure 43 Structure of the RIS cell with loaded power amplifier (a) top layer and (b) bottom layer

Combined with the high-power capacity characteristics of the power amplifier, the RIS integrated with active power amplifiers has the capability of spatial power transfer. When the power amplifier is digitally modulated for periodic switching, the RIS acquires nonlinear harmonic beam modulation characteristics with enhanced modes. It can allocate energy and information to different harmonic beams to achieve simultaneous transmission of energy and information, laying a solid foundation for further application of RIS in intelligent energy-carrying communication systems, as shown in Figure 44.

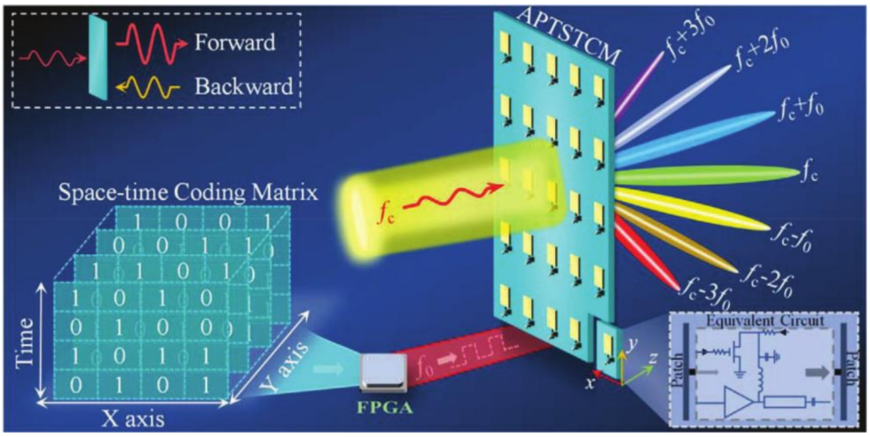


Figure 44 RIS electromagnetic energy amplification, harmonic modulation and non-reciprocal transmission

In order to overcome the challenge due to the "multiplicative fading" effect, which describes that the equivalent path loss of the transmitter-RIS-receiver link is the product of the path losses of the transmitter-RIS and RIS-receiver links, Prof. Linglong Dai's team from Tsinghua University proposed the concept of active RIS and the corresponding methods for signal modelling and system design [174]. As shown in Figure 45, the active RIS can amplify the reflected signals via power amplifiers integrated into their elements and compensate the path loss caused by the multiplicative fading effect. The experimental measurements based on a prototype with 64 active RIS elements at 3.5 GHz verified a 10-dB signal enhancement compared to that of a metallic plate. Different from the negligible thermal noise from a passive RIS, an active RIS introduces additional and non-negligible thermal noise at the same time of signal amplification.

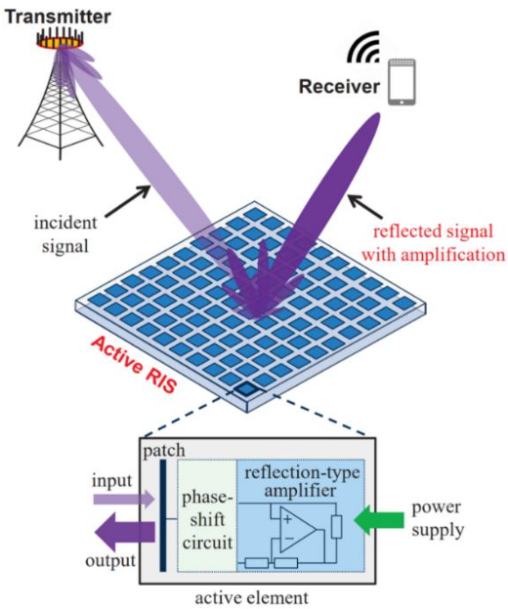


Figure 45 An active RIS modulates the reflected singal with amplification

Integreated design of active and passive RIS [175]: The integrated design with both active and passive RISs has the potential to achieve their combined advantage. For example, a hybrid RIS with both passive and active elements can achieve better communication performance than the conventional RIS with active or passive elements only. Specifically, there generally exists a trade-off between deploying more active elements to achieve the appealing power amplification gain and deploying more passive elements to attain a higher beam- forming gain, thus leading to the new design issue of active versus passive elements allocation. In addition, another type of the integrated design is deploying both stand-alone active and passive RISs in the wireless network to improve the communication performance. The advantages are two-folds. First, deploying multiple cooperative RISs provides the opportunity to construct a multi-hop reflection path between the transmitter and receiver to bypass environmental obstacles. Second, compared with the conventional multi-passive-RIS networks, adding several active RISs in the network can substantially enhance the communication performance, since active RISs can opportunistically amplify the reflected signal along the multi-reflection path, thus effectively compensating the severe path loss.

6.3. RIS-Aided Large Scale Antenna Array

Due to the large path loss of millimeter-wave, it is generally necessary to use a larger-scale antenna array to obtain a higher beamforming gain to compensate for the path loss. Limited by hardware cost, power consumption, heat dissipation, and other factors, large-scale antenna arrays usually adopt a digital-analog hybrid beamforming architecture. RIS can realize a large-scale antenna array with smaller volume and higher quality at lower cost and power consumption. Using RIS to replace the traditional phased array antenna of the base station can significantly reduce the cost and power consumption of the base station. In addition, intelligent regulation of RIS through digital coding can achieve more flexible beamforming and obtain larger beam scanning angles. A large number of RIS units can further improve the beamforming accuracy of the RIS. Using RIS as an analog antenna array for the transmitter replaces (all or part of) the analog array portion of a digital-analog hybrid beamforming architecture, with the baseband signal processing remained outside the RIS. During communication, the base station uses a digital antenna array to transmit signals to the RIS, then, RIS reflects or transmits the signal to the target user. Compared with the traditional antenna array, using RIS as an analog antenna array may not be directly connected to the radio frequency circuit of the base station through a cable, but connected through an air interface. It is worth noting that RIS, as an analog antenna array of the transmitter, is generally closer to the base station, so it is not necessary to consider defining a new air interface. At the same time, since RIS is a part of the base station, it will not change the network architecture of the system.

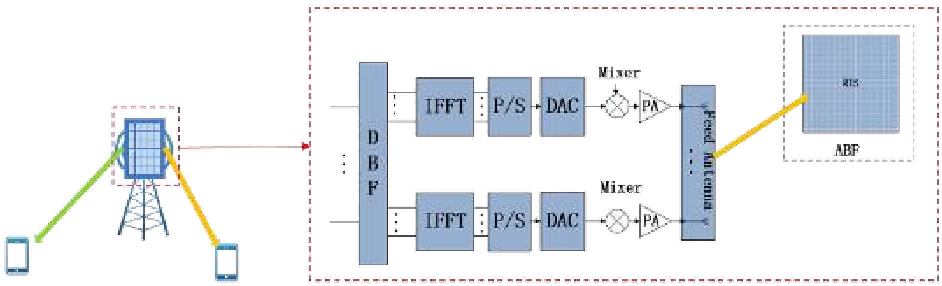


Figure 46 RIS-based transmitter architecture

6.4. RIS-Aided Transceiver

RIS can implement wireless communication multiplexing technology and build multi-mode multiplexing transmitters. RIS loaded with specific space-time codes can be used to precisely control the propagation direction of electromagnetic (EM) waves and the distribution of harmonic frequencies, integrate energy radiation and information modulation functions, and also encode and process digital information in the time and space domains. By optimizing the space-time-coding (STC) matrix, information can be directly encoded into the spatial spectrum and frequency spectrum characteristics of EM waves to realize the multi-channel wireless communication technology with space-division multiplexing (SDM) and frequency-division multiplexing (FDM) [176]. This new multiplexing wireless communication transmitter based on STC-RIS has the advantages of low cost and simple architecture, without using radiofrequency components, such as antenna arrays, filters and mixers required in traditional SDM and FDM technology. According to the number of target users and the corresponding spatial locations, the STC-RIS using the direct information encoding scheme can transmit real-time information to multiple users simultaneously and independently, without the need for digital-to-analog conversion and frequency mixing. And it has the characteristics of directional modulation and secure communication. The undesired users located at other directions cannot correctly demodulate the message. This STC-RIS provides a low-cost and low-complexity solution to implement SDM and FDM technology, and provides ideas for the design of new system wireless communication transmitter [177]-[179].

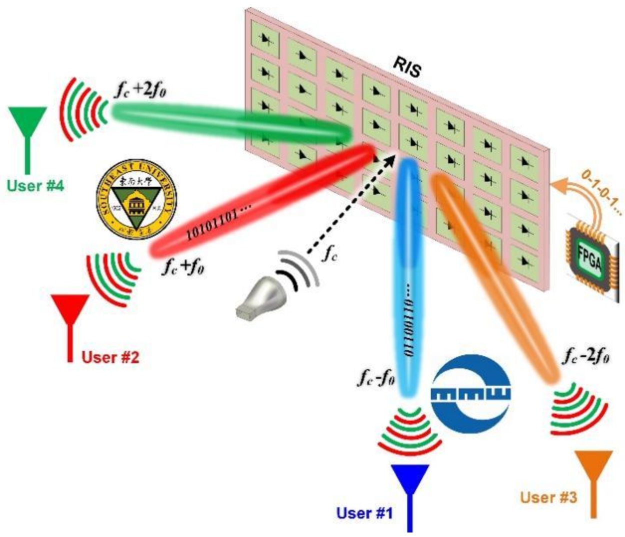


Figure 47 RIS-aided space- and frequency-division multiplexing transmitter

Since the space-time coding (STC) scheme was proposed, RISs have gradually possessed the capacities of the joint controls of amplitude, phase, frequency, polarization, wavefront characteristics, which lays the theoretical foundation for the low-cost, high-integrated, multi-mode multiplexed wireless communication technology. By applying the linearly time-varying control signal sequences with different slopes to different polarization channels of anisotropic STC RIS, the information can be modulated onto different polarization channels and frequency channels, thereby realizing the frequency-polarization-division multiplexed signal modulations [180]. On this basis, by introducing time delay gradients into the control signal sequences of each channel, the information of different channels can be directed to the target positions, thereby realizing the space-frequency-polarization-division multiplexed signal modulations, and RIS can perform frequency-polarization-division multiplexed wireless transmissions towards the different-located users through independent spatial channels. The principle of space-frequency-polarization-division multiplexed wireless communication transmitter is simple, and no complex radio-frequency devices are required, which greatly simplifies the architecture of the wireless communication system. Compared with the early RIS transmitters, the communication system built by this transmitter can improve the channel capacity and space utilization in a higher dimension, which provides new ideas and new solutions for its application in multi-user cooperative wireless communications.

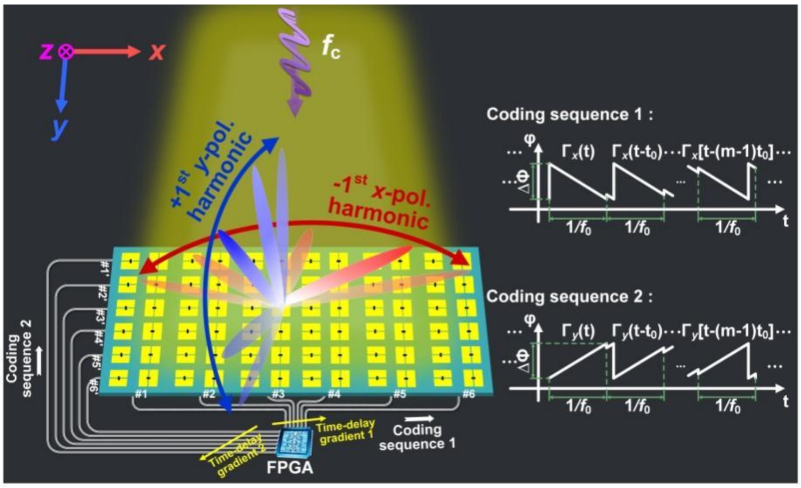
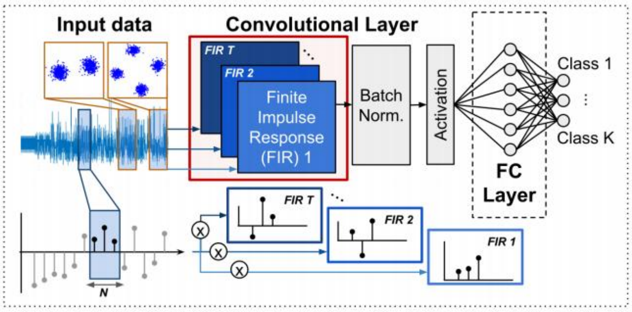


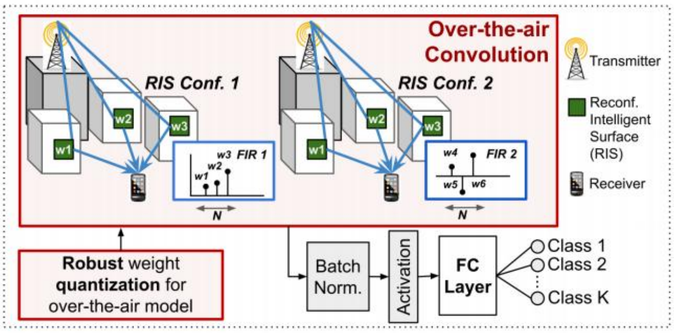
Figure 48 RIS-aided space-frequency-polarization-division multiplexing transmitter

6.5. Air Computing

Wireless analog computing allows the computation offloading to wireless environments through carefully constructed transmission signals. In this section, we introduce a RIS-based over-the-air convolution and give a detailed overview of inference tasks in convolutional neural networks. Specifically, such an architecture is designed by designing the surrounding wireless propagation environment through RIS, and called "AirNN". AirNN exploits the physics of wave reflection to represent digital convolutions in the analog domain, which is an important part of the CNN architecture. Compared with traditional communication, the receiving end has to respond to channel-induced transitions, usually this response can be expressed as a finite impulse response (FIR) filter, and AirNN actively creates signal reflections to simulate a specific FIR filter through RIS. AirNN involves two steps: First, the weights of neurons in a CNN are extracted from a finite set of channel impulse responses (CIRs) corresponding to achievable FIR filters. Second, each CIR is designed via RIS, and the reflected signals are combined at the receiver to determine the output of the convolution [181]. The comparison between traditional air computing and the new RIS-based AirNN, are shown in the following.



(a)



(b)

Figure 49 Comparisons between traditional air computing and the new RIS-based AirNN

As shown in Figure 49, (a) conventional CNN architecture, highlights the convolution step, with input data in the form of raw IQ samples and digital convolution operations in software that are represented as a bank of FIR filters (shown in red box), (b)with different RIS configurations resulting in specific channel transformations equivalent to the convolution operation shown in (a). AirNN architecture shows the same convolution operation using RIS networks for regulation and manipulation of wireless environments.

To fulfil future communication and computing requirements, new materials are needed to complement the existing technologies of metasurfaces, enabling further diversification of electronics and their applications. In this section, we introduce the concept of reconfigurable intelligent computational surface (RICS), which is composed of two reconfigurable multifunctional layers: the 'reconfigurable beamforming layer' which is responsible for tunable signal reflection, absorption, and refraction, and the 'intelligence computation layer' that concentrates on metamaterials-based computing [182]. By exploring the recent trends on computational metamaterials, RICSs have the potential to make joint communication and computation a reality.

As conceptually sketched in Figure 50, an RICS is composed of a smart controller and three layers: the reconfigurable beamforming layer, the intelligence computation layer, and the control layer. The first two multifunctional layers interplay with each other and should be jointly configured. The inner control layer is a control circuit board which is triggered by a smart controller, which focuses on adjusting the tunable parameters of the beamforming layer and can be implemented by a field-programmable gate array. The architecture design of an RICS. In order to meet the diversification of computational tasks, the intelligence computation layer can be configured by different kinds of metamaterials, e.g., neuromorphic computing metamaterials for wireless spectrum learning or analog computing metamaterials for secrecy signal processing.

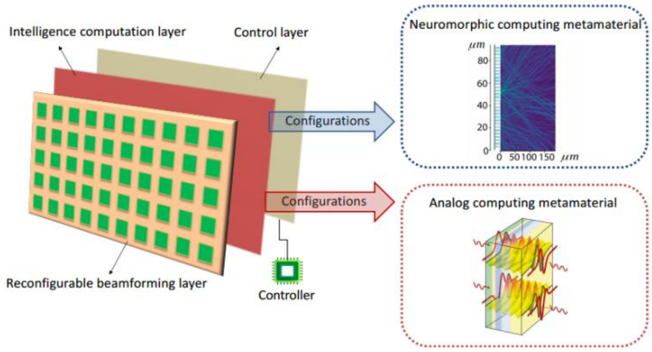


Figure 50 Architecture of intelligent computational surface

7. Current Technique Status of RIS

Many administrations and funding agencies world-wide started to support RIS-specific research projects years ago [183][184].

7.1. Research Projects

(1) North America

In 2018, US National Science Foundation (NSF) developed a research project to evaluate the feasibility of wireless environment programming. The objective of the project was to explore possible ways to adjust the wireless channel and create more favorable conditions for wireless communication. Specifically, the study examined the impact of small wireless electromagnetic units on the end-to-end wireless channel status and how these units could be dynamically adjusted based on control equipment feedback to measure real-time changes in the wireless channel.

In 2019, a research project about liquid metal-based flexible metasurface to explore their limitations and potential was initiated by NSF. The project aims to work out a new theoretical foundation to explore the limit and potential of the liquid metal-based flexible metasurface. The exploration is a benefit for designing deployable, movable, terrain-adapted RIS that can be tuned to radio signals on demand in real time.

In 2020, NSF launched a research project on the coexistence of passive and active networks via RIS. The goal of the project was to leverage RIS to suppress interference at the receiver and enable the seamless coexistence of multiple passive and active wireless communication systems. The project addressed the overall and cross-layer design, performance analysis, deployment, and optimization methods of RIS-enhanced spectrum coexistence networks. Specifically, to evaluate the impact of RIS deployment on the wireless propagation environment in the spectrum coexistence scenario, the project proposed an integral model that measures system performance. A systematic network planning method was developed to enable seamless communication where passive and active equipment coexists, which is used to determine the deployment quantity and layout of RIS. In addition, an online optimization framework for distributed spectrum coexistence was proposed to dynamically optimize the configuration of RIS. To verify the feasibility of RIS-enhanced spectrum coexistence in practical environments, RIS with near-continuous beam control capability was designed. In this way, the project demonstrated the efficacy of RIS in suppressing interference at the receiver, enabling the seamless coexistence of multiple passive and active wireless communication systems.

(2) Europe

In 2017, the VISORSURF project was launched by the Europe Union (EU) with the goal of developing a comprehensive set of software and hardware components for intelligent, interconnected objects with programmable electromagnetic behavior, known as Hyper Surfaces. The project involved the integration of an embedded electronic control unit with predefined software for programming interference. The control units activate the required electromagnetic behavior and adjust the structure of the Hyper Surface accordingly.

In Nov. 2019, the project of Europe Artificial Intelligence Aided D-Band Network for 5G Long Term Evolution (ARIADNE) was initiated, planning to combine the high-band advance wireless radio architecture and AI network processing and management, in order to form a new type of intelligent communication system.

In Jan. 2021, the EU initiated the RISE-6G project with the aim of realizing an intelligent dynamic programmable wireless environment. The objective of RISE-6G includes: firstly, defining a new type of network architecture and management strategy involving multiple RISs; secondly, utilizing the proposed radio wave propagation model to describe the basic limitations; thirdly, working out the solutions based on the dynamic programmable wireless environment with high capacity, high energy efficiency, low electromagnetic field pollution, and high location precision; fourthly, proposing an innovative prototype benchmark.

In May 2021, the EU-funded PathFinder project proposed the Wireless 2.0 mode, hoping to adopt wireless channels to the business needs of cellular networks. This technology proposes to optimize wireless channels by designing and deploying RIS. The project aims to establish theoretical and algorithmic foundations for RIS-enabled Wireless 2.0 networks and promote the further transformation of wireless networks. The research issues that the PathFinder project focuses on include RIS/radio wave interaction models inspired by physical environments, establishing theoretical and algorithmic foundations for RIS-enabled Wireless 2.0 networks; RIS network communication and information theory models; performance analysis models for large-scale deployment of RIS networks; operation schemes and optimization algorithms for RIS networks; and measurement and validation of RIS prototypes and key algorithms.

From the end of 2022, the 6G-LICRIS project funded by the German Federal Ministry of Education and Research aims to significantly improve the capacity and coverage of the future 6G network with minimal energy demand by using RIS. The project is planned to run for three years.

(3) Japan and South Korea

In Nov. 2018, NTT DOCOMO, in collaboration with Metawave Corporation, announced the demonstration of 5G mobile communication system using 28GHz-band 5G and the world’s first meta-structure reflect-array technology.

In Jan. 2020, NTT DOCOMO working in collaboration with the global glass manufacturer AGC announced today that it has successfully conducted the trial of a prototype transparent dynamic metasurface using 28 GHz 5G radio signals. The new metasurface achieves dynamic manipulation of radio-wave reflection and penetration in a highly transparent package suitable for unobtrusive use in the windows of buildings and vehicles as well as on billboards. AGC manufactured the optically transparent metasurface using microfabrication techniques based on a theoretical model proposed and designed by DOCOMO. Slightly moving the glass substrate of the designed optically transparent metasurface enables dynamic control of radio waves in three modes: full penetration of incident radio waves, partial reflection of incident radio waves, and full reflection of all radio waves. Compared to conventional methods using semiconductors, this new design offers two advantages: it allows dynamic control while maintaining the transparency of the window, and it facilitates the enlargement of the substrate.

In Jan. 2021, NTT DOCOMO and AGC announced that they had developed a prototype technology that efficiently guides 28-GHz 5G radio signals received from outdoors to specific locations indoors using a film-like metasurface lens that attaches to window surfaces. The new metasurface lens is made with an artificially engineered material featuring a large number of sub-wavelength unit cells arranged periodically on a two-dimensional surface. Elements arranged in various shapes on the metasurface substrate can be attached to a glass window to direct radio signals to specific points ("focal points") indoors. It is believed that radio waves from an outdoor base station could be received on a window's broad surface and then efficiently propagated to specific focal points inside a building with the help of repeaters and reflectors. The material has no effect on LTE and sub-6 band radio waves, so it can be used to improve indoor reception of 28 GHz radio signals without affecting the performance of legacy wireless frequencies.

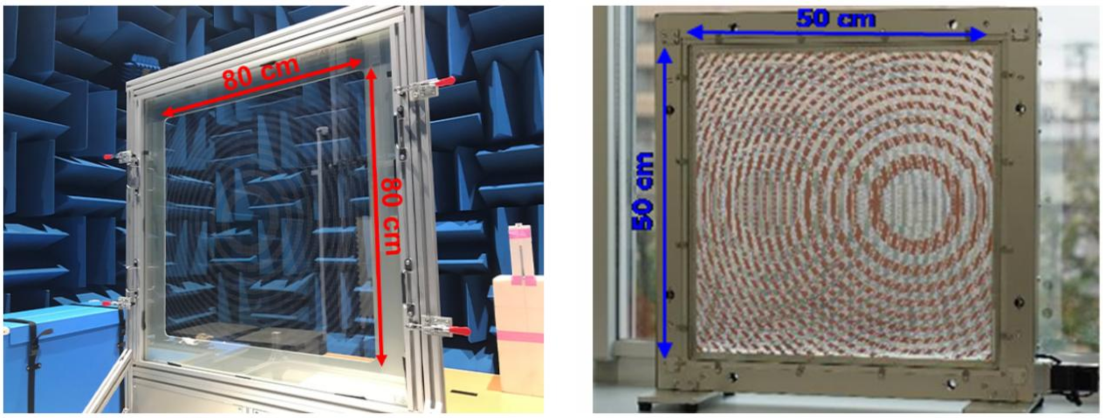


Figure 51 Static metasurface lens (left); Dynamic metasurface lens (right)

(4) China

In 2014, Academician Cui Tiejun, Southeast University, first proposed the concept of digital metamaterials and demonstrated the first programmable metamaterial. By utilizing FPGA to output control sequence to adjust the diode switch in the metasurface unit, the control of electromagnetic wave was realized in physical space, which is a pioneer in the research of digital programmable metamaterials and has attracted a lot of attention in the world. In 2020, the study designed and implemented a system-level solution for wireless communication of sub-wavelength-spaced dual-channel signals based on artificial surface plasmon metamaterial technology. The use of this artificial surface plasmon system allows for the high-quality transmission of sub-wavelength-spaced dual-channel signals without line-of-sight. This innovative solution solves the issue of the weak anti-interference capability of sub-wavelength spaced signals in traditional technology, offering a new approach for the development of highly integrated dense non-line-of-sight wireless communication technology.

In 2016, Prof. Yang Fan’s team of Tsinghua University proposed the theory of interface electromagnetism, which studies the unique and abundant electromagnetic phenomena near the interface of matter (natural or man-made), as well as its theories, methods, devices, systems and applications. And it has been regarded as an important branch of modern electromagnetics. The phase-controlled electromagnetic surface technology based on the interface electromagnetic theory has become one of the effective ways to realize RIS technology. It can integrate the functions of phase-controlled and radiation, and realize the phase-controlled radiation system without phase shifters. It has the outstanding advantages of low cost, low power consumption, simple structure, thin plane and so on.

In 2021, Prof. Feng Yijun's team from Nanjing University made a substantial breakthrough in the key technologies of RIS. They successfully developed a low-cost, large-area, scalable and efficient intelligent surface with application advantages such as dynamic adjustment of multi-bit phase state and independent control of unit, which can flexibly realize the distribution regulation of dynamic and complex beam and electromagnetic wave environment.

In 2021, Prof. Yin Haifan’s team from Huazhong University of Science and Technology developed RIS-aided wireless communication prototype system and successfully broke the performance record in the literature by achieving a 27 dB gain of the received signal enhancement without changing the power of the transmitted signal. The team completed the first outdoor long-distance signal transmission experiment of RIS, and realized a real-time playback of high-definition video streams at a transmission distance of 500 meters. In addition, in the wall-penetration test, the developed RIS prototype also achieves a power gain of 26 dB, which greatly compensates the signal’s wall-penetration loss and guarantees the communication quality[110].

Since 2021, Prof. Li Long’s team and Prof. Zhang Shun’s team from Xidian University have independently developed a millimeter wave passive micro-base station, a 2-bit RIS system, and transmission metasurfaces with an integrated active power amplifier. The wireless RIS prototype system adopts digital coding metamaterials technology and an intelligent splicing scheme, which can be flexibly applied to 5G/6G indoor wireless communication systems to extend the coverage and improve the signal strength in specific areas. The active RIS prototype system has the ability to perform secondary field enhancement regulation on space electromagnetic waves, which can realize the transmission of energy and information at the same time, laying a solid foundation for the further application of RIS in intelligent energy-carrying communication systems.

In 2021, ZTE completed the first stage of prototype verification for static hypersurface technology of intelligent surfaces and initially explored the feasibility of using this technology to enhance fixed coverage in 5G blind spots and weak areas. In 2022, ZTE innovatively proposed a smart hypersurface dynamic cooperation technology based on 5G base stations. The core of this technology is that the base station sends beam IDs and other information to the intelligent surface through the air interface, guiding it to dynamically select and switch beams to achieve dynamic beam scanning and user tracking. This solution applies key 6G intelligent hypersurface technology to 5G.

7.2. Prototype Testing and Evaluation

7.2.1. Methodology and Environment

7.2.1.1. RF Measurement under Multiple AoA/AoD of RIS

The RF parameters should be tested in the OTA chamber in case accuracy is required. In addition, considering RF parameters will be influenced by the angle relation of impinging/reflected beam of RIS, it is necessary to test RF parameters under the different assumptions of the angle relation of impinging/reflected beam, as shown in Figure 52. Although there are many combinations of impinging/reflected beams in terms of angle relation, probably only some classic combinations among them are necessary, such as the angle relation is 30º, 60º, 90º, or 120º.

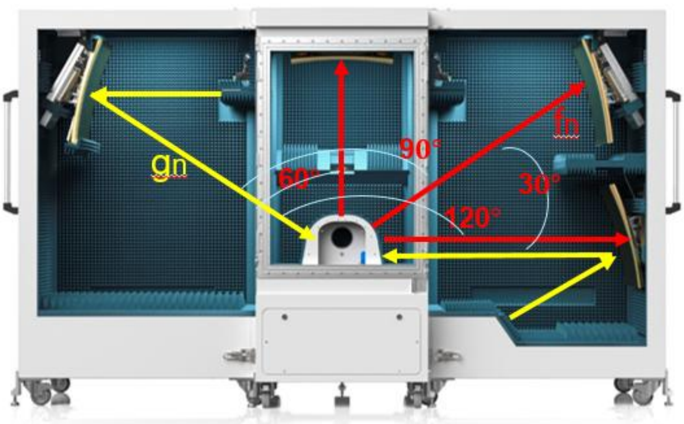


Figure 52 Chamber setup

7.2.1.2. RIS Array RCS Characterization Measurement

To better understand channel modeling and simulation for RIS scenarios, the RCS characteristics of RIS materials need to be measured. This can be achieved through the use of a dual-base RCS measurement system, illustrated in Figure 53. The system comprises a network analyzer and a two-axis rotating stage. The network analyzer performs S-parameter measurements, while the rotating stage features two coaxial rocker arms that hold transmitting and receiving antennas connected to the network analyzer's two ports. The RIS material under investigation is positioned at the center of the rotating stage to facilitate the measurements. In the RCS measurement of RIS materials, the position of the transmitting antenna is fixed, then the receiving antenna is rotated, and the S21 parameter is measured for each receiving antenna position, so as to obtain the RCS characteristics of the RIS material at a certain incident angle.

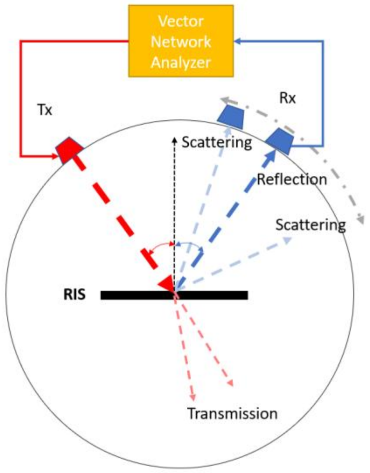


Figure 53 Dual-base RCS measurement system for RIS material EM characteristics

7.2.1.3. Channel Measurement for RIS-assisted Wireless Channels

To understand the characteristics of RIS assisted wireless channel, measurement system to perform channel measurement is needed, i.e., channel sounding system.

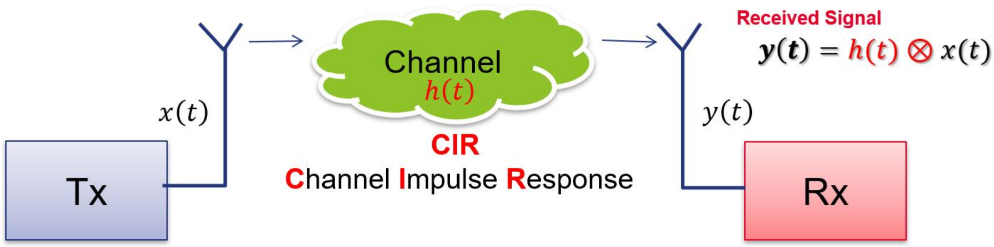


Figure 54 Diagram of channel sounding system

The simplified diagram of a channel-sounding system is illustrated in Figure 54. A typical channel-sounding system consists of a transmitter and a receiver. The transmitter transmits a pre-designed waveform as the input signal to stimulate the wireless channel, and the input signal propagates through the wireless channel. The faded signal arrives at the receiver, then channel impulse response (CIR) can be extracted from the received signal. On the one hand, the channel can be measured as a whole, performing end-to-end channel measurement for containing the RIS. On the other hand, the RIS-assisted wireless channel can be separated into two parts, the channel from the transmitter to RIS and the channel from RIS to the receiver, which can be measured independently.

Using RIS as a passive reflector or lens in coverage enhancement scenarios typically requires a large size of RIS, e.g., several meters. Considering the distance between RIS and UE is not too far, which may only sometimes satisfy the far-field distance condition for the RIS array. For example, in a RIS with a 2m×2m size, working at 3GHz, the far-field distance is about 160m, and UEs within this distance to RIS are in the near-field area of the RIS array. Thus, channel measurement and modeling for near-field channels should be considered. For instance, the channel characteristics may be inconsistent for the RIS array (e.g., corner and center of the RIS array), which should be measured separately.

The wireless channel characteristics can be measured in either the time domain or frequency domain, resulting in two types of channel sounding approaches, i.e., time domain sounding technique and frequency domain sounding technique. Typical channel-sounding techniques for channel measurement and their Pros and Cons are listed in Table 5.

Table 5. Typical Channel Sounding Techniques

	Frequency Domain Sounding	**Time Domain Sounding**	
	Frequency Swept	Sliding Correlator	Wideband Correlation
Advantage	• Much broader bandwidth • Best receiving sensitivity	• Can use low-cost narrow band digitizer	• Fast measurement speed
Disadvantage	• Low measurement speed • Limited measurement distance	• Low measurement speed	• More expensive Wideband digitizer needed

The primary consideration of a channel sounding system for RIS-assisted channel measurement is the Doppler frequency requirement. The wideband correlation approach is the only method that can meet the requirements of the CIR capturing speed, whether in outdoor scenarios, including outdoor-to-indoor scenarios with up to 833Hz Doppler shift, or in indoor scenarios (greater than two times of maximum Doppler shift, i.e., ~1.7kHz for outdoor and outdoor to indoor, and ~280Hz for indoor). Another requirement is an angular measurement, i.e., AoA (Angle of Arrival) and AoD (Angle of Departure) for the RIS-assisted channel. SISO channel sounding system needs to use RDA (Rotated Directional Antenna) approach or virtual array approach to perform the angular measurement, which will be very slow due to the mechanical movement during the test; the MIMO channel sounding system uses a physical array antenna to extract AoA and AoD by phase array processing algorithms, which can achieve accurate AoA/AoD with high measurement speed. Considering the Doppler frequency requirement, MIMO channel sounding system architecture should be used for RIS-assisted channel measurement. A typical system diagram of channel sounding for RIS-assisted channel measurement is shown in Figure 55.

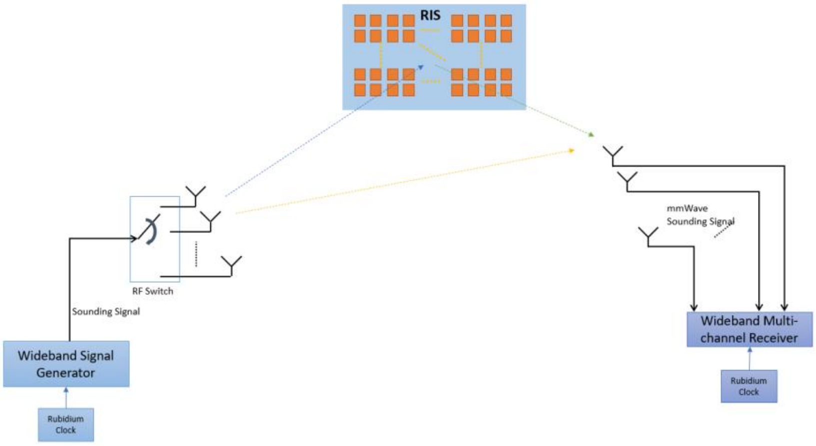


Figure 55 Channel sounding diagram for RIS-assisted channel measurement (end-to-end channel measurement)

The system for measuring the channel described above can also be used to test the channel measurements from the base station to the RIS, as well as from the RIS to the terminal channel. Taking into account the near-field channel measurement requirements for the RIS-to-UE connection, it is necessary to perform multiple measurements with the channel-sounding antenna array located at different positions of the RIS array. These measurements can capture and extract the channel characteristics of the sub-channels from the RIS sub-array to the UE, which can then be combined to build a near-field channel model for the RIS-to-UE channel. Figure 56 presents a channel-sounding measurement that was carried out using the R&S®TS-5GCS channel-sounding solution. We clearly see along with the line of sight peak, a second peak introduced by RIS deployment is clearly visible.

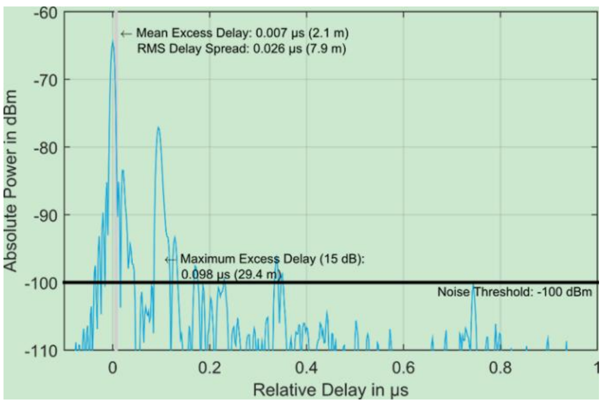


Figure 56 RIS-assisted channel measurement

7.2.2. Testing and Evaluation

(1) North America

In Feb. 2020, Massachusetts Institute of Technology (MIT) released a metasurface prototype named RFocus. The RFocus consists of 3720 low-cost antennas (At scale, the cost of each element is a few cents), which forms a 6 square-meter surface. RFocus can work both as a “mirror” or a “lens”, with the controller choosing the right mode. That is, radio endpoints can be on the same side of the surface, or on opposite sides. Based on the practical measurement, the prototype improves the median signal strength by 9.5X without increasing the antenna or output power. RFocus not only enhances Wi-Fi signals, but also amplifies 5G base station signals and provides data connectivity to small devices such as the Internet of Things. Although a dedicated controller is required to manage the miniaturized antenna array, RFocus can adaptively configure the operating mode of the antenna unit through low-power electronic circuitry to achieve a low-power passive mode, since the surface itself does not emit new radio waves.

Figure 57 MIT RFocus prototype

In the same year, University of California, San Diego established a ScatterMIMO prototype. This prototype is a kind of passive metasurface system. Based on the practical measurement under a typical indoor office scenario, the average system capacity can be improved by 2 dB, and the coverage can be extended from 30m to 45m with the assistance of the SatterMIMO system.

(2) Europe

In Mar. 2022, another project funded by European Union, namely SURFER, was launched, aiming to utilize surface wave communication (SWC) in indoor communication. In contrast with FSC-based RISs, SWC enables reliable, energy-efficient, and interference-free communications in indoor environments. Surface waves glide at the interface of materials, and their propagation is inherently confined on their surfaces. Compared with FSC, SWC offers much easier interference management and an inherently low probability of intercept.

(3) Japan and South Korea

In Nov. 2018, NTT DOCOMO, in collaboration with Metawave Corporation, conducted the demonstration of 5G mobile communication system using 28GHz-band 5G. The 5G trial site is located at Koto-ku, Tokyo. 5G data communication using 28GHz band was measured between the 5G base station located on Tokyo International Exchange Center rooftop and the 5G mobile station running the experimental vehicle. There was no direct path between the 5G base station and the 5G test vehicle due to the shading of the Tokyo International Exchange Center. The location of the meta-structures reflector used in the demonstration, the reflection direction, and the beam shape of the reflected wave is determined so that the area of the 5G site is expanded using these tiny structures to form the beam arranged in the plane of the reflect-array. As a result of this demonstration, the communication speed achieved was 560 megabits per second (Mbps) with Metawave's meta-structure reflect-array in place, compared to 60 Mbps with no reflector. This greatly improved the communication quality in areas lacking 5G coverage, extended the communication range by about 35 meters, and increased the communication speed of vehicles equipped with 5G mobile stations by 500 Mbps.

In Jan. 2020, NTT DOCOMO working in collaboration with the global glass manufacturer AGC announced today that it has successfully conducted the trial of a prototype transparent dynamic metasurface using 28 GHz 5G radio signals. In the trial, radio waves were beamed perpendicularly to measure penetration in two modes: full penetration, where the metasurface substrate and movable transparent substrate were attached to each other, and full reflection, where the metasurface substrate and movable transparent substrate were separated by more than 200 micrometers. Tests of both modes at 28 GHz produced successful results. Radio waves passed through the substrate in penetration mode and were blocked in reflection mode, in both cases without attenuation. The distance between the two substrates was manually controlled in the current test, but in future tests, a piezoelectric actuator will be used to switch between penetration and reflection modes at high speed.

In Jan. 2021, NTT DOCOMO and AGC announced that they had developed a prototype technology that efficiently guides 28-GHz 5G radio signals received from outdoors to specific locations indoors using a film-like metasurface lens that attaches to window surfaces. The trial confirmed that the metasurface lens improves the power level of 28 GHz radio signals received at indoor focal points. The trial also confirmed the ability to control focal-point position as well as the ability to switch from single to dual focal points.

In Mar. 2022, LG conducted field testing and verification for RIS at 3.5GHz and 28GHz. In Apr., KYOCERA conducted field testing based on 5G RIS prototype at 28GHz, and proved that the RIS system could effectively improve network coverage.

(4) China

From 2018 to now, Prof. Jin Shi's team of Southeast University, in cooperation with Academician Cui Tiejun and Prof. Cheng Qiang's team, has realized real-time wireless transmission of SISO and MIMO based on RIS. A series of works such as modeling of free space path loss of RIS, modeling of actual environment channel of RIS, measurement verification of channel interoperability, and modeling of power consumption for RIS has been carried out. In 2019, the research and development of a series of RIS prototypes in 5G Sub-6 GHz and millimeter wave frequency bands were completed. Prof. Yang Fan's team cooperated with mainstream operators and vendors, and has completed the indoor and outdoor tests of 5G millimeter wave by using the self-developed RIS module with 2304 units. On top of this, Prof. Feng Yijun's team from Nanjing University, in collaboration with Huawei, carried out the prototype field trial under 5G wireless network (2.6GHz band), which verified the feasibility of the application of RIS in the real network environment.

In Jun. 2021, ZTE and China Unicom completed the verification of RIS technology under 5G network of the intermediate frequency band. The test results show that in the cell edge under the non-line-of-sight scenario, the receiving signal strength can be improved by 10 dB, and the throughput can be improved by more than 40%. ZTE and China Telecom completed the verification of RIS technology under the 5G network of the millimeter frequency band. The test results show that in the area with 150 meters away from the base station under the non-line-of-sight scenario, the receiving signal strength can be improved by 12.5 dB, and the throughput can be improved by more than 296%. China Mobile and Southeast University completed the verification of RIS technology based on 5G practical network. The test results show that RIS can flexibly adjust the signal beam in the wireless environment according to the distribution of users and significantly improve the signal strength, network capacity, and user rate in the weak coverage area of the network. The validation efforts foreshadow the prospect of a wide range of applications of information metamaterial technology in future mobile communication networks.

In Aug. 2021, the Future Network System Optimization Innovation Laboratory, jointly established by Shenzhen Research Institute of Big Data, the Chinese University of Hong Kong (Shenzhen) and Huawei, completed a RIS prototype without the requirement of channel state information and verified the feasibility of RIS technology without changing the existing mobile network structure and protocols. RIS technology developed by the laboratory is suitable for low-cost and large-scale promotion and deployment in the existing 5G network. At present, the joint research and development team led by Prof. Luo Zhiquan has completed the preliminary test and verification based on the practical 5G network environment (2.6GHz), and confirmed that RIS technology based on blind beam formalization could bring all-round performance improvement to 5G network. According to the test results, the typical indoor scenario with poor coverage can effectively improve the coverage performance by 14dB, the SINR by 14dB and the data rate by 200%. In the outdoor scenario with lower multipath, the rank of the wireless channel can be raised one order, and the data rate can be improved by 50% by introducing the RIS system. The team has completed the preliminary preparation work for the prototype's large-scale application, and the next step is to plan to carry out verification and application in richer scenarios in a real network to support system-level optimization of the 5G network.

In the middle of 2022, China Unicom and Rohde & Schwarz joined forces with Tsinghua University, Actenna Technology and others to conduct RIS technology trials. The RIS verification environment was divided into indoor testing and outdoor testing, with RIS test subjects and instruments mainly used in the indoor test. RSRP and throughput were tested using QualiPoc software and drive test terminals. An R&S TSME6 scanner was used to verify that RIS can solve problems like blind spot coverage in a real network environment. In addition, the outdoor test also verified the performance of the RIS hypersurface in a chamber environment, using the R&S SMW200A vector signal generator as a signal source and the R&S®FSW signal and spectrum analyzer to test the antenna directional map and the adjacent channel leakage ratio (ACLR). In the same year, ZTE Corporation became a pioneer in developing a prototype intelligent hypersurface with cooperative beamforming capabilities, and successfully completed technical verification in both laboratory and field environments - a first in the industry. The results demonstrate that compared to static hypersurfaces that can only improve coverage at fixed points, the cooperative beamforming technology of base stations and intelligent hypersurfaces can significantly enhance the coverage of base stations, while also supporting seamless user connectivity in mobile scenarios[185].

In 2022, the IMT-2030 (6G) Promotion Group established a "Test Task Force" and organized five potential key 6G technology tests, including smart super-surface and pass-sense integration, and released the tests at the "Global 6G Development Conference" held in Shanghai on Nov. 15-16, 2022. The intelligent super-surface technology test included 8 units, including ZTE, Huawei, CICT, China Unicom, Xidian University Huazhong University of Science and Technology, Southeast University, and Tsinghua University. Considering the technology's maturity, the focus for testing and verification in 2022 was on RIS for coverage enhancement scenarios. The test content included indoor coverage enhancement, outdoor coverage enhancement, multi-user interference testing, and the basic function test of RIS's gate flap power. The test results showed that RIS can actively control the wireless propagation environment to flexibly regulate the beam pointing in the desired direction, which has significant performance advantages in coverage enhancement. RIS is also low-power and easy to deploy, but currently faces challenges in devices, regulation, algorithms, and other areas. In Feb. 2023, ZTE's dynamic RIS was selected for the Barcelona 2023 Global Mobile Congress Best Mobile Technology Breakthrough Award shortlist.

7.3. Standard Evolution and Ecological Construction

(1) IMT-2030(6G) Promotion Group

In Jun. 2020, the IMT-2030(6G) established the RIS Task Group, which the crucial members of RIS Task Group include the universities and enterprises working on RIS. Since its establishment, the task force has organized a series of activities to promote the research, standardization, and industrialization process of RIS technology. On Sept. 17, 2021, and Nov. 16, 2022, the IMT-2030 (6G) Promotion Group released the first and second editions of the Research Report on RIS at the 6G Workshop RIS Technology Forum.

(2) China Communications Standards Association

China Communications Standards Association (CCSA) is responsible for domestic communication standardization work. In Sep. 2020, a project titled “Study on RIS” was approved in CCSA TC5 WG6 #55, including the study on deployment scenarios of RIS, the progress of research on materials, related algorithms, system architecture and network design, measurement verification and test, and etc.

(3) RIS TECH Alliance (RISTA)

The RIS TECH Alliance (RISTA) inauguration ceremony and 1st general assembly was held in Beijing on Apr. 7, 2022. 87 online and offline RISTA member representatives from colleges and universities, enterprises, scientific research institutes, think tanks and industrial organizations attended the conference.

The RISTA is a cross-industry, open, and non-profit social organization that is formed by enterprises, public institutions, associations, colleges and universities, and scientific research institutes related to RIS on the basis of voluntariness, equality, and mutual benefits. The RISTA is committed to bringing together the entities in the RIS ecosystem to deepen their exchange and cooperation, thus promoting the research, standardization, and industrialization of RIS-related technologies.

At the inaugural meeting of the RISTA, major appointments were made for the tech alliance chairman, vice chairman, chairman unit, special advisor, and chairman of the expert committee. Academician Cui Tiejun was appointed as the chairman of the RISTA, with Beijing University of Posts and Telecommunications, Southeast University, Tsinghua University, China Telecom, China Institute of Electronics on Communication Society, China Unicom, China Academy of Information and Communications Technology, China Mobile, and ZTE Corporation as the chairman units (in the order of the Chinese phonetic of the units). Mr. Yang Zemin was appointed as a special advisor, and Academician Cui Tiejun of the Chinese Academy of Sciences, as well as Academicians Wu Jiangxing, Liu Yunjie, and Zhang Ping of the Chinese Academy of Engineering, Academician Luo Zhiquan of the Royal Canadian Academy of Sciences, and Academician Zhang Rui of the Singapore Academy of Engineering were appointed as the chairman of the RISTA Expert Committee. The RISTA includes a council, a standing council, an expert committee, and a secretariat, as well as five working groups. It plans to hold an annual RIS Technology Forum as the RISTA flagship yearly meeting. The constitution, working group settings, membership application, and RISTA's 2022 work plan were considered and adopted. Academician Cui Tiejun, the chairman of the RISTA, gave a special report on intelligent hypersurface technology.

Figure 58 RISTA Founding Ceremony

(4) ETSI

In Jun. 2021, ETSI's Industry Specification Group (ISG) on RIS (ISG RIS) was approved and subsequently launched in September. This group enables ETSI members to coordinate their pre-standardization research efforts on RIS technology across various EU collaborative projects and global initiatives, with the aim of paving the way for future standardization of the technology. The group's primary objective is to review and establish global standardization of reconfigurable intelligent surface technology. In 2021, the ISG initiated three new work projects focused on examining RIS application scenarios and deployment approaches, technical challenges and architectures, communication models, and channel models, with the intent to produce technical reports, white papers, and proofs of concept. ISG RIS is about to publish two of the first three group reports in March 2023, on channel and physical models of RIS, and deployment scenarios and use cases, respectively. ISG RIS is also looking forward to completing the work item on controlling aspect and standard impact of RIS, as well as establishing new work items on potential hardware designs of RIS in 2023.

8. RIS Trends Outlook

8.1. Iterative Evolution: Upward Spiral of 6G Technologies in 5G Evolution

Before the inception of RIS, some related fundamental theories represented by the metamaterial theory, the surface electromagnetics theory, and the generalized Snell's law have been well developed, laying a solid foundation for the establishment of the theoretical framework of RIS. In terms of key technologies, those related to RIS, such as phased arrays and programmable logic gates, have also been applied in other fields. The unit-cell design for RIS is mainly related to RF characteristics such as amplitude, phase, frequency, and wavelength, and is basically not affected by the underlying technologies such as signal waveform, modulation code, and frame structure. RIS is consequently compatible with many other physical layer technologies. Moreover, RIS system has the potential of flexibly deploying in wireless networks, thus the existing theoretical and technical foundations support the development of RIS in 5G evolution. RIS working mode will change from static, semi-static to dynamic in the process of iterative evolution, resulting in suitable deployment and control strategies for different scenarios.

During the 5G phase, the preliminary integration of the RIS system with existing base stations and terminals can be realized by in-band signaling, and designing the sub-wavelength RIS system in the sub-6 GHz band. Furthermore, explore potential interfaces and corresponding protocols between RIS and the base station, which hopefully be helpful for RIS to smartly reconfigure the wireless propagation environment.

8.2. Industry Implementation: RIS Standardization Outlook

In December 2021, a study item on network-controlled repeater (NCR) was approved in 3GPP Rel-18 [186]. In June 2022, a work item on NCR was approved in 3GPP Rel-18 [187]. Since the characteristic of RIS is similar to NCR, we can obtain reference and support from NCR for the RIS standardization. RIS as a new technology has recently been a hot research topic in the academia and industry. But extensive technical studies and various prototypes have led to difficulties in the RIS standardization. With the increasing maturity and stability of the RIS equipment, RIS standardization will be more important in the future.

Based on the above analysis, the standardization outlook of RIS is as follows. Based on the industry's maturity and implementation complexity, it is recommended to promote the future Rel-18 NCR evolution towards RIS relay for 5G-Advanced. Further study should be conducted on far-field channel models to encourage the development and application of moderate-sized RIS panels controlled by FPGA. This will prompt research on near-field channel models and very large RIS panels controlled by ASIC. Finally, standardization of RIS technology can be realized in the 6G phase.

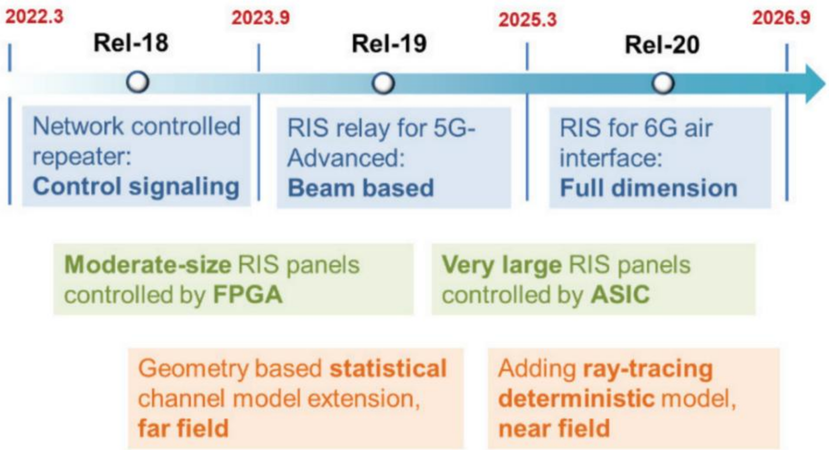


Figure 59 RIS standardization outlook

From the perspective of RIS engineering application, a three-stage approach for network deployment and iterative evolution of RIS is proposed as follows. Stag 1: RIS is used for coverage holes by deploying multiple non-standard static RIS panels in the 5G existing network. Stage 2: RIS is used to optimize continuous network coverage by deploying the semi-dynamically adjustable RIS based on the 5G-Advanced standardization. Stage 3: RIS is used to build a smart radio environment that brings a new communication network paradigm to 6G, by ubiquitously deploying dynamic RIS in the future mobile communication network.

8.3. Open Cooperation: Construction of RIS Ecosystem

RIS has the great potential to be implemented in existing networks and bring a new network paradigm to meet the needs of future mobile communication and has the initially demonstrated powerful performance in a number of areas. However, RIS faces problems and challenges such as the technical research, engineering application, network deployment, and standardization process before large-scale commercial use.

Since the current upstream and downstream industries of RIS are relatively independent, an integrated RIS ecosystem is urgently needed, to cover the entire industry chain, and bring together enterprises, universities, research institutes, and end-users. The RIS ecosystem promotes in-depth cooperation and exchange between solution providers, academic institutions, the organizations related to metamaterials or elements, and those in information and communications technology and other related verticals, thus promoting the research, standardization, and industrialization of RIS-related technologies.

9. Reference

[1] Q. Gao, Q. Huang, X. Meng, Massive MIMO Technology Report[R]，IMT-2030(6G), 2021.
[2] M. Di Renzo, A. Zappone, M. Debbah, M.-S. Alouini, C. Yuen, J. de Rosny, and S. Tretyakov, “Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead,” IEEE J. Sel. Areas Commun., vol. 38, no. 11, pp. 2450-2525, Nov. 2020.
[3] ZTE, Southeast University, China Unicom Co-hosting 1st RIS Forum [E]. https://www.mscbsc.com/info/Nw5111e. 2021-09-26.
[4] RIS Techonology Alliance (RISTA) was founded in Beijing [E]. 科技日报, http://www.stdaily.com/index/kejixinwen/202204/78120a63e7e04bb4b6a0053367a83b1f.shtml. 2022.
[5] T. Cui, S. Jin, J. Zhang, Y, Zhao, RIS Technology Report[R]. IMT-2030(6G), 2021.
[6] Cross-disciplinary innovation, China Mobile and Cui Tiejun academician team took the lead in completing RIS technology [E].
https://www.c114.com.cn/news/118/a1168348.html. 2021.
[7] ZTE and China Telecom completed the industry's first 5G high-frequency outfield RIS technology verification test [E].
https://www.c114.com.cn/news/127/a1167281.html. 2021.
[8] ZTE and China Unicom completed the verification of RIS technology in the outfield of the world's first 5G IF network [E]. https://www.c114.com.cn/news/127/a1167167.html. 2021.
[9] Perfect combination of mathematics and communication - Professor Luo Zhiquan's team has cooperated with Huawei to achieve a breakthrough in the application of RIS technology in 5G networks [E]. http://www.sribd.cn/article/361/. 2021.
[10] 5G Evolution and 6G: HAPS, metasurface lens and pinching antenna [E]. https://www.nttdocomo.co.jp/english/info/media_center/event/mwc21/contents/exhibits06/. 2021.
[11] W. Chen, C.-K. Wen, X. Li, and S. Jin, ``Channel customization for joint Tx-RISs-Rx design in hybrid mmWave systems,’’ [Online]. Available: https://arxiv.org/abs/2109.13058v1.
[12] T. Huang, Research on RIS for Terahertz Communication [D]. Thesis of Beijing University of Posts and Telecommunications, 2021.
[13] S. Yu, C. Liu, J. Qian. Construction and optimization of high-speed and large-capacity visible light communication system based on HDMA for 6G [J]. Jiangxi Communication Technology, 2022.
[14] H. Abumarshoud, L. Mohjazi L, O. A. Dobre, et al. LiFi through reconfigurable intelligent surfaces: A new frontier for 6G? [J]. IEEE Vehicular Technology Magazine, 2021, 17(1): 37-46.
[15] A.R. Ndjiongue, T. M. N. Ngatched, O. A. Dobre, et al. Design of a power amplifying-RIS for free-space optical communication systems[J]. IEEE Wireless Communications, 2021, 28(6): 152-159.
[16] J. Feng. NTN non-terrestrial network technology and its industry analysis [J], Satellite TV and broadband multimedia, vol. 11, pp. 31-32, 2021.
[17] B. Zheng, S. Lin and R. Zhang, "Intelligent Reflecting Surface-Aided LEO Satellite Communication: Cooperative Passive Beamforming and Distributed Channel Estimation," IEEE Journal on Selected Areas in Communications, vol. 40, no. 10, pp. 3057-3070, Oct. 2022.
[18] X. Bai, F. Zhang, L. Sun, et al., “Radiation-type programmable metasurface for direct manipulation of electromagnetic emission,” Laser & Photonics Reviews, vol. 16, p. 2200140, 2022.
[19] S. Li, B. Duo, X. Yuan, Y.-C. Liang, and M. Di Renzo, “Reconfigurable intelligent surface assisted UAV communication: Joint trajectory design and passive beamforming,” IEEE Wireless Communications Letters, vol. 9, no. 5, pp. 716–720, 2020.
[20] J. Guo, L. Yu, Z. Chen, Y. Yao, Z. Wang, Zh. Wang, and Q. Zhao. RIS-assisted secure UAV communications with resource allocation and cooperative jamming[J]. IET Communications, Apr. 2022. DOI: 10.1049/cmu2.12416.

[21] Z. Chen, J. Ye, and L. Huang, A Two-Stage Beamforming Design for Active RIS Aided Dual Functional Radar and Communication, 2023 IEEE Wireless Communications and Networking Conference (WCNC), 2023.
[22] E. Björnson, H. Wymeersch, B. Matthiesen, P. Popovski, L. Sanguinetti and E. d. Carvalho, "Reconfigurable Intelligent Surfaces: A signal processing perspective with wireless applications," IEEE Signal Processing Magazine, vol. 39, no. 2, pp. 135-158, March 2022.
[23] H. Wymeersch, J. He, B. Denis, A. Clemente and M. Juntti, "Radio Localization and Mapping With Reconfigurable Intelligent Surfaces: Challenges, Opportunities, and Research Directions," IEEE Vehicular Technology Magazine, vol. 15, no. 4, pp. 52-61, Dec. 2020.
[24] J. He, H. Wymeersch, L. Kong, O. Silvén and M. Juntti, "Large Intelligent Surface for Positioning in Millimeter Wave MIMO Systems," in IEEE 91st Vehicular Technology Conference (VTC2020-Spring), 2020.
[25] J. He, H. Wymeersch, T. Sanguanpuak, O. Silven and M. Juntti, "Adaptive Beamforming Design for mmWave RIS-Aided Joint Localization and Communication," in IEEE Wireless Communications and Networking Conference Workshops (WCNCW), 2020.
[26] E. C. Strinati and e. al, "Reconfigurable, intelligent, and sustainable wireless environments for 6G smart connectivity," IEEE Communications Magazine, vol. 59, no. 10, pp. 99-105, October 2021.
[27] G. C. Alexandropoulos, N. Shlezinger and P. d. Hougne, "Reconfigurable Intelligent Surfaces for Rich Scattering Wireless Communications: Recent Experiments, Challenges, and Opportunities," IEEE Communications Magazine, vol. 59, no. 6, pp. 28-34, June 2021.
[28] T. Bai, C. Pan, Y. Deng, M. Elkashlan, A. Nallanathan and L. Hanzo, "Latency Minimization for Intelligent Reflecting Surface Aided Mobile Edge Computing," in IEEE Journal on Selected Areas in Communications, vol. 38, no. 11, pp. 2666-2682, Nov. 2020.
[29] M. Cui, G. Zhang, and R. Zhang, "Secure wireless communication via intelligent reflecting surface," IEEE Wireless Commun. Lett., vol. 8, no. 5, pp. 1410–1414, 2019.
[30] S. Hong, C. Pan, H. Ren, K. Wang and A. Nallanathan, "Artificial-Noise-Aided Secure MIMO Wireless Communications via Intelligent Reflecting Surface," in IEEE Transactions on Communications, vol. 68, no. 12, pp. 7851-7866, Dec. 2020.
[31] S. Tian, X. Zhang, X. Wang, J. Han, and L. Li, "Recent advances in metamaterials for simultaneous wireless information and power transmission" *Nanophotonics*, vol. 11, no. 9, 2022, pp. 1697-1723.
[32] C. Pan *et al.*, "Intelligent Reflecting Surface Aided MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer," in *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 8, pp. 1719-1734, Aug. 2020
[33] Q. Wu and R. Zhang, "Joint Active and Passive Beamforming Optimization for Intelligent Reflecting Surface Assisted SWIPT Under QoS Constraints," IEEE J. Sel. Areas Commun., vol. 38, no. 8, pp. 1735-1748, Aug. 2020.
[34] Q. Wu, X. Guan and R. Zhang, "Intelligent Reflecting Surface-Aided Wireless Energy and Information Transmission: An Overview," Proceedings of the IEEE, vol. 110, no. 1, pp. 150-170, Jan. 2022.
[35] M. Chang, J. Han, X. Ma, H. Xue, X. Wu, L. Li, and T. J. Cui, "Programmable metasurface for simultaneously wireless information and power transfer system," ZTE Communications, vol. 20, no. 2, pp. 48–62, Jun. 2022.
[36] W. Wu, Zi Wang, Lu Yuan, Fuhui Zhou, Fei Lang, Baoyun Wang, and Qihui Wu, "IRS-Enhanced Energy Detection for Spectrum Sensing in Cognitive Radio Networks," IEEE Wirel. Commun. Lett., vol. 10, no. 10, pp. 2254-2258, Oct. 2021.
[37] W. Wu, Zi Wang, Fuhui Zhou, Baoyun Wang, Qihui Wu and Naofal Al-Dhahir, "Joint Sensing and Transmission Optimization in IRS-Assisted CRNs: Throughput Maximization," in Proc. IEEE Global Commun. Conf. (GLOBECOM) 2022, 2022, to be published.

[38] W. Yan, X. Yuan, Z.-Q. He, and X. Kuai, “Passive Beamforming and Information Transfer Design for Reconfigurable Intelligent Surfaces Aided Multiuser MIMO Systems,” IEEE J. Select. Areas Commun., vol. 38, no. 8, pp. 1793–1808, Aug. 2020, doi: 10.1109/JSAC.2020.3000811.
[39] Z. Tian, Z. Chen, M. Wang, Y. Jia, L. Dai and S. Jin, "Reconfigurable Intelligent Surface Empowered Optimization for Spectrum Sharing: Scenarios and Methods," IEEE Vehicular Technology Magazine, vol. 17, no. 2, pp. 74-82, Jun. 2022.
[40] J. Yuan, Y. -C. Liang, J. Joung, G. Feng and E. G. Larsson, "Intelligent Reflecting Surface-Assisted Cognitive Radio System," in IEEE Transactions on Communications, vol. 69, no. 1, pp. 675-687, Jan. 2021
[41] L. Zhang, Y. Wang, W. Tao, Z. Jia, T. Song and C. Pan, "Intelligent Reflecting Surface Aided MIMO Cognitive Radio Systems," in IEEE Transactions on Vehicular Technology, vol. 69, no. 10, pp. 11445-11457, Oct. 2020
[42] X. Guan, Q. Wu and R. Zhang, "Joint Power Control and Passive Beamforming in IRS-Assisted Spectrum Sharing," in IEEE Communications Letters, vol. 24, no. 7, pp. 1553-1557, July 2020.
[43] Z. Peng, Z. Zhang, C. Pan, L. Li and A. L. Swindlehurst, "Multiuser Full-Duplex Two-Way Communications via Intelligent Reflecting Surface," in IEEE Transactions on Signal Processing, vol. 69, pp. 837-851, 2021.
[44] Y. Zhang, C. Zhong, Z. Zhang and W. Lu, "Sum Rate Optimization for Two Way Communications With Intelligent Reflecting Surface," in IEEE Communications Letters, vol. 24, no. 5, pp. 1090-1094, May 2020.
[45] C. Pan et al., "Multicell MIMO Communications Relying on Intelligent Reflecting Surfaces," in IEEE Transactions on Wireless Communications, vol. 19, no. 8, pp. 5218-5233, Aug. 2020.
[46] G. Zhou, C. Pan, H. Ren, K. Wang and A. Nallanathan, "Intelligent Reflecting Surface Aided Multigroup Multicast MISO Communication Systems," in IEEE Transactions on Signal Processing, vol. 68, pp. 3236-3251, 2020.
[47] H. Yang, X. Cao, J. Gao. Recent advances in reconfigurable metasurfaces and their applications [J]. Journal of Radars, 10(2):206-219, 2021.
[48] X. Meng, Electromagnetic vortex wave generation and target near-field scatting based on artificial electromagnetic metasurface [D]. Thesis of Xidian University, 2019.
[49] S. Yu, L. Li, G. Shi, C. Zhu, X. Zhou, and Y. Shi, "Design, fabrication, and measurement of reflective metasurface for orbital angular momentum vortex wave in radio frequency domain," Applied Physics Letters, 108, 121903, 2016.
[50] M. Jian, R. Liu, E. Basar, Y. Liu and C. Huang, "Reconfigurable Intelligent Surface Aided Non-Coaxial OAM Transmission for Capacity Improvement," 2022 IEEE/CIC International Conference on Communications in China (ICCC), Sanshui, Foshan, China, 2022, pp. 594-599. doi: 10.1109/ICCC55456.2022.9880812
[51] S. Yu, L. Li, G. Shi, C. Zhu, and Y. Shi, "Generating multiple orbital angular momentum vortex beams using a metasurface in radio frequency domain," Applied Physics Letters, 108, 241901, 2016.
[52] X. Dong, Research on the generation of vortex electromagnetic wave based on reflective metasurface [D]. Thesis of Nanjing University of Aeronautics and Astronautics, 2019.
[53] Z. Yang, M. Chen, Z. Zhang, C. Huang, "Energy Efficient Semantic Communication over Wireless Networks with Rate Splitting," in IEEE Journal on Selected Areas in Communications, 2023, to appear.
[54] VESELAGO V G. The electrodynamics of substances with simultaneously negative values of ε and μ[J]. Soviet physics uspekhi，1968，10（4）：509-514.
[55] PENDRY J B, HOLDEN A J, STEWART W J, et al. Extremely low frequency plasmons in metallic mesostructures[J]. Physical review letters，1996，76（25）：4773.
[56] PENDRY J B, HOLDEN A J, ROBBINS D J, et al. Magnetism from conductors and enhanced nonlinear phenomena[J]. IEEE transactions on microwave theory and techniques，1999，47（11）：

2075-2084.
[57] SIEVENPIPER D, ZHANG L, BROAS R F J, et al. Highimpedance electromagnetic surfaces with a forbidden frequency band[J]. IEEE transactions on microwave theory and techniques，1999，47（11）：2059-2074.
[58] L. Zhang, X. Chen, Y. Zheng, T. Cui. Electromagnetic metasurfaces and information metasurfaces [J]. Chinese journal of radio science,2021,36(06):817-828.
[59] Yu N F, Genevet P, Kats M A, et al . Light propagation with phase discontinuities: Generalized laws of reflection and refraction [J]. Science, 2011, 334(6054): 333–337. DOI: 10.1126/science.1210713.
[60] CUI T J, QI M Q, WAN X, et al. Coding metamaterials, digital metamaterials and programmable metamaterials[J]. Light:science & applications，2014，3（10）: e218-e218.
[61] MA Q, BAI G D, JING H B, et al. Smart metasurface with self-adaptively reprogrammable functions[J]. Light: science & applications，2019，8（1）：98.
[62] CUI T J, LIU S, ZHANG L. Information metamaterials and metasurfaces[J]. Journal of materials chemistry C，2017，5（15）：3644-3668.
[63] F. K. Gruber and E. A. Marengo, “New aspects of electromagnetic information theory for wireless and antenna systems,” IEEE Trans. Antennas Propag., vol. 56, no. 11, pp. 3470-3484, Nov. 2008.
[64] Wan, J. Zhu, Z. Zhang, and L. Dai, “Capacity for electromagnetic information theory,” arXiv preprint arXiv:2111.00496, Nov. 2021.
[65] Cui Tie-Jun, Wu Hao-Tian, Liu Shuo, Research progress of information metamaterials [J], Acta Phys. Sin., 2020, 69(15): 158101. doi: 10.7498/aps.69.20200246.
[66] L. N. Dworsky, Modern Transmission Line Theory and Applications, 1st Ed., Wiley, 1980.
[67] K. Sarabandi and N. Behdad, "A Frequency Selective Surface With Miniaturized Elements," *IEEE Transactions on Antennas & Propagation,* vol. 55, pp. 1239-1245, 2007.
[68] A. Fallahi and J. Perruisseau-Carrier, "Design of tunable biperiodic graphene metasurfaces," *Phys.rev.b,* vol. 86, pp. 4608-4619, 2012.
[69] S. B. Glybovski, S. A. Tretyakov, P. A. Belov, Y. S. Kivshar, and C. R. Simovski, "Metasurfaces: From microwaves to visible," *Physics Reports,* vol. 634, pp. 1-72, 5/24/ 2016.
[70] Y. Ra'Di, C. R. Simovski, and S. A. Tretyakov, "Thin Perfect Absorbers for Electromagnetic Waves: Theory, Design, and Realizations," *Physical Review Applied,* vol. 3, p. 037001, 2015.
[71] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect metamaterial absorber," *Physical Review Letters,* vol. 100, p. 207402, 2008.
[72] N. Gagnon, A. Petosa, and D. A. McNamara, "Research and Development on Phase-Shifting Surfaces (PSSs)," *IEEE Antennas and Propagation Magazine,* vol. 55, pp. 29-48, 2013.
[73] D. Sievenpiper, Z. Lijun, R. F. J. Broas, N. G. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band," *IEEE Transactions on Microwave Theory and Techniques,* vol. 47, pp. 2059-2074, 1999.
[74] F. Yang and Y. Rahmat-Samii, "Microstrip antennas integrated with electromagnetic band-gap (EBG) structures: a low mutual coupling design for array applications," *IEEE Transactions on Antennas & Propagation,* vol. 51, pp. 2936-2946, 2003.
[75] B. H. Fong, J. S. Colburn, J. J. Ottusch, J. L. Visher, and D. F. Sievenpiper, "Scalar and Tensor Holographic Artificial Impedance Surfaces," *IEEE Transactions on Antennas and Propagation,* vol. 58, pp. 3212-3221, 2010.
[76] D. R. Jackson, C. Caloz, and T. Itoh, "Leaky-Wave Antennas," *Proceedings of the IEEE,* vol. 100, pp. 2194-2206, 2012.
[77] D. Rutledge, J. B. Hacker, M. Kim, R. M. Weikle, R. P. Smith, and E. Sovero, "Oscillator and amplifier grids," in *1992 IEEE MTT-S Microwave Symposium Digest*, 1992, pp. 815-818 vol.2.
[78] J. W. Mink, "Quasi-Optical Power Combining of Solid-State Millimeter-Wave Sources," *IEEE Transactions on Microwave Theory and Techniques,* vol. 34, pp. 273-279, 1986.

[79] K. Chang and C. Sun, "Millimeter-Wave Power-Combining Techniques," *IEEE Transactions on Microwave Theory & Techniques,* vol. 31, pp. 91-107, 2003.

[80] J. B. Hacker, R. M. Weikle, M. Kim, and P. De Lisio, "A 100-element planar Schottky diode grid mixer," *Microwave Theory & Techniques IEEE Transactions on,* vol. 40, pp. 557-562, 1992.

[81] M. E. Bialkowski, A. W. Robinson, and H. J. Song, "Design, development, and testing of X-band amplifying reflectarrays," *IEEE Transactions on Antennas & Propagation,* vol. 50, pp. 1065-1076, 2002.

[82] X. Yang, S. Xu, F. Yang, M. Li, H. Fang, and Y. Hou, "A Distributed Power-Amplifying Reflectarray Antenna for EIRP Boost Applications," *IEEE Antennas and Wireless Propagation Letters,* vol. 16, pp. 2742-2745, 2017.

[83] A. Krasnok, M. Tymchenko, and A. Alù, "Nonlinear metasurfaces: a paradigm shift in nonlinear optics," *Materials Today,* 2017.

[84] H. Yang et al., "A 1-Bit 10×10 Reconfigurable Reflectarray Antenna: Design, Optimization, and Experiment," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 6, pp. 2246-2254, June 2016.

[85] J. Zhang, Y. Zhang, Y. Yu, et al., “3-D MIMO: How much does it meet our expectations observed from channel measurements?,” *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 8, pp. 1887-1903, Aug. 2017.

[86] “Guidelines for evaluation of radio interface technologies for IMT-2020,” ITU-R M.2412, https://www.itu.org, Tech. Rep., 2017.

[87] T. Cui, M. Qi, X. Wan, et al., “Coding Metamaterials, Digital Metamaterials and Programmable Metamaterials,” *Light: Science & Applications*, vol. 3, e218, Oct. 2014.

[88] “Study on channel model for frequencies from 0.5 to 100 GHz, version 15.0.0,” 3GPP TR 38.901, https://portal.3gpp.org, Tech. Rep., 2018.

[89] J. Zhan, J. Zhang, L. Tian et al., “Comparative channel study of ray tracing and measurement for an indoor scenario at 28 GHz,” in 12th European Conference on Antennas and Propagation (EuCAP 2018), 2018, pp. 1-5

[90] F. Wang, Y. Zhang, P. Tang et al., “Effects of Inaccuracies of Indoor Environment Databases on Ray Tracing Results,” in 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring), 2021, pp. 1-7.

[91] J. Dou, Y. Chen, N. Zhang. On the channel modeling of intelligent controllable electro-magnetic-surface [J]. Chinese journal of radio science, 2021, 36(3): 368-377.

[92] E. Basar, I. Yildirim and F. Kilinc, “Indoor and Outdoor Physical Channel Modeling and Efficient Positioning for Reconfigurable Intelligent Surfaces in mmWave Bands,” IEEE Transactions on Communications, vol. 69, no. 12, pp. 8600-8611, Dec. 2021

[93] Singh C, Singh K, Liu K H. Fast Beam Training for RIS-Assisted Uplink Communication[J]. arXiv preprint arXiv:2107.14138, 2021.

[94] J. He, H. Wymeersch, T. Sanguanpuak, O. Silven and M. Juntti, "Adaptive Beamforming Design for mmWave RIS-Aided Joint Localization and Communication," 2020 IEEE Wireless Communications and Networking Conference Workshops (WCNCW), 2020, pp. 1-6.

[95] W. Chen, C. -K. Wen, X. Li and S. Jin, "Adaptive Bit Partitioning for Reconfigurable Intelligent Surface Assisted FDD Systems With Limited Feedback," in IEEE Transactions on Wireless Communications, vol. 21, no. 4, pp. 2488-2505, April 2022.

[96] R. Schroeder, J. He, M. J. Juntti, Channel Estimation for RIS-Aided mmWave MIMO Systems via Atomic Norm Minimization, ICC Workshops 2022: 1219-1224, , Korea, May 16-20, 2022.

[97] G. C. Alexandropoulos and E. Vlachos, "A Hardware Architecture For Reconfigurable Intelligent Surfaces with Minimal Active Elements for Explicit Channel Estimation," in IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2020.

[98] G. C. Alexandropoulos, N. Shlezinger, I. Alamzadeh, M. F. Imani, H. Zhang and Y. C. Eldar,

"Hybrid reconfigurable intelligent metasurfaces: Enabling simultaneous tunable reflections and sensing for 6G wireless communications," arxiv, 2021.

[99] B. Zheng, C. You, W. Mei and R. Zhang, "A Survey on Channel Estimation and Practical Passive Beamforming Design for Intelligent Reflecting Surface Aided Wireless Communications," IEEE Communications Surveys & Tutorials, vol. 24, no. 2, pp. 1035-1071, Second quarter 2022.

[100] H. Zhang, N. Shlezinger, I. Alamzadeh, G. C. Alexandropoulos, M. F. Imani and Y. C. Eldar, "Channel Estimation with Simultaneous Reflecting and Sensing Reconfigurable Intelligent Metasurfaces," in IEEE 22nd International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), 2021.

[101] D. Mishra and H. Johansson, “Channel estimation and low-complexity beamforming design for passive intelligent surface assisted MISO wireless energy transfer,” in Proc. IEEE Int. Conf. Acoust. Speech Signal Process., pp. 4659–4663, 2019.

[102] T. L. Jensen and E. De Carvalho, “An optimal channel estimation scheme for intelligent reflecting surfaces based on a minimum variance unbiased estimator,” in Proc. IEEEInt. Conf.Acoust. Speech Signal Process., pp. 5000–5004, 2020.

[103] B. Zheng and R. Zhang, “Intelligent reflecting surface-enhanced OFDM: Channel estimation and reflection optimization,” IEEE Wireless Commun. Lett., 9(4):518–522, 2020.

[104] C. Hu, L. Dai, S. Han, and X.Wang, “Two-timescale channel estimation for reconfigurable intelligent surface aided wireless communications,” IEEE Trans. Commun., 69(11):7736–7747, 2021.

[105] Z. Wang, L. Liu, and S. Cui, “Channel estimation for intelligent reflecting surface assisted multiuser communications: Framework, algorithms, and analysis,” IEEE Trans. Wireless Commun., 19(10):6607–6620, 2020.

[106] B. Zheng, C. You and R. Zhang, "Intelligent Reflecting Surface Assisted Multi-User OFDMA: Channel Estimation and Training Design," IEEE Transactions on Wireless Communications, vol. 19, no. 12, pp. 8315-8329, Dec. 2020.

[107] G. Zhou, C. Pan, H. Ren, P. Popovski and A. L. Swindlehurst, "Channel Estimation for RIS-Aided Multiuser Millimeter-Wave Systems," in IEEE Transactions on Signal Processing, 70:1478-1492, 2022.

[108] C. You, B. Zheng, and R. Zhang, “Channel estimation and passive beamforming for intelligent reflecting surface: Discrete phase shift and progressive refinement,” IEEE J. Sel. Areas Commun., vol. 38, no. 11, pp. 2604–2620, Nov. 2020.

[109] B. Zheng, C. You, and R. Zhang, “Fast channel estimation for IRS-assisted OFDM,” IEEE Wireless Commun. Lett., 10(3):580–584, Mar. 2021.

[110] X. Pei, H. Yin, L. Tan, L. Cao, Z. Li, K. Wang, K. Zhang, and E. Bjornson, “RIS-aided wireless communications: Prototyping, adaptive beamforming, and indoor/outdoor field trials,” IEEE Trans. Commun., vol. 69, no. 12, pp. 8627–8640, Dec. 2021.

[111]D. Shen and L. Dai, "Dimension Reduced Channel Feedback for Reconfigurable Intelligent Surface Aided Wireless Communications," in IEEE Transactions on Communications, 69(11):7748-7760, Nov. 2021

[112] W. Chen, C.-K. Wen, X. Li, and S. Jin, “Adaptive bit partitioning for reconfigurable intelligent surface assisted FDD systems with limited feedback,” IEEE Trans. Wireless Commun., vol. 21, no. 4, pp. 2488-2505, Apr. 2022.

[113] C. You, B. Zheng, and R. Zhang, “Fast beam training for IRS-assisted multiuser communications,” IEEE Wireless Commun. Lett., vol. 9, no. 11, pp. 1845–1849, Nov. 2020.

[114] X. Hu, R. Zhang, and C. Zhong, “Semi-passive elements assisted channel estimation for intelligent reflecting surface-aided communications,” IEEE Trans. Wireless Commun., 21(2):1132–1142, 2022.

[115] Y. Jin, J. Zhang, X. Zhang, H. Xiao, B. Ai, and D. W. K. Ng, “Channel estimation for semi-passive reconfigurable intelligent surfaces with enhanced deep residual networks,” IEEE Trans.

Veh. Technol., 70(10):11083–11088, 2021.

[116] Z. Chen, G. Chen, J. Tang; S. Zhang, D. K. C. So, O. A. Dobre, K. -K. Wong and J. Chambers, "Reconfigurable Intelligent Surface-Assisted B5G/6G Wireless Communications: Challenges, Solution and Future Opportunities," in IEEE Communications Magazine, vol. 61, no. 1, pp. 16-22, January 2023.

[117] Z. Chen, J. Tang, X. Y. Zhang, D. K. C. So, S. Jin and K. -K. Wong, " Hybrid Evolutionary-Based Sparse Channel Estimation for IRS-Assisted mmWave MIMO Systems," in IEEE Transactions on Wireless Communications, vol. 21, no. 3, pp. 1586-1601, March 2022.

[118] C. Cai, X. Yuan, and Y.-J. A. Zhang, "RIS Partitioning Based Scalable Beamforming Design for Large-Scale MIMO: Asymptotic Analysis and Optimization", 2022. [Online], Available: https://arxiv.org/abs/2203.08377.

[119] J. He, H. Wymeersch, M. D. Renzo, M. J. Juntti, Learning to Estimate RIS-Aided mmWave Channels. IEEE Wirel. Commun. Lett. 11(4): 841-845, 2022.

[120] C. Liu, X. Liu, D. W. K. Ng, and J. Yuan, "Deep residual learning for channel estimation in intelligent reflecting surface-assisted multi-user communications," IEEE Trans. Wireless Commun., vol. 21, no. 2, pp. 898-912, Feb. 2022.

[121] A. M. Elbir and S. Coleri, "Federated learning for channel estimation in conventional and IRS-assisted massive mimo," arXiv preprint arXiv:2008.10846, 2020.

[122] M. Xu, S. Zhang, C. Zhong, J. Ma, and O. A. Dobre, "Ordinary differential equation-based CNN for channel extrapolation over RIS-assisted communication," IEEE Commun. Lett., vol. 25, no. 6, pp. 1921-1925, June 2021.

[123] S. Liu, Z. Gao, J. Zhang, M. D. Renzo, and M. -S. Alouini, "Deep denoising neural network assisted compressive channel estimation for mmWave intelligent reflecting surfaces," IEEE Trans. Veh. Technol., vol. 69, no. 8, pp. 9223-9228, Aug. 2020.

[124] A. Taha, M. Alrabeiah, and A. Alkhateeb, "Enabling large intelligent surfaces with compressive sensing and deep learning," IEEE Access, vol. 9, pp. 44304-44321, 2021.

[125] S. Zhang, S. Zhang, F. Gao, J. Ma, and O. A. Dobre, "Deep learning optimized sparse antenna activation for reconfigurable intelligent surface assisted communication," IEEE Trans. Commun., vol. 69, no. 10, pp. 6691-6705, Oct. 2021.

[126] Y. Yang, B. Zheng, S. Zhang, and R. Zhang, "Intelligent reflecting surface meets OFDM: Protocol design and rate maximization," IEEE Trans. Commun., vol. 68, no. 7, pp. 4522-4535, July 2020,

[127] Y. Rubanova et al., "Latent ODEs for irregularly-sampled time series," arXiv preprint arXiv:1907.03907, 2019.

[128] C. Huang, G. C. Alexandropoulos, C. Yuen, and M. Debbah, "Indoor signal focusing with deep learning designed reconfigurable intelligent surfaces," 2019 IEEE 20th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), 2019, pp. 1-5.

[129] C. Huang, R. Mo, and C. Yuen, "Reconfigurable intelligent surface assisted multiuser MISO systems exploiting deep reinforcement learning," IEEE J. Sel. Areas Commun., vol. 38, no. 8, pp. 1839-1850, Aug. 2020.

[130] Y. Lu, M. Hao, and R. Mackenzie, "Reconfigurable intelligent surface based hybrid precoding for THz communications," Intelligent and Converged Netw., vol. 3, no. 1, pp. 103-118, March 2022.

[131] X. Gao, L. Dai, Y. Sun, S. Han, and I. Chih-Lin, "Machine learning inspired energy-efficient hybrid precoding for mmWave massive MIMO systems," 2017 IEEE International Conference on Communications (ICC), Paris, France, 2017, pp. 1-6.

[132] C. Huang et al., "Multi-hop RIS-empowered Terahertz communications: A DRL-based hybrid beamforming design," IEEE J. Sel. Areas Commun., vol. 39, no. 6, pp. 1663-1677, June 2021.

[133] N. Abuzainab, M. Alrabeiah, A. Alkhateeb, and Y. E. Sagduyu, "Deep learning for THz

drones with flying intelligent surfaces: Beam and handoff prediction," 2021 IEEE International Conference on Communications Workshops (ICC Workshops), Montreal, QC, Canada, 2021, pp. 1-6.

[134] W. Liu, H. Ren, C. Pan, F. Shu, S. Jin and J. Wang, "Low-overhead Beam Training Scheme for Extremely Large-Scale RIS in Near-field,", arXiv:2211.15910, 2022.

[135] Z. Yang, Y. Liu, Y. Chen, and N. Al-Dhahir, "Machine learning for user Partitioning and phase shifters design in RIS-aided NOMA networks," IEEE Trans. Commun., vol. 69, no. 11, pp. 7414-7428, Nov. 2021.

[136] C. Jia, H. Gao, N. Chen, and Y. He, "Machine learning empowered beam management for intelligent reflecting surface assisted MmWave networks," China Commun., vol. 17, no. 10, pp. 100-114, Oct. 2020.

[137] G. Lee, M. Jung, A. T. Z. Kasgari, W. Saad, and M. Bennis, "Deep reinforcement learning for energy-efficient networking with reconfigurable intelligent surfaces," ICC 2020 - 2020 IEEE International Conference on Communications (ICC), Dublin, Ireland, 2020, pp. 1-6.

[138] L. Li et al., "Enhanced reconfigurable intelligent surface assisted mmWave communication: A federated learning approach," China Commun., vol. 17, no. 10, pp. 115-128, Oct. 2020.

[139] W. Ni, Y. Liu, Z. Yang, H. Tian, and X. Shen, "Federated learning in multi-RIS-aided systems," IEEE Int. Things Journal, vol. 9, no. 12, pp. 9608-9624, 15 June15, 2022.

[140] J. Kim et al., “Exploiting multiple intelligent reflecting surfaces in multi-cell uplink mimo communications,” arXiv preprint arXiv:2011.01141, 2020.

[141] A. Al-Hilo, M. Samir, M. Elhattab, C. Assi, and S. Sharafeddine, "Reconfigurable intelligent surface enabled vehicular communication: Joint user scheduling and passive beamforming," IEEE Trans. Veh. Technol., vol. 71, no. 3, pp. 2333-2345, March 2022.

[142] B. Zheng, Q. Wu and R. Zhang, "Intelligent Reflecting Surface-Assisted Multiple Access With User Pairing: NOMA or OMA?," *IEEE Communications Letters*, vol. 24, no. 4, pp. 753-757, April 2020.

[143] Q. Wu, X. Zhou, W. Chen, J. Li and X. Zhang, "IRS-Aided WPCNs: A New Optimization Framework for Dynamic IRS Beamforming," IEEE Transactions on Wireless Communications, vol. 21, no. 7, pp. 4725-4739, July 2022.

[144] C. Huang, R. Mo and C. Yuen, ``Reconfigurable intelligent surface assisted multiuser miso systems exploiting deep reinforcement learning," in IEEE Journal on Selected Areas in Communications, vol. 38, no. 8, pp. 1839-1850, Aug. 2020.

[145] C. Huang, Z. Yang, G. C. Alexandropoulos, K. Xiong, L. Wei, C. Yuen, Z. Zhang and M. Debbah, ``Multi-hop RIS-empowered terahertz communications: a DRL-based hybrid beamforming design", in IEEE Journal on Selected Areas in Communications, vol. 39, no. 6, pp. 1663-1677, June 2021

[146] G. Chen, Q. Wu, W. Chen, D. W. K. Ng, and L. Hanzo, "IRS-aided Wireless Powered MEC Systems: TDMA or NOMA for Computation Offloading," IEEE Transactions on Wireless Communications, 2022, early access, doi: 10.1109/TWC.2022.3203158.

[147] X. Mu, Y. Liu, L. Guo, J. Lin, and N. Al-Dhahir, “Exploiting Intelligent Reflecting Surfaces in NOMA Networks: Joint Beamforming Optimization”, IEEE Transactions on Wireless Communications; vol. 19, no. 10, pp. 6884-6898, Oct. 2020.

[148] M. Hua and Q. Wu, "Joint Dynamic Passive Beamforming and Resource Allocation for IRS-Aided Full-Duplex WPCN," IEEE Transactions on Wireless Communications, vol. 21, no. 7, pp. 4829-4843, July 2022.

[149] Y. Liu, X. Mu, X. Liu, M. Di Renzo, Z. Ding, and R. Schober, “Reconfigurable Intelligent Surface (RIS) Aided Multi-User Networks: Interplay Between NOMA and RIS”, IEEE Wireless Communications; vol. 29, no. 2, pp. 169-176, April 2022.

[150] G. Chen, Q. Wu, C. He, W. Chen, J. Tang, and S. Jin, "Active IRS Aided Multiple Access for Energy-Constrained IoT Systems," IEEE Transactions on Wireless Communications, 2022, early access,

doi: 10.1109/TWC.2022.3206332
[151] D. Zhang, Q. Wu, M. Cui, G. Zhang and D. Niyato, "Throughput Maximization for IRS-Assisted Wireless Powered Hybrid NOMA and TDMA," IEEE Wireless Communications Letters, vol. 10, no. 9, pp. 1944-1948, Sept. 2021.
[152] X. Shao, L. Cheng, X. Chen, C. Huang and D. W. K. Ng, "Reconfigurable Intelligent Surface-Aided 6G Massive Access: Coupled Tensor Modeling and Sparse Bayesian Learning," in IEEE Transactions on Wireless Communications, 2022, doi: 10.1109/TWC.2022.3182653.
[153] Y. Zhao and X. Lv, "Network Coexistence Analysis of RIS-Assisted Wireless Communications," in IEEE Access, vol. 10, pp. 63442-63454, 2022, doi: 10.1109/ACCESS.2022.3183139.
[154] M. Jian and Y. Zhao, "A Modified Off-grid SBL Channel Estimation and Transmission Strategy for RIS-Assisted Wireless Communication Systems," 2020 International Wireless Communications and Mobile Computing (IWCMC), Limassol, Cyprus, 2020, pp. 1848-1853, doi: 10.1109/IWCMC48107.2020.9148537.
[155] Y. Zhao, M. Jian. Application and Challenge of 6G RIS Technology [J]. Radio Communications Technology, 2021,47(06):679-691.
[156] Zhao, Y.; Lv, X. Reconfigurable Intelligent Surfaces for 6G: Applications, Challenges and Solutions. Preprints 2022, 2022120006 (doi: 10.20944/preprints202212.0006.v2).
[157] B. Zheng, C. You and R. Zhang, "Efficient Channel Estimation for Double-IRS Aided Multi-User MIMO System," in IEEE Transactions on Communications, vol. 69, no. 6, pp. 3818-3832, June 2021.
[158] B. Zheng, C. You and R. Zhang, "Double-IRS Assisted Multi-User MIMO: Cooperative Passive Beamforming Design," in IEEE Transactions on Wireless Communications, vol. 20, no. 7, pp. 4513-4526, July 2021.
[159] Y. Zhao and X. Lv, "Network Coexistence Analysis of RIS-Assisted Wireless Communications," in IEEE Access, vol. 10, pp. 63442-63454, 2022, doi: 10.1109/ACCESS.2022.3183139.
[160] Y. Zhao, J. Zhang, B. Ai. Applications of Reconfigurable Intelligent Surface in Smart High-Speed Railway Communications [J]. ZTE TECHNOLOGY JOURNAL, 2021,27(04):36-43.
[161] Z. Zhang and L. Dai, “A Joint Precoding Framework for Wideband Reconfigurable Intelligent Surface-Aided Cell-Free Network,” IEEE Transactions on Signal Processing, vol. 69, pp. 4085-4101, June 2021.
[162] Y. Liu, X. Mu, J. Xu, R. Schober, Y. Hao, H. V. Poor, and L. Hanzo, “STAR: Simultaneous Transmission And Reflection for 360 Coverage by Intelligent Surfaces”, IEEE Wireless Communications; vol. 28, no. 6, pp. 102-109, December 2021.
[163] J. Xu, Y. Liu, X. Mu and O. A. Dobre, "STARSs: Simultaneous Transmitting and Reflecting Reconfigurable Intelligent Surfaces," in IEEE Communications Letters, vol. 25, no. 9, pp. 3134-3138, Sept. 2021.
[164] J. Xu, Y. Liu, X. Mu, R. Schober and H. V. Poor, "STARSs: A Correlated T&R Phase-Shift Model and Practical Phase-Shift Configuration Strategies," in IEEE Journal of Selected Topics in Signal Processing, doi: 10.1109/JSTSP.2022.3175030.
[165] J. Xu et al., "Simultaneously Transmitting and Reflecting Intelligent Omni-Surfaces: Modeling and Implementation," in IEEE Vehicular Technology Magazine, vol. 16, no. 5, pp. 1097-1111, Aug. 2022.
[166] X. Mu, Y. Liu, L. Guo, J. Lin and R. Schober, "Simultaneously Transmitting and Reflecting (STAR) RIS Aided Wireless Communications," in IEEE Transactions on Wireless Communications, vol. 21, no. 5, pp. 3083-3098, May 2022.
[167] J. He, A. Fakhreddine and G. C. Alexandropoulos, "Simultaneous indoor and outdoor 3D localization with STAR-RIS-assisted millimeter wave systems," in IEEE Vehicular Technology

Conference, London/Beijing, UK/China, 26–29 September 2022.

[168] G. C. Alexandropoulos, I. Vinieratou and H. Wymeersch, "Localization via Multiple Reconfigurable Intelligent Surfaces Equipped With Single Receive RF Chains," IEEE Wireless Communications Letters, vol. 11, no. 5, pp. 1072-1076, May 2022.

[169] J. He, A. Fakhreddine, C. Vanwynsberghe, H. Wymeersch and G. C. Alexandropoulos, "3D localization with a single partially-connected receiving RIS: Positioning error analysis and algorithmic design," IEEE Transactions on Vehicular Technology (under review), 2022.

[170] J. He, A. Fakhreddine, H. Wymeersch and G. C. Alexandropoulos, "Compressed-sensing-based 3D localization with distributed passive reconfigurable intelligent surfaces," in IEEE International Conference on Acoustics, Speech, and Signal Processing, under review, Rhodes, Greece, 4–9 June 2023.

[171] O. Daniel, H. Wymeersch and J. Nurmi, "Delay–Accuracy Tradeoff in Opportunistic Time-of-Arrival Localization," IEEE Signal Processing Letters, vol. 25, no. 6, pp. 763-767, June 2018.

[172] W. Tang et al., “MIMO transmission through reconfigurable intelligent surface: System design, analysis, and implementation,” IEEE J. Sel. Areas Commun., vol. 38, no. 11, pp. 2683–2699, Nov. 2020.

[173] X. Wang, J. Han, S. Tian, D. Xia, L. Li, and T. J. Cui, “Amplification and Manipulation of Nonlinear Electromagnetic Waves and Enhanced Nonreciprocity using Transmissive Space-Time-Coding Metasurface,” Adv. Sci., vol. 9, no. 11, pp. 2105960, Apr. 2022.

[174] Z. Zhang, L. Dai, X. Chen, C. Liu, F. Yang, R. Schober, and H. V. Poor, “Active RIS vs. passive RIS: Which will prevail in 6G?,” arXiv Preprint, arXiv:2103.15154, Mar. 2021.

[175] Z. Kang, C. You, and R. Zhang“Active-IRS-Aided Wireless Communication: Fundamentals, Designs and Open Issues”, [Online]. Available:arXiv preprint arXiv:2301.04311.

[176] L. Zhang, M. Z. Chen, W. Tang, J. Y. Dai, L. Miao, X. Y. Zhou, S. Jin, Q. Cheng, T. J. Cui, A wireless communication scheme based on space- and frequency-division multiplexing using digital metasurfaces. Nature Electronics, 2021, 4 (3), 218-227.

[177] X. Bai et al., “High-efficiency transmissive programmable metasurface for multimode OAM generation,” Adv. Opt. Mater., vol. 8, no. 17, 2020, Art. no. 2000570.

[178] Z. Li, W. Chen, and H. Cao, “Beamforming Design and Power Allocation for Transmissive RMS-based Transmitter Architectures,” in IEEE Wireless Commun. Lett., vol. 11, no. 1, pp. 53-57, Jan. 2022.

[179] Z. Li, W. Chen, Z. Liu, H. Tang, J. Lu, “Joint Communication and Computation Design in Transmissive RMS Transceiver Enabled Multi-Tier Computing Networks,” in J. Sel. Areas Commun., to appear, 2022.

[180] J. C. Ke, X. Chen, W. Tang, M. Z. Chen, L. Zhang, L. Wang, J. Y. Dai, J. Yang, J. W. Zhang, L. Wu, Q. Cheng, S. Jin, T. J. Cui. Space-frequency-polarization-division multiplexed wireless communication system using anisotropic space-time-coding digital metasurface[J]. National Science Review, 2022, 9(11): nwac225.

[181] S. G. Sanchez, *et al.*, "AirNN: Over-the-Air Computation for Neural Networks via Reconfigurable Intelligent Surfaces," in *IEEE/ACM Transactions on Networking*, doi: 10.1109/TNET.2022.3225883.

[182] B. Yang, et al. "Reconfigurable Intelligent Computational Surfaces: When Wave Propagation Control Meets Computing." arXiv preprint arXiv:2208.04509 (2022).

[183] R. Liu, Q. Wu, M. Di Renzo and Y. Yuan, "A Path to Smart Radio Environments: An Industrial Viewpoint on Reconfigurable Intelligent Surfaces," in IEEE Wireless Communications, vol. 29, no. 1, pp. 202-208, February 2022.

[184] R. Liu, G. C. Alexandropoulos, Q. Wu, M. Jian and Y. Liu, "How Can Reconfigurable Intelligent Surfaces Drive 5G-Advanced Wireless Networks: A Standardization Perspective," 2022 IEEE/CIC International Conference on Communications in China (ICCC Workshops), Sanshui, Foshan,

China, 2022, pp. 221-226. doi: 10.1109/ICCCWorkshops55477.2022.9896658

[185] R. Liu, J. Dou, P. Li, J. Wu and Y. Cui, "Simulation and Field Trial Results of Reconfigurable Intelligent Surfaces in 5G Networks," in IEEE Access, vol. 10, pp. 122786-122795, 2022. doi: 10.1109/ACCESS.2022.3223447

[186] "New SI: Study on NR Network-controlled Repeaters," RP-213700, 3GPP TSG RAN Meeting #94e，2021.

[187] "New WID on NR network-controlled repeaters," RP-222673, 3GPP TSG RAN Meeting #97-e，2022.

Mar. 2023

DOI: 10.12142/RISTA.202302002