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Review:

Reconfigurable intelligent surfaces for 6G: applications, challenges, and solutions*

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Abstract: Scholars are expected to continue enhancing the depth and breadth of theoretical research on reconfigurable intelligent surface (RIS) to provide a higher theoretical limit for RIS engineering applications. Notably, significant advancements have been achieved through both academic research breakthroughs and the promotion of engineering applications and industrialization. We provide an overview of RIS engineering applications, focusing primarily on their typical features, classifications, and deployment scenarios. Furthermore, we systematically and comprehensively analyze the challenges faced by RIS and propose potential solutions including addressing the beamforming issues through cascade channel decoupling, tackling the effects and resolutions of regulatory constraints on RIS, exploring the network-controlled mode for RIS system architecture, examining integrated channel regulation and information modulation, and investigating the use of the true time delay (TTD) mechanism for RIS. In addition, two key technical points, RIS-assisted non-orthogonal multiple access (NOMA) and RIS-based transmitter, are reviewed from the perspective of completeness. Finally, we discuss future trends and challenges in this field.

Key words: 6G; Reconfigurable intelligent surface (RIS); Cascade channel decoupling; RIS regulatory constraint; RIS system architecture; True time delay

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1 Introduction

6G is anticipated to be used for wireless communications for over a decade after 2030, with the objective of supporting the future intelligent society (Zhao YJ et al., 2019). To realize the vision of 6G, several potential key technologies have been proposed, including artificial intelligence (AI), multiple-input multiple-output (MIMO), and reconfigurable intelligent surface (RIS) (Yuan YF et al., 2020). Among these, RIS has garnered significant attention from both academia and industry due to its two-dimensional super surface structure, intelligent programmability, the ability to manipulate electromagnetic waves, as well as technical characteristics of cost-effectiveness, low power consumption, and simplified deployment.

Currently, from a theoretical perspective, the research accomplishments of RIS have established a strong foundation for engineering applications. It is expected that scholars will continue to enhance the depth and breadth of theoretical research on RIS, thereby providing a higher theoretical upper limit for RIS engineering applications. While remarkable progress has been made in academic research breakthroughs, significant advancements have also been achieved in engineering application research and industrial promotion. NTT DOCOMO was the first to conduct trials on RIS as early as in 2018 (NTT DOCOMO and Metawave Announce Successful Demonstration of

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28 GHz-Band 5G Using World's First Meta-Structure Technology (https://www.businesswire.com/news/home/20181204005253/en). However, in the subsequent two years, RIS primarily remained active in the academic research domain and did not garner widespread attention in the industrial sector. In June 2020, ZTE Corporation, in collaboration with Southeast University and other organizations, established the "RIS Task Force" within the China IMT-2030 (6G) Promotion Group, attracting participation from over 30 universities and enterprises to collectively drive the technical research, standardization, and industrialization of RIS. The establishment of this task force drew considerable industry attention to RIS and facilitated its transition from academia to industry (Ma et al., 2022). Since 2020, academia and industry have collaboratively conducted various RIS industry promotion activities, greatly advancing the technical research and industrialization of RIS. In September 2020, ZTE Corporation, along with domestic and international enterprises and universities, established the "RIS Research Project" in CCSA TC5-WG6. On September 17th, 2021, the IMT-2030 (6G) Promotion Group officially released the industry's first research report on intelligent hypersurface technology during the 6G seminar. On September 24th, 2021, ZTE Corporation, Southeast University, China Unicom, and others jointly hosted the "1st Reconfigurable Intelligent Surface Technology Forum." On April 7th, 2022, the RIS Technology Alliance (RISTA) was established, and the inaugural general meeting of RISTA members took place in Beijing (http://www.risalliance.com/LiveVideoServer/risWeb/events_202204_en.html).

As the research on RIS applications deepens, the challenges faced by RIS are gradually being uncovered. If these challenges are not effectively addressed, large-scale deployment of RIS could become difficult. However, based on our limited literature search, only a few studies have focused on analyzing and studying the issues encountered by RIS in engineering applications (Zhao YJ and Jian, 2022; Zhao YJ and Lv, 2022). Building upon our previous work (Zhao YJ and Jian, 2022; Zhao YJ and Lv, 2022), this paper aims to provide a comprehensive and in-depth analysis of the challenges and potential solutions in RIS engineering applications. Our research indicates that although the engineering applications of RIS will encounter numerous challenges, corresponding solutions exist to overcome them. This paper particularly focuses on the typical problems in the practical network deployment of RIS, such as multi-user access and network coexistence, aiming to consolidate existing research in this area and encourage further investigations.

2 Overview on engineering applications of RIS

In this section, we first briefly discuss the evolution of RIS from traditional multi-antenna technology. Next, we provide an outline of the engineering application of RIS, encompassing its technical features, typical classifications, and network deployment scenarios.

2.1 Evolution from multiple antennas to RIS

This part discusses three technical concepts: the enhancement of MIMO technology and the basic concepts and development of cell-free massive MIMO and RIS. We intend to explore the logical relationship among these three technological evolutions from two perspectives.

2.1.1 Utilization and transformation of wireless channel

The objective of MIMO technology evolution is to approach the capacity upper bound of the natural wireless channel without altering its propagation environment. One traditional approach to achieving this is by continuously increasing the number of MIMO antennas to leverage array gain and spatial multiplexing. However, the performance improvement achieved through antenna scaling has reached a saturation point.

Another direction in MIMO technology evolution is the shift from centralization to distribution. Distributed MIMO (D-MIMO), also known as coordinated multiple point (CoMP), involves segmenting the wireless channel using distributed antennas. This reduces the channel transformation of each segment, leading to decreased channel change rate and variance (yielding macro diversity). By increasing the density of distributed antennas and further segmenting the channel, the temporal change of each channel segment becomes negligible, transforming the overall wireless channel into an approximately constant parameter channel with a known time-varying channel. However, deploying densely distributed antennas brings challenges in terms of site selection, synchronization, power supply, backhaul link, and cost-related issues. Consequently, the implementation of densely deployed distributed antennas in engineering becomes difficult. Despite the proposal and standardization of CoMP features in the 4G stage, their successful deployment in networks has been limited due to engineering complexities.

Both increasing antenna size and deploying antennas in a distributed and cooperative manner aim to maximize the capacity of the natural wireless channel without altering its propagation environment. However, in traditional networks, adaptation to wireless channels is passive, and there is no control over the dynamic and manual manipulation of channel propagation. The emergence of RIS introduces new possibilities for enhancing wireless communication system performance. RIS possesses the characteristics of passive regulation, low cost, and easy deployment, making it viable for widespread deployment in the natural propagation environment. This allows for accurate regulation of the wireless channel by the RIS.

2.1.2 From the perspective of network architecture evolution: The cellular limitation is overcome and a novel network paradigm is established

The evolution of MIMO technology from centralized MIMO to D-MIMO/CoMP has contributed to a shift from cellular to cell-free network architecture. This evolution breaks the limitation of traditional cellular networks and enables multi-point to multi-point joint optimization using a larger transceiver antenna set. However, the network architecture evolution of traditional MIMO technology focuses primarily on optimizing the distribution of transceiver nodes and expanding cooperation sets, without considering the wireless channel itself as a component of network architecture evolution.

The widespread deployment of RIS introduces a paradigm shift where the wireless channel becomes an integral part of the network. By regulating the wireless propagation environment through RIS, it becomes possible to achieve joint optimization of transceiver nodes and the wireless channel. This integration of RIS enables a new approach to network architecture evolution, where the wireless channel is considered as a crucial element in achieving optimal performance.

2.2 Technical features and typical classification of RIS

The main technical features of RIS can be summarized as follows (Fig. 1):

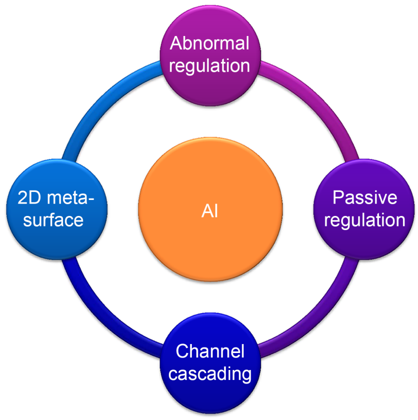

Fig. 1 Technical features of RIS

A reconfigurable artificial two-dimensional meta-surface: From three-dimensional meta-materials to two-dimensional meta-surfaces, the interface effect produces amplitude and phase abrupt changes that are different from the integral effect of three-dimensional meta-materials.

Passive regulation: Except for the controller, RIS does not require a dedicated power supply to regulate radio waves.

Abnormal regulation: RIS can abnormally regulate the propagation characteristics of radio waves, such as phase, polarization mode, amplitude, and delay. In particular, RIS can negatively refract and reflect electromagnetic waves.

Channel cascading: The channel of RIS-assisted communications is the cascade of base station (BS)–RIS and RIS–user equipment (UE) segmented channels that requires a new channel estimation and beam shaping design, presenting new challenges to algorithm design.

AI driven: AI can be a foundational enabling technology for channel estimation, beamforming, and resource management in RIS to establish a smart wireless environment.

RIS technology is significantly different from traditional technologies, such as massive MIMO (Lu et al., 2014), CoMP (Xu et al., 2012), MIMO relay (Darsena et al., 2019), backscatter (van Huynh et al., 2018), and smart repeater (ZTE, 2021) (Table 1). While these

Table 1 Comparison between RIS and traditional technologies

Technology	Operating mechanism	Duplex	RF chains	Thermal noise	Hardware cost	Energy consumption	Role	Architecture
RIS	Passive/active* tune	Full duplex	No	No	Low	Low	Helper	Distributed
Backscatter	Passive tune	Full duplex	No	No	Very low	Very low	Source	Distributed
MIMO relay	Active receive and transmit	Half/full duplex	Yes	Yes	High	High	Helper	Distributed
Massive MIMO	Active transmit and receive	Half/full duplex	Yes	Yes	Very high	Very high	Source/ destination	Centralized
CoMP/D-MIMO	Active transmit and receive	Half/full duplex	Yes	Yes	Very high	Very high	Source/ destination	Distributed
Smart repeater	Active/passive receive and transmit	Half/full duplex	Yes	Yes	Medium	Medium	Helper	Distributed

* Zhang ZJ et al. (2023) proposed an active RIS with low rated power. This type of RIS adopts simple low-power amplifier transistor circuit, so it has the characteristics of low cost and low power consumption

traditional technologies may excel in certain technical indicators, they do not possess the complete set of advantages offered by RIS, namely low power consumption, low cost, and easy deployment. RIS demonstrates unique potential in supporting green communication, enabling ubiquitous deployment, and facilitating wireless environment reconstruction. These advantages make RIS stand apart from traditional technologies and position it as a promising solution for future wireless communication systems.

The technical features of RIS highlight its main advantages, including the ability to support abnormal regulation, low power consumption, low cost, simple structure, and easy deployment. These advantages pave the way for widespread deployment of RIS in wireless networks and enable the establishment of intelligent and controllable wireless environments. These can be summarized as three key technical advantages—ubiquitous deployment, passive green, and endogenous intelligence—that essentially promise a new paradigm for future wireless networks (Fig. 2).

With the advancement of RIS engineering research, diverse technical characteristics and variations of RIS have emerged in the industry. Here, various types of RIS reported in the literature have been summarized and classified (Table 2). We observe that each type of RIS exhibits specific technical characteristics. Nonetheless, the types of RIS that will be deployed on a large scale in the future are still uncertain.

2.3 Typical deployment scenarios of RIS

In previous articles (Zhao YJ et al., 2021; Zhao YJ and Jian, 2022), we have discussed a few typical

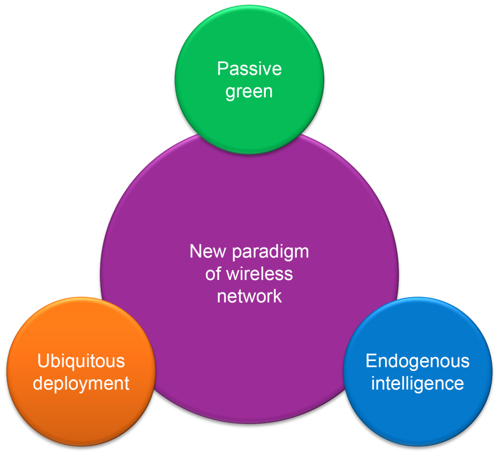

Fig. 2 Bringing a new paradigm for future wireless networks

RIS deployment scenarios. Here, we attempt to classify typical network deployments of RIS according to the characteristics of application scenarios.

This subsection classifies and summarizes the typical deployment scenarios of RIS from four aspects: development mode, coexistence and sharing, increasing rank and coverage, and coverage area.

1. From the perspective of network deployment mode, RIS deployment scenarios can be classified into the standalone mode and network-controlled mode. The two modes are different in terms of the control link requirements, measurement/control signaling interaction, and network deployment complexity, and have their own advantages and disadvantages. For a detailed discussion, please refer to Section 3.3.

2. From the perspective of coexistence and sharing, RIS deployment scenarios can be classified into multi-operator network coexistence, single-user

Table 2 RIS types

Feature	Type
Refraction/ reflection	Refractive RIS
	Reflective RIS
	Simultaneously transmitting and reflecting RIS (STAR-RIS) (Liu et al., 2022b)
Regulation functions	Spatial modulation, RIS-based transmitter (Cui, 2018; Guo et al., 2020)
	Radio channel regulation, intelligent reconfiguration of wireless channels
	RIS-based novel phased array antenna
	RIS-based simultaneous wireless information and power transfer
Regulation mechanisms	PIN diode tube, varactor diode, MEMS, liquid crystal, graphene
Frequency band	Sub-6 GHz Millimeter-Wave band Terahertz band Optical band
Active or passive	Passive RIS Active RIS (Zhang ZJ et al., 2023)
Dynamicity	Static state Semi-static regulation Dynamic regulation
Measurement/ sensing	Consisting of passive elements only
	Including passive elements and some active elements with measuring/sensing ability (Taha et al., 2021)
Deployment mode	Network-controlled
	Standalone (Zhang YW et al., 2022; Zhu JA et al., 2023)

access, and multi-user access, multi-RIS deployment, and spectrum properties (such as licensed spectrum and unlicensed spectrum).

3. From the perspective of rank increasing and covering enhancement, RIS deployment scenarios can be classified into the following: deployment near Node B (NB), deployment at the cell edge, deployment in the middle of the cell, and ubiquitous deployment.

4. From the perspective of coverage area, RIS deployment scenarios can encompass remote areas, urban indoor/outdoor, and NTN and UAV.

Table 3 provides four types of RIS deployment scenarios, including typical deployment variations and their respective key points.

3 Technical challenges and solutions

To enable the above engineering applications, many technical challenges need to be addressed first. This section focuses on exploring several important aspects, including beamforming of cascade channels, RIS regulation constraints, RIS system architecture for network-controlled mode, integration of channel regulation and information modulation, and true time delay (TTD) mechanisms for RIS. In addition, two key technical points, RIS-assisted non-orthogonal multiple access (NOMA) and RIS-based transmitter, are reviewed from the perspective of completeness.

3.1 Cascade channel decoupling for solving RIS beamforming

The integration of RIS introduces the capability to control the electromagnetic propagation environment, transforming it from a naturally uncontrollable state to a human-controllable state. This active regulation of the electromagnetic propagation environment opens up new possibilities for channel communication. However, the cascade channels formed with the introduction of RIS present significant challenges in designing the RIS beamforming matrix. In this subsection, we provide a preliminary analysis of these challenges and briefly introduce a novel channel decoupling solution. Further articles will delve into a more comprehensive discussion and provide detailed evaluation.

3.1.1 Challenges of cascade channels

The RIS cascade channel model $\boldsymbol{H}_{\mathrm{DL}}$ proposed in Zhao YJ and Lv (2022) is discussed below (ignoring the direct channel between BS–UEs). As shown in Eq. (1), the regulation matrix $\boldsymbol{\Phi}$ of RIS is located between the two segmented channel matrices (the channel $\boldsymbol{G}$ between NB and RIS and the channel $\boldsymbol{H}$ between RIS and UE). It is exceedingly complicated to solve the regulation matrix $\boldsymbol{\Phi}$ that can suitably match two segmented channels simultaneously.

$$\boldsymbol{H}_{\mathrm{DL}} = \boldsymbol{H\Phi G}. \tag{1}$$

For the case where UE is equipped with a single antenna, Wei et al. (2021) showed that the channel Eq. (1) can be converted into the following form:

Table 3 Four types of RIS deployment scenario

Deployment scenario	Variation	Key points
Deployment mode	(1) Network-controlled mode (2) Standalone mode	(1) Control link (2) Measurement and control signaling
Coexistence and sharing	(1) Multi-operator network coexistence (2) Single-user access and multi-user access (3) Multi-RIS deployment (4) Spectrum properties, such as licensed spectrum, or unlicensed spectrum	(1) Identification and collaboration of multiple RISs (2) Interference and coordination of coexistence and sharing in networks
Increasing rank and coverage	(1) Deployment near NB (2) Deployment at the cell edge (3) Deployment in the middle of the cell (4) Ubiquitous deployment	(1) Increasing rank (2) Covering enhancement (3) Near field*/far field
Coverage area	(1) Remote areas (2) Urban indoor/outdoor (3) NTN, UAV (Basharat et al., 2021; Liu et al., 2021; Pan et al., 2021; Bansal et al., 2023; Mizmizi et al., 2023)	(1) Wide area: semi-dynamic/static adjustment, which is used to improve capacity and coverage (2) Local area: dynamic and accurate channel regulation (3) Challenges of power supply and control link deployment

*(a) RIS is widely deployed, and near field becomes a typical scenario; (b) RIS passive regulation and low radiation, suitable for near-field communication; (c) The near field of active phased array antenna may only be applicable to IoT

$$\boldsymbol{H}_{\mathrm{DL}} = \boldsymbol{H}\mathrm{diag}(\boldsymbol{\Phi})\boldsymbol{G} = \boldsymbol{\Phi}\mathrm{diag}(\boldsymbol{H})\boldsymbol{G}, \tag{2}$$

where $\boldsymbol{\Phi}=[\phi_1, \phi_2, \cdots, \phi_N]$ is the $1\times N$ reflecting vector at the RIS with ϕ_n representing the reflecting coefficient at the n^{th} RIS element ($n = 1, 2, \cdots, N$). $\boldsymbol{H}=[h_1, h_2, \cdots, h_N]$ is the channel between RIS elements and UE antenna.

Eq. (2) can easily decompose $\boldsymbol{HG}$ to obtain the regulation matrix $\boldsymbol{\Phi}$. However, for the case where the UE is configured as multiple antennas, the above-mentioned conversion is no longer valid.

3.1.2 Channel decoupling for solving RIS beamforming

We re-examined the regulation mechanism of RIS and found that the regulation of incident electromagnetic wave by RIS can be further divided into two sub-processes that can be respectively named as the response of the receiving sub-process to the incident electromagnetic wave and the regulation response of the outgoing sub-process. Therefore, the RIS regulation matrix $\boldsymbol{\Phi}_{\mathrm{RIS}}$ used for incident electromagnetic waves can be decomposed into two regulation matrix components corresponding to the above two sub-response processes, namely, the reception response matrix $\boldsymbol{\Phi}_1$ and the outgoing regulation matrix $\boldsymbol{\Phi}_2$. The incident response of RIS to electromagnetic waves is similar to the response of the reception matrix of analog beamforming in the massive MIMO hybrid beamforming (Zhu GX et al., 2017). Accordingly, the expression of downlink signal of the RIS cascade channel is

$$\boldsymbol{H}_{\mathrm{DL}} = \boldsymbol{H}_{\text{ris–ue}}\boldsymbol{\Phi}_2\boldsymbol{\Phi}_1\boldsymbol{G}_{\text{nb–ris}}. \tag{3}$$

In other words, the RIS regulation matrix $\boldsymbol{\Phi}$ is decomposed into two matrix components $\boldsymbol{\Phi}_1$ and $\boldsymbol{\Phi}_2$ (i.e., $\boldsymbol{\Phi} = \boldsymbol{\Phi}_2\boldsymbol{\Phi}_1$), such that the solution of RIS regulation matrix $\boldsymbol{\Phi}$ is transformed into the optimization of two independent components $\boldsymbol{\Phi}_1$ and $\boldsymbol{\Phi}_2$.

As per the above analysis, if the singular value decomposition (SVD) mechanism is applied to solve the beamforming matrix of RIS, the channel $\boldsymbol{G}$ between NB and RIS can be decomposed by SVD to obtain the receiving matrix component $\boldsymbol{\Phi}_1$ of RIS, and the channel $\boldsymbol{H}$ between RIS and UE can be decomposed by SVD to obtain the reflection regulation matrix component $\boldsymbol{\Phi}_2$ of RIS, independently. Therefore, we can obtain the entire regulation matrix $\boldsymbol{\Phi}$ of RIS to optimally match the channels of $\boldsymbol{G}$ and $\boldsymbol{H}$ segments simultaneously. In other words, the cascade channel is decoupled, and the channels of $\boldsymbol{G}$ and $\boldsymbol{H}$ segments can be optimized independently.

As the deployment of RIS is generally fixed, the segmented channel $\boldsymbol{G}$ between NB and RIS is a slow-changing channel, while the segmented channel $\boldsymbol{H}$

between RIS and UE is a rapidly varying channel, also called a time dual-scale channel (Hu et al., 2021). If the regulation matrix component of the RIS beamforming is decoupled and segmented, $\boldsymbol{\Phi}_1$ can be calculated over a long period, and $\boldsymbol{\Phi}_2$ can be calculated over a short period. In addition, iteratively optimizing the cascade channel is not required, which subatantially reduces complexity. For example, if the codebook-based mechanism is used, the codebook can be searched to match the channel $\boldsymbol{G}$ with a longer period, while the codebook has to be searched to match the channel $\boldsymbol{H}$ with a shorter period.

3.2 Influences and solutions of RIS regulatory constraints

From a system model perspective, the cascade channel comprising the NB and RIS can be compared to a combination of a digital phased array and an analog phased array, similar to the architecture of traditional massive MIMO with hybrid beamforming. In this analogy, the precoding performed by the NB can be seen as digital beamforming, while the array regulation of the RIS corresponds to analog beamforming. Therefore, the spatial constraints that arise due to analog beamforming in traditional massive MIMO hybrid beamforming are present in the cascade system architecture composed of RIS and NB.

3.2.1 Influences of RIS regulatory constraints

The existing RIS, which lacks radio frequency (RF) units, does not possess filtering capabilities and typically has broadband tuning capability, covering several GHz of bandwidth (Wang et al., 2019). This broadband tuning characteristic of RIS is advantageous for wireless broadband communication and facilitates support for multiple frequency bands (Cui et al., 2020). However, each element of the RIS can set only a single weighting coefficient at a time, and it cannot set different weighting coefficients for different signals on different sub-bands within the RIS's tuned frequency range (Avazov et al., 2021). In other words, RIS with tuning capabilities employs the same weighting coefficient matrix to tune all signals within a wider frequency band. Consequently, the existing RIS cannot optimally match multiple sub-band channels simultaneously, which can lead to significant network coexistence problems (Zhao YJ and Jian, 2022; Zhao YJ and Lv, 2022), and cannot effectively support multiuser access with orthogonal frequency-division multiple access (OFDMA).

This problem is not exclusive to RIS but already exists in the context of hybrid beamforming for massive MIMO systems. Analog beamforming, in particular, suffers from a similar limitation where the phase shifter has only one adjustable phase state, resulting in a single analog beam across the entire system bandwidth. As a result, multiple UEs using OFDMA have to share the same analog beamforming matrix. Although different UE channels are orthogonal in the frequency domain, they are constrained by sharing the same analog beamforming matrix, thereby limiting the degree of freedom in their respective channel spaces and preventing optimal matching (Rotman et al., 2023).

The influence of RIS tuning limitation was analyzed in our previous study (Zhao YJ and Lv, 2022). Without losing generality, assuming a scattering path (the channel component of nb-ris-ue) and a direct path (the channel component of nb-ue), the formula can be written as follows:

$$\begin{aligned}\boldsymbol{Y}_{\text{ue\_A}} = (&\boldsymbol{H}_{\text{ris\_A–ue\_A}}\boldsymbol{\Theta}_{\text{ris\_A}}\boldsymbol{G}_{\text{nb\_A–ris\_A}}\\ &+\boldsymbol{H}_{\text{nb\_A–ue\_A}})\boldsymbol{F}_{\text{A}}\boldsymbol{X}_{\text{ue\_A}} + \boldsymbol{W}_{\text{ue\_A}},\end{aligned} \tag{4}$$

$$\begin{aligned}\boldsymbol{Y}_{\text{ue\_B}} = (&\boldsymbol{H}_{\text{ris\_B–ue\_B}}\boldsymbol{\Theta}_{\text{ris\_A}}\boldsymbol{G}_{\text{nb\_B–ris\_A}}\\ &+\boldsymbol{H}_{\text{nb\_B–ue\_B}})\boldsymbol{F}_{\text{B}}\boldsymbol{X}_{\text{ue\_B}} + \boldsymbol{W}_{\text{ue\_B}},\end{aligned} \tag{5}$$

where $\boldsymbol{Y}_{\text{ue\_A}}$ is the received signal at ue_A served by nb_A of network N_A, $\boldsymbol{Y}_{\text{ue\_B}}$ is the received signal at ue_B served by nb_B of network N_B, and $\boldsymbol{\Theta}_{\text{ris\_A}}$ is the tuning coefficient matrix of RIS_A for ue_A.

Since RIS_A can have only one tuning state at a time, its coefficient matrix $\boldsymbol{\Theta}_{\text{ris\_A}}$ suitable for the channel of ue_A is also used to tune the incident signals from network N_B simultaneously. As shown in Eq. (5), the tuning coefficient matrix for the signal of ue_B is also $\boldsymbol{\Theta}_{\text{ris\_A}}$, leading to the deterioration of ue_B performance.

1. Impacts on multi-user access

OFDMA is adopted for multi-user access. Different UE channels based on OFDMA are orthogonal in the frequency domain but share the same RIS tuning coefficient matrix, which restricts the freedom of channel spaces of these UEs, and cannot match their channel spaces well. As shown in Fig. 3, the downlink signals of two users ue_A and ue_B belonging to the same NB are simultaneously incident on the RIS panel and are tuned by the same matrix $\boldsymbol{\Phi}_1$. The beamforming matrix $\boldsymbol{\Phi}_1$ aligns with $\mathrm{ue_A}$; however, $\mathrm{ue_B}$ cannot be covered by the beam, resulting in substantial degradation of $\mathrm{ue_B}$ performance.

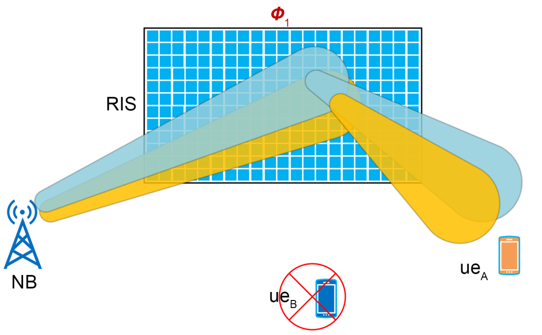

Fig. 3 Impacts on multi-user access. References to color refer to the online version of this figure

2. Impacts on multi-network coexistence

As shown in Fig. 4, there are two overlapping networks, namely network A and network B (denoted as N_A and N_B, respectively) that operate on two adjacent frequency bands. $\mathrm{nb_A}$ belongs to network N_A and $\mathrm{nb_B}$ belongs to network N_B. $\mathrm{ue_A}$ and $\mathrm{ue_B}$ are served by $\mathrm{nb_A}$ and $\mathrm{nb_B}$, respectively. The $\mathrm{RIS_A}$ of network N_A tunes the signal from the network N_A using the coefficient matrix $\boldsymbol{\Phi}_1$ based on the channel of $\mathrm{ue_A}$. $\mathrm{RIS_A}$ also tunes the signal from the network N_B simultaneously using the same coefficient matrix $\boldsymbol{\Phi}_1$ for the signal of network N_A. Therefore, the tuning of $\mathrm{RIS_A}$ causes an unexpected disturbance on the channel of the non-target signal from network N_B.

3.2.2 Solutions of RIS regulatory constraints

In this subsection, two novel RIS design mechanisms proposed by Zhao YJ and Jian (2022) and Zhao YJ and Lv (2022), including a RIS blocking mechanism and a novel multi-layer RIS structure with an out-of-band filter, are further explored. The former adopts the idea of reducing influence, while the latter adopts the idea of eliminating influence. The advantages and possible negative effects of these two mechanisms are analyzed and evaluated comprehensively.

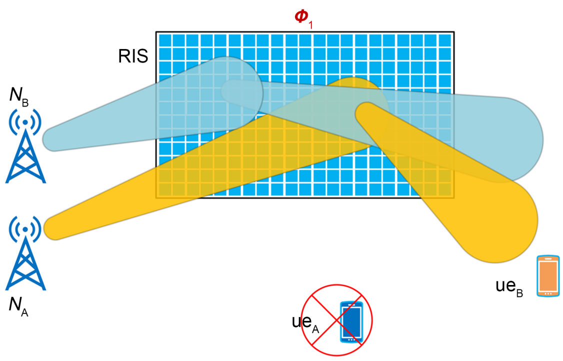

Fig. 4 Impacts on multi-network coexistence. References to color refer to the online version of this figure

1. RIS blocking schemes

We proposed a RIS blocking mechanism to solve problems of the RIS network coexistence (Zhao YJ and Jian, 2022; Zhao YJ and Lv, 2022). The basic concept underlying the RIS blocking mechanism is that the incident signals of different UEs can be assigned to different sub-blocks of the RIS, and each sub-block can use an independent coefficient matrix to tune incident signals, as shown in Fig. 5. The antenna array elements of RIS can also be grouped by interval sampling (Fig. 6). Here, it is preferred that the RIS adopts more dense antenna elements, such that the interval of antenna elements of each sub-group after grouping still meets the conditions of less than or equal to $\lambda/2$, where λ is the wavelength..

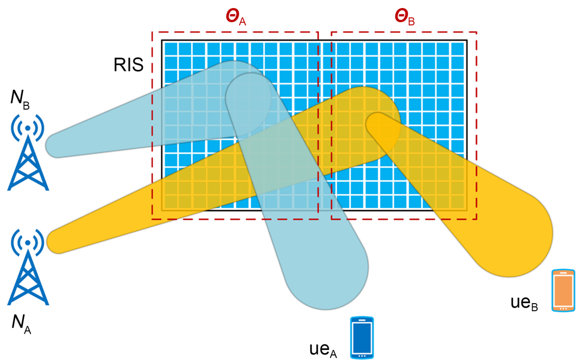

Fig. 5 Tuning incident signals on a sub-block by using an independent coefficient matrix separately. References to color refer to the online version of this figure

From the perspective of the UE source, this mechanism is used for multi-UE scheduling when UEs belong to the same network. When UEs are from different networks, this mechanism is used for RIS network coexistence, in which scenario, the RIS can be divided only in a static or semi-static manner, since it is difficult to dynamically coordinate between NBs, particularly NBs emerging from different operators. It is necessary to ensure an appropriate RIS antenna size and optimize a reasonable blocking ratio for different

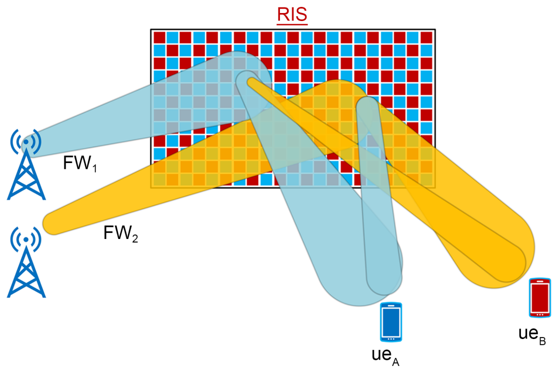

Fig. 6 Blocking of the RIS antenna array elements based on interval decimation for grouping. FW: forming weight. References to color refer to the online version of this figure

networks to ensure the performance of the network to the extent possible while satisfying coexistence.

Without loss of generality, assuming that a RIS is divided into two sub-blocks and that the $\mathrm{ue_A}$ signal is set as the target signal, the formula can be written as follows:

$$\boldsymbol{Y}_{\mathrm{ue\_A}}=\sqrt{\beta}\ (\boldsymbol{H}_{\mathrm{ris\_sub1-ue\_A}}\boldsymbol{\Theta}_{\mathrm{ris\_A}}\boldsymbol{G}_{\mathrm{nb\_A-ris\_sub1}} +\boldsymbol{H}_{\mathrm{nb\_A-ue\_A}})\boldsymbol{F}_{\mathrm{A}}\boldsymbol{X}_{\mathrm{ue\_A}}+ \sqrt{1-\beta}\ (\boldsymbol{H}_{\mathrm{ris\_sub2-ue\_A}}\boldsymbol{\Theta}_{\mathrm{ris\_B}}\boldsymbol{G}_{\mathrm{nb\_A-ris\_sub2}})\boldsymbol{F}_{\mathrm{A}}\boldsymbol{X}_{\mathrm{ue\_A}}+\boldsymbol{W}_{\mathrm{ue\_A}}, \tag{6}$$

where β is the energy proportion of the $\mathrm{ue_A}$ incident signal on its RIS sub-block, $1-\beta$ is the energy proportion of the $\mathrm{ue_A}$ incident signal on another RIS sub-block, $\boldsymbol{\Theta}_{\mathrm{ris\_A}}$ is the optimal tuning matrix of the RIS sub-block for the $\mathrm{ue_A}$ signal, and $\boldsymbol{\Theta}_{\mathrm{ris\_B}}$ is the optimal tuning matrix of the RIS sub-block for the $\mathrm{ue_B}$ signal.

2. Multi-layer RIS with filter layer(s)

In our previous articles (Zhao YJ and Jian, 2022; Zhao YJ and Lv, 2022), a novel RIS structure, i. e., multi-layer RIS with filter layers, was proposed. Without losing generality, here we consider a RIS with a double-layer meta-surface structure as an example. The first layer of the RIS is a bandpass filter using a meta-surface. The bandpass filter allows only signals in the target band to pass through, while the signals in the adjacent non-target bands (out-of-band signals) are filtered. The second layer of the RIS is a conventional programmable meta-surface that can realize typical programmable functions of RIS. The programmable meta-surface tunes only the target signal, since the non-target signal has been filtered by the first layer, as shown in Fig. 7.

The expressions of the $\mathrm{ue_A}$ signal served by $\mathrm{nb_A}$ and the $\mathrm{ue_B}$ signal served by $\mathrm{nb_B}$ can be modified using Eqs. (4) and (5), as shown in Eqs. (7) and (8), respectively.

$$\boldsymbol{Y}_{\mathrm{ue\_A}}=(\boldsymbol{H}_{\mathrm{ris\_A-ue\_A}}\boldsymbol{\Theta}_{\mathrm{ris\_A}}\boldsymbol{G}_{\mathrm{nb\_A-ris\_A}}+\boldsymbol{H}_{\mathrm{nb\_A-ue\_A}})\boldsymbol{F}_{\mathrm{A}}\boldsymbol{X}_{\mathrm{ue\_A}} +(\boldsymbol{H}_{\mathrm{ris\_B-ue\_A}}\beta\boldsymbol{\Theta}_{\mathrm{ris\_B}}\boldsymbol{G}_{\mathrm{nb\_A-ris\_B}})\boldsymbol{F}_{\mathrm{A}}\boldsymbol{X}_{\mathrm{ue\_A}}+\boldsymbol{W}_{\mathrm{ue\_A}}, \tag{7}$$

$$\boldsymbol{Y}_{\mathrm{ue\_B}}=(\boldsymbol{H}_{\mathrm{ris\_B-ue\_B}}\boldsymbol{\Theta}_{\mathrm{ris\_B}}\boldsymbol{G}_{\mathrm{nb\_B-ris\_B}}+\boldsymbol{H}_{\mathrm{nb\_B-ue\_B}})\boldsymbol{F}_{\mathrm{B}}\boldsymbol{X}_{\mathrm{ue\_B}} +(\boldsymbol{H}_{\mathrm{ris\_A-ue\_B}}\beta\boldsymbol{\Theta}_{\mathrm{ris\_A}}\boldsymbol{G}_{\mathrm{nb\_B-ris\_A}})\boldsymbol{F}_{\mathrm{B}}\boldsymbol{X}_{\mathrm{ue\_B}}+\boldsymbol{W}_{\mathrm{ue\_B}}. \tag{8}$$

Here, $\beta\in(0,1)$ refers to the filter coefficient of $\mathrm{RIS_A}$.

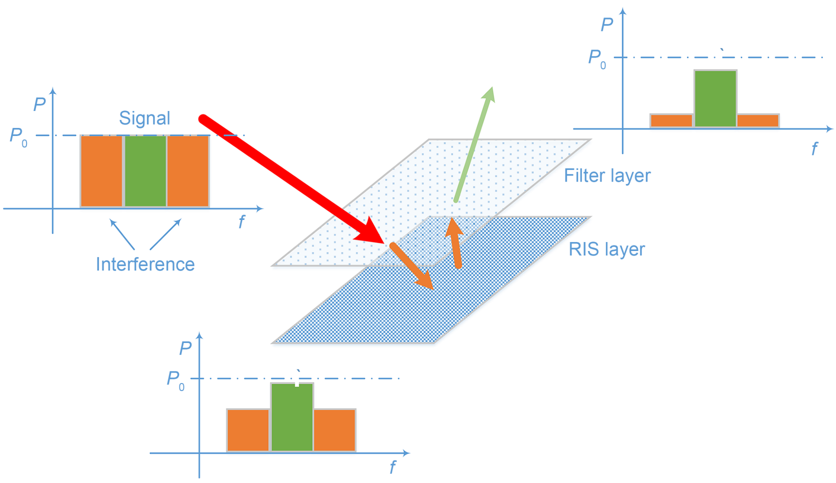

Fig. 7 Out-of-band filtering using a RIS with a double-layer structure (reflecting the RIS). Reprinted from Zhao YJ and Lv (2022), Copyright 2022, with permission from the authors, licensed under CC BY 4.0. References to color refer to the online version of this figure

3.3 RIS system architecture for network-controlled mode

Most existing studies on RIS assume the presence of a controller connected to the network to control the electromagnetic regulation behavior of the RIS. Particularly in multi-RIS scenarios, a controller is needed to manage the cooperation among multiple RISs. When RIS is deployed in a cellular network, it operates in a network-controlled mode, enabling better network performance but introducing complexity in controlling information interaction.

To address the complexity of control information interaction, recent literature (Zhang YW et al., 2022; Zhu JA et al., 2023) proposed the adoption of a standalone mode for RIS, where the RIS has self-control capabilities. One approach suggested in Zhang YW et al. (2022) is blind beamforming, which allows the RIS to achieve self-regulation and beamforming. However, blind beamforming based on statistical channel information is inferior to beamforming with known channel state information (CSI) and is only suitable for single-user scenarios. Another mechanism proposed in Zhu JA et al. (2023) is interference-based channel estimation and beamforming, which again is limited to single-user scenarios. Both mechanisms require the RIS to have knowledge of the targeted user and optimization objectives, either through information provided by the network or by increasing the complexity of the RIS. However, these mechanisms do not fully address the coordination and optimization challenges in scenarios involving multiple users and networks. Although they reduce the interaction between the NB and the RIS by enabling distributed computing capabilities, they do not eliminate the interaction completely.

To simplify the terminology, the deployment mode where RIS is controlled by the network is referred to as “network-controlled mode,” and the mode where RIS is self-controlled is referred to as “standalone mode.” Table 4 provides a comparison of the advantages and challenges of these modes, while Table 5 outlines the requirements and potential solutions of network-controlled mode.

Through a comparative analysis of Tables 4 and 5 and combining the characteristics of licensed spectrum and unlicensed spectrum, the following conclusions can be drawn:

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

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

3.4 Integrated channel regulation and information modulation

A novel function of RIS known as symbiotic radio (SR) transmission has been proposed (Hua et al., 2022), which is different from the current mainstream research where RIS assists existing communication systems. In SR, the RIS serves a dual role: it enhances the transmission of the primary wireless network through passive beamforming, while also transmitting its own information to receivers using reflected signals. This concept bears resemblance to spatial modulation transmission, where information is encoded by the indices of active transmitting antennas to improve spectral efficiency. In this case, the RIS functions as both an information source node and a helper to enhance the performance of the primary link through passive

Table 4 Advantages and challenges of network-controlled mode and standalone mode

Type	Advantage	Challenge
Network-controlled mode	(1) Support multi-network collaboration (2) Support 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

Table 5 Requirements and potential solutions of network-controlled mode

Item	Requirement	Potential solution
Feedback of CSI and scheduling of beamforming	(1) The large number of antenna elements in the ultra-large antenna array results in significant pilot and channel information feedback overhead (2) Real-time demand of channel measurement and feedback	(1) Utilize channel sparsity, and adopt compression sensing and other mechanisms to reduce overhead (2) Using statistical channel information (3) Using the dual time scale property of cascade channels (4) Beam scanning and codebook quantization
Network control link	The control link needs to be specially deployed, resulting in the complexity and cost of deployment. Especially in remote areas, complexity and cost are very big problems	Flexible choice of wired or wireless links
Interactive flow of control and measurement signaling	The protocol standardization of interactive flow of control and measurement signaling is necessary	The related protocol flow can be standardized in the future 5G-A or 6G standards (Jian et al., 2022)

beamforming. By comparing various similar technologies such as backscatter (van Huynh et al., 2018), spatial modulation (Basar, 2020), and information metasurfaces (Cui, 2018), it can be observed that information modulation is fundamentally achieved through amplitude/phase modulation of the carrier.

3.4.1 Requirements and challenges

Existing research primarily focuses on using RIS to simultaneously provide information modulation and transmission functions, enabling support for passive Internrt-of-Things (IoT) communications through traditional backscatter technology. However, there is currently a lack of literature investigating information modulation and transmission based on RIS to facilitate the electromagnetic wave regulation function of RIS itself, particularly supporting the interaction of control and measurement information between RIS−NB and RIS–UE.

The auxiliary functions facilitated by RIS-based backscatter include:

1. Identification of RIS IDs in various deployment scenarios: This enables NB/UE to discover the presence of surrounding RISs, obtain their position and characteristic parameters, and effectively use them.

2. Transmission of measurement and controlling information: RIS can be used to transmit RIS control signaling/CSI.

3. Electromagnetic environment regulation and information modulation: RIS functions are also used for regulating the electromagnetic environment and performing information modulation, similar to backscatter.

In RIS-based information modulation, each RIS symbol is transmitted over K successive legacy symbol periods. For a large K, the information modulation using RIS symbols can be treated as a spread-spectrum code, with repetition in the time/frequency domain and spreading in the spatial domain (antenna domain, i.e., different antennas).

Since the data rate of measurement and control information exchanged between RIS and NB is relatively low, the RIS-based backscatter should meet the requirements of this information exchange. However, there are still challenges in better supporting the exchange of measurement and control information while ensuring the performance of the primary system (traffic transmission between NB and UE). In this regard, the major challenges are analyzed, and preliminary solutions are proposed.

1. Challenge 1

When RIS is used as a backscatter for information modulation, it introduces additional noise that causes random fluctuations in the regulation coefficient originally used for channel regulation. This effect is similar to traditional active-phased antennas or relays, where the analog transmitter introduces phase or amplitude noise. Since the modulation of the information bits is random, the resulting noise is random. The unexpected channel fluctuations caused by RIS-based information modulation lead to inaccurate CSI estimation, and the modulation disrupts the phase and amplitude of the beamforming coefficient, which were initially used for channel regulation in the primary system.

This gives rise to two problems: (1) CSI measurement estimation error: The fluctuations caused by RIS-based modulation result in imprecise estimation of the CSI. (2) Beam regulation error during primary system data transmission: The modulation disrupts the phase and amplitude of the beamforming coefficient, affecting the accuracy of beam regulation in the primary system. For example, when RIS modulates information using ON/OFF modulation, during the OFF slot, the primary system cannot transmit information, leading to a reduction in the available time domain resources for the primary system. The information modulation using an ON–OFF regulator causes capacity loss for the main transmitter, which is reflected in the power loss during the OFF state. The signal energy of the main transmitter is zero during the OFF state, resulting in reduced effective power, signal-to-noise ratio, and capacity loss. This reduction in time domain resources leads to a decrease in channel capacity. For infinite-length coding, the ratio of the OFF state can be translated into the reduction ratio of the total channel capacity. In other words, the unavailability of the OFF state results in the loss of time domain resources, thereby reducing the channel capacity.

2. Challenge 2

The signal from the direct channel can interfere with the modulation information of the RIS, particularly when the direct channel signal is strong. The receiver in backscatter communication (BC) often experiences strong interference from the direct link signal. To address this issue, several interference cancellation technologies have been developed (Bharadia et al., 2015; Kellogg et al., 2016; Yang et al., 2018).

3. Challenge 3

RIS-based information modulation and transmission rely on the presence of the primary system signal, and the transmission direction of the primary system signal must be taken into account. In scenarios where the traffic load of the primary system is light or there is minimal signal transmission on the downlink/uplink, it becomes challenging for BC to effectively use the carrier resources of the primary system for timely information modulation and transmission. This leads to lower information rates and increased delays. To address this problem, one possible solution is to introduce additional reference signals. These reference signals serve two purposes: first, they can supplement and enhance the measurement requirements of the primary system, and second, they can assist the backscatter device (BD) with information modulation and transmission. Examples of such additional reference signals include dedicated downlink reference signals and UE uplink sounding reference signal. By incorporating these additional reference signals, the BD can improve its information modulation and transmission capabilities while meeting the measurement needs of the primary system.

4. Challenge 4

In traditional RIS beamforming optimization, the focus is typically on the optimization for the NB/UE in the primary system. However, if the BC receiver is not integrated with the NB/UE, the RIS beam may not align properly with the BC receiver, resulting in poor signal quality for the BC receiver. To improve the reception of the BC signal, the RIS needs to optimize its beamforming to align with the BC receiver. However, this optimization for BC reception can lead to performance degradation of the primary system, particularly in high-frequency narrow-beam scenarios.

5. Challenge 5

The utilization of RIS as a BD can have a significant impact on the communication of the primary system, particularly due to its large antenna aperture and deployment on the main propagation path of the primary system. If the RIS obtains its regulated energy source through wireless energy collection, it can greatly affect the signal energy of the primary system path, thereby impacting its performance.

To address this challenge, several solutions can be considered. First, the RIS can be divided into sub-blocks, where only certain sub-blocks are dedicated to backscatter functions. This approach reduces the original unique functions of the RIS for the primary system, allowing better control over the impact on primary system performance. Second, joint optimization mechanisms can be explored to optimize both the functions of the RIS for the primary system and the information modulation/energy collection functions of the BD. Note that typical BDs are generally small in size, implying that their impact on the primary system may not be significant.

3.4.2 Solution: a novel frame structure

Here, a novel frame structure is provided to realize that RIS supports channel regulation and information modulation simultaneously, as shown in Fig. 8.

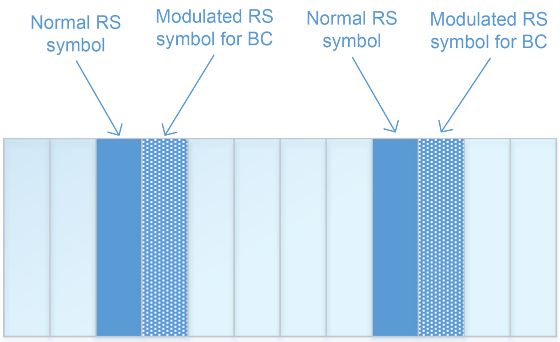

Fig. 8 A novel frame structure for a RIS-integrated channel regulation and information modulation (RS: reference signal; BC: backscatter communication)

1. Pilot time slot only regulates the channel of the primary system without modulating information.

2. Backscatter time slot enables channel regulation and information modulation simultaneously.

3. Ensuring reference signals in both time slots is recommended for effective estimation of the channels of the two types of time slots. The difference between these two channels is the modulated information. By using reference signal, we can estimate these two channels more accurately.

4. The design of the frame structure needs to consider time domain correlation, overhead, and reference signal structure.

5. In addition, RIS can consider designing a silent time slot/frame, such that only the signals of the direct channels/signals can be detected in these time slots/frames and the detection performance of these signals can be guaranteed.

3.5 True time delay schemes for RIS

During the investigation of analog beamforming in massive MIMO hybrid beamforming, it has been observed that a phenomenon called the beam splitting (the concept of the beam angle changing as a function of frequency is called beam squint ("squint" phenomenon)) occurs in different frequency sub-bands under broadband conditions, also known as the rainbow effect. To address this issue, researchers have proposed the utilization of the TTD mechanism to mitigate the phase deflection disparity caused by time delay among different sub-bands (Yan et al., 2019; Park et al., 2023). Additionally, Lin et al. (2021) highlighted the applicability of TTD in resolving the "squint" problem encountered by RIS.

The TTD mechanism employs precise control and adjustment of delays to align the phase differences across different frequency sub-bands. By adjusting the delay disparities, independent phase adjustment effects can be achieved for each frequency sub-band. Ratnam et al. (2022) explored the potential of TTD to enable frequency-dependent analog beamforming. However, this research primarily focuses on the analog beamforming challenges in large-scale MIMO, which differs from the requirements of RIS. It is crucial to thoroughly investigate the mechanism of RIS scenarios to realize independent analog beamforming in different sub-bands based on TTD. This capability can support the need for different UE to independently adopt their own beamforming in their respective occupied sub-bands within the framework of OFDMA.

3.5.1 Concepts of TTD scheme

In principle, the TTD circuit introduces a group delay to the received signal. The delay is denoted as $\tau_{\mathrm{TTD},n}$ in the n^{th} array element; accordingly, the received OFDM symbol of the m^{th} sub-carrier is

$$\boldsymbol{Y}_m = \boldsymbol{w}_{\mathrm{TTD},m}\boldsymbol{H}_m\boldsymbol{v}\boldsymbol{X}_m + \boldsymbol{N}_m, \tag{9}$$

where the channel at the m^{th} sub-carrier is denoted as $\boldsymbol{H}_m$, $\boldsymbol{v}$ is the transmission precoding matrix on the NB side, $\boldsymbol{X}_m$ is the data sequence, and the frequency domain noise $\boldsymbol{N}_m$ is Gaussian-distributed.

The combiner specified by TTD arrays $\boldsymbol{w}_{\mathrm{TTD},m}\in\mathbb{C}^N$ is frequency-dependent, i.e., its n^{th} element is

$$w_{\mathrm{TTD},m,n} = \mathrm{e}^{\mathrm{j}2\pi f_m \tau_{\mathrm{TTD},n}}, \tag{10}$$

where the RF of the m^{th} sub-carrier is denoted as f_m.

This model is valid as long as cyclic prefix (CP) is longer than the propagation delay $\varGamma_{l,q,n}$ and the cumulative delay $\tau_{\mathrm{TTD},n}$ of the TTD circuit:

$$N_{\mathrm{cp}}T > \max_{l,q,n} \varGamma_{l,q,n} + \max_{l,q,n} \tau_{\mathrm{TTD},n}, \tag{11}$$

where N_{cp} is the number of samples for CP, and T is the duration of each sample.

3.5.2 RIS using TTD to support frequency-dependent beamforming for multi-user access with OFDMA

As mentioned above, it is assumed that RIS can have only one phase/amplitude modulation weighted mode at a time; thus, the general beamforming can suitably match the channel of only one UE. In the scenario of multi-user OFDMA, wherein different UEs use different sub-bands in the frequency-division multiplexing (FDM) mode, RIS will not be able to suitably match the frequency orthogonal channels of these UEs.

In this subsection, we discuss the application of the TTD mechanism in RIS to support the frequency-independent beamforming for different UEs using OFDMA in their respective occupied sub-bands. TTD mechanism is flexible in phase adjustment of different sub-bands; in other words, it increases phase freedom in the frequency domain, leading to scheduling performance gains.

Here, we consider the case where two UEs (ue_1 and ue_2) use OFDMA as an example. ue_1 occupies the sub-band B_1, and ue_2 occupies the sub-band B_2. The precoding matrix $\boldsymbol{W}_1$ of ue_1 is calculated based on the channel $\boldsymbol{H}_1$ of ue_1 corresponding to the center frequency point f_1 of B_1. The precoding matrix $\boldsymbol{W}_2$ of ue_2 is calculated based on the channel $\boldsymbol{H}_2$ corresponding to the center frequency point f_2 of B_2. The phase difference vector resulting from $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$ is denoted as $\boldsymbol{\Phi}$, and φ_n represents the phase difference of the n^{th} antenna caused by $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$.

The delay difference corresponding to the phase difference can be calculated by the following equation, wherein the time delay difference is inversely calculated according to the phase difference.

$$w_{m,n} = \alpha_n \exp\left(-\mathrm{j}\left(2\pi\left(f_m - f_{\mathrm{c}}\right)\tau_n + \varphi_n\right)\right). \quad (12)$$

The TTD coefficient matrix of m^{th} sub-carrier is $\boldsymbol{W}_m = \mathrm{diag}(\boldsymbol{w}_m)$, where $\boldsymbol{w}_m = [w_{m,1}, w_{m,2}, \ldots, w_{m,N}]$.

The basic process of implementing TTD mechanism is as follows:

1. Considering sub-band 1 (center frequency point f_1) as the reference frequency $f_{\mathrm{c}}=f_1$, the RIS regulation matrix $\boldsymbol{\Phi}_{f1}=[\varphi_{f1,1}, \varphi_{f1,2}, \cdots, \varphi_{f1,N}]$ corresponding to f_1 is calculated by the traditional method; here N is the number of antennas. Thereafter, the phase difference φ_n corresponds to the m^{th} sub-carrier of the n^{th} antenna in sub-band 2 (center frequency point f_2).

2. After incorporating time delay τ_n, an additional phase offset $\Delta\varphi_n$ will be introduced at f_1; thus, the original regulation matrix $\boldsymbol{\Phi}_{f1}$ requires revision, i.e., $w'_{f1,n}=w_{f1}\times \mathrm{e}^{-\mathrm{j}\Delta\varphi_n}$.

3. Because the phase difference between the two sub-bands is realized based on the time delay, a beam squint is introduced into all sub-carriers, except the center frequency points of bandwidths BW1 and BW2, due to the time delay τ_n. Particularly, when the delay τ_n is substantial, it produces a more pronounced beam squint effect (owing to a large phase difference φ_n, it is necessary to set a large delay τ_n accordingly). Furthermore, the beam squint effect is significant, resulting in performance degradation. To minimize the impact of the beam squint mentioned above, the following factors should be considered when optimizing the algorithm: (1) The optimization objective is to maximize the sum capacity of multiple sub-bands; (2) At least several constraints should be considered, i.e., the range of allowable delay τ_n, the performance impact caused by beam squint (e.g., compared with the TTD used to perfectly eliminate beam squint), and the minimum traffic delay (such as ultra-reliable low-latency communications (URLLC)); (3) To minimize the influence of beam squint, during multi-user scheduling, it should be verified that the beam phase difference of different UEs is not exceedingly large.

4. Other considerations, including the number of delay/phase quantization bits (e.g., 1–2 bits), the complexity and cost, and the range of time delay/phase, need to be addressed.

5. To reduce complexity, K adjacent antenna elements of RIS can be grouped and the time delay be shared.

3.6 RIS-assisted NOMA

NOMA has emerged as a promising technology for future wireless communication systems as it can provide services to multiple users simultaneously on the same wireless resource, leading to enhanced spectral efficiency, support for massive connectivity, and low latency (Liu et al., 2017). The RIS mechanisms discussed in the previous subsections can generally be directly applied to orthogonal multiple access (OMA). However, introducing RIS in the NOMA presents new challenges and opportunities (Yang et al., 2021). The interaction between RIS and NOMA is a win-win approach, where NOMA introduces more potential multi-access capability into the RIS-assisted multi-user system, enabling flexible resource allocation, while RIS facilitates the reconstruction of wireless channels to assist NOMA pairing, further improving the system's overall performance (Ding ZG et al., 2022). RIS is a channel changing technique that can enhance or degrade the channel quality of individual users by adjusting the reflection coefficients and deployment locations of the RIS, rendering NOMA designs smarter (Liu et al., 2022a).

As previously mentioned, resource allocation and optimization have received significant research attention to fully leverage the benefits of RIS-NOMA systems and further enhance communication performance. Specifically, by jointly optimizing communication resources such as beamforming, power, and sub-channels, along with the regulation coefficients of the RIS, the performance can be significantly improved.

Zuo et al. (2020) investigated the resource allocation for the RIS-NOMA system. They optimized not only the phase shift and power allocation but also the channel assignment and decoding order to maximize the system's throughput. Considering a RIS-NOMA system with multiple users, Wu et al. (2021) proved that dynamic phase shift is unnecessary for both downlink and uplink NOMA systems, which simplifies the problem and reduces signaling overhead. Mu et al. (2021) proposed a joint optimization algorithm for the deployment location, reflection coefficient, and power allocation of the RIS. They showed that this algorithm can achieve performance close to optimal. For the RIS-NOMA system with a BS equipped with multiple antennas, Mu et al. (2020) proposed a joint optimization scheme that involves active beamforming at the BS and passive beamforming at the RIS, to maximize the sum rate. Mu et al. (2020) proposed a preliminary RIS-enhanced multi-antenna NOMA transmission framework, considering different types of RIS, and proposed a convex optimization based algorithm to obtain local optimal solutions to maximize system throughput. NOMA combined with traditional OMA, such as RIS-assisted NOMA-TDMA (time division multiple access) systems, can provide a flexible and efficient balance between system complexity and throughput performance (Liu et al., 2022b).

Previous studies on uplink communication scenarios have primarily focused on maximizing throughput in passive and active RIS-assisted NOMA-TDMA scenarios (Zhang DC et al., 2021). In Cantos et al. (2022), a RIS was connected to an uplink NOMA service provided by multi-antenna receivers, for effective data collection from large-scale devices. In this literature, maximum minimum fairness of the network was achieved by optimizing the receiving beamforming, RIS reflection, and transmission power allocation of the equipment.

AI, including advanced machine learning techniques such as supervised learning, unsupervised learning, and reinforcement learning, is considered one of the most promising technologies for 6G. These techniques can intelligently solve dynamic and uncertain environments in RIS-NOMA systems (Li HD et al., 2021; Taha et al., 2021).

In addition to optimizing resource scheduling, the deployment location of the RIS is another degree of freedom that can impact system performance. It is because the path loss of the RIS auxiliary link depends on the product of the distance between the BS–RIS link and the RIS–user link (Özdogan et al., 2020). Therefore, to fully use the potential of RIS, it is necessary to jointly consider the optimization of RIS location and the optimal allocation of wireless resources to users. Liu et al. (2022a) provided preliminary results on the joint optimization of RIS deployment and NOMA schemes for multi-user networks assisted by RIS.

Despite the progress made in channel estimation for RIS-assisted systems, channel estimation errors cannot be avoided in practical settings due to defects in RIS hardware and CSI feedback delay, which can lead to degraded performance. Therefore, a novel and robust RIS-NOMA design with imperfect CSI is needed to balance the trade-off between performance and complexity. The transmission rate and active/passive beamformers should be carefully designed to account for imperfect CSI and ensure reliable NOMA transmission. Moreover, as demonstrated in Zhao MM et al. (2021), controlling the RIS reflection amplitude can be a low-cost alternative to traditional reflective phase beamforming when CSI errors are a serious problem, while achieving comparable, or even better performance. With respect to the imperfect successive interference cancellation (SIC) in NOMA, the ability to manipulate wave polarization with the RIS in a dual-polarized MIMO-NOMA network was studied in de Sena et al.

(2021). A new strategy was proposed to alleviate the impact of imperfect SIC and use polarization diversity.

3.7 RIS-based transmitter

As mentioned in Section 2, RIS can not only regulate channels but also function as novel passive modulating transmitters for information modulation (Khaleel and Basar, 2021; Yuan J et al., 2021; Li QC et al., 2023b, 2023c). RIS-based transmitters offer a low-complexity, low-cost, and low-power consumption architecture for information modulation. These transmitters can be understood in the context of three traditional concepts: information modulation technology, backscatter technology (or symbiotic communication technology), and information metamaterial technology.

Traditional information modulation technologies, such as spatial scattering modulation (Ding YC et al., 2017) and spatial index modulation (Ding Y et al., 2018), use reconfigurable antennas or scatterers to transmit additional information by exploiting variations in the received signal's characteristics in rich scattering environments (Basar et al., 2017). In contrast, RISs are intelligent devices designed to intentionally control the propagation environment to enhance the quality of receiver signals (Basar et al., 2019; di Renzo et al., 2019). RIS can modulate information similar to information modulation technology by regulating electromagnetic waves and offer stronger capabilities for novel RIS-based transmitters. Basar (2020) proposed two schemes: RIS-based spatial shift keying (RIS-SSK) and RIS-based spatial modulation (RIS-SM), which use RIS to improve signal quality in hostile fading channels. Additionally, information modulation was achieved by selecting specific receive antenna indices based on information bits. Cui et al. (2017) introduced the concept of "information metamaterials/metasurfaces." Cui et al. (2020) established the relationship between geometric information entropy of the codebook and the physical information entropy of the scattering far-field pattern from an information theory perspective. A similar concept is SR, where a BD modulates its own information over an incident signal from a transmitter by varying its reflection coefficient (Long et al., 2018).

The idea of using RIS as a transmitter has been verified through a test-bed platform in an academic paper. Specifically, Tang et al. (2019) implemented an eight-phase-shift-keying (8-PSK) transmitter using a programmable surface with 256 reconfigurable elements. High phase modulation resolution was achieved by changing the bias voltage of varactor diodes. The authors demonstrated that the reconfigurable surface could modulate the unmodulated carrier through controlled bias voltage digital-to-analog converter (DAC). Tang et al. (2020) proposed a mathematical model to characterize RIS-based MIMO transmission, and a nonlinear modulation technique was introduced to achieve high-order modulation under constant envelope constraints, applied to RIS-based MIMO transmission. This architecture was further used to propose the world's first prototype for real-time RIS-based MIMO-QAM (quadrature amplitude modulation) wireless communication. RIS loaded with specific spatio-temporal codes can precisely control the propagation direction of electromagnetic waves and the distribution of harmonic frequencies, enabling the integration of energy radiation and information modulation functionalities, and encoding and processing digital information in both time and space domains. By optimizing the space-time coding matrix, information can be directly encoded into the spatial-spectrum and spectral-spatial characteristics of the electromagnetic wave, enabling multi-channel wireless communication technologies such as space-division multiplexing and frequency-division multiplexing (FDM) (Zhang L et al., 2021).

This novel RIS-based transmitter offers advantages of low cost and a simple structure without the need for RF components like antenna arrays, filters, and mixers required by traditional methods. However, there are still engineering implementation challenges that need to be addressed for this novel transmitter system architecture, requiring further in-depth research to resolve them. Practical engineering applications can only be achieved once these engineering challenges are resolved.

4 Future trends and challenges

To further promote the industrialization process of RIS, certain aspects still need further in-depth research and industrialization promotion.

4.1 A new structure of RIS: RIS integrated with photovoltaic panels

As mentioned earlier, the deployment of RIS in future wireless networks may raise power supply concerns, particularly in remote areas. However, RIS itself is a plate-like structure with low power consumption, making it a natural idea to consider integrating RIS with photovoltaic panels, especially in outdoor scenarios, to address power requirements.

There are two potential modes for integrating RIS with photovoltaic panels:

Mode 1: In this mode, a novel RIS structure is designed where an optically transparent RIS is placed on the surface of the photovoltaic panel. The RIS regulates wireless electromagnetic waves while allowing visible light energy to reach the photovoltaic panel's surface, generating electricity to support the RIS control unit and potentially meeting the power demands of other surrounding equipment.

Mode 2: This mode involves deploying additional photovoltaic panels specifically for supplying power to the RIS. Since both the photovoltaic panels and RIS are plate-like structures, it is relatively straightforward to design composite structures combining them. This mode does not introduce a new RIS structure but rather represents a new combined deployment approach.

Naturally, the integrated structure faces certain challenges. For instance, photovoltaic power generation is most efficient during strong sunlight in the daytime. However, data traffic is typically higher during the daytime and evening, while there is minimal traffic during the middle of the night, resulting in lower power consumption. Therefore, the peak traffic in the daytime aligns with the peak photovoltaic power generation, and energy storage modules can be used primarily for evening traffic and a smaller amount of midnight traffic. Additionally, integrated design poses difficulties due to the different deployment angle requirements of photovoltaic panels and RIS panels. Other challenges include low light on cloudy days and the possibility of relatively low transmittance of RIS.

The low power consumption feature of RIS passive regulation coupled with the use of green energy such as photovoltaic will truly achieve the goal of future green communication.

4.2 Complexity of RIS network deployment and optimization

The introduction of RIS will bring a new network paradigm to the future network; however, it will be likely to lead to pose the complexity issues pertaining to network deployment and optimization, including:

1. Multiple transmission nodes sharing the same RIS.

2. Collaborative scheduling when a transmission node uses multiple RISs at the same time simultaneously.

3. Control link between the transmission node and RIS (such as NB–RIS backhaul link).

4. The challenge faced by during network topology planning and optimization. RIS enhances and expands the signal coverage area, which may disrupt the traditional strictly divided sector coverage characteristics and induce complexity during network planning and optimization.

5. Station-site selection and power supply. The simplicity, low cost, and low power consumption of RIS make it possible to enable deploying RIS more widely. However, its ubiquitous deployment may also bring new challenges to RIS power supply and management.

6. Different scenarios require different types of RIS. It is necessary to design different forms of RIS.

4.3 Engineering errors

The engineering implementation of RIS may introduce errors due to cost and complexity constraints. It is important to account for these engineering errors when designing and optimizing algorithms. The primary engineering deviations in RIS can be categorized as follows: (1) regulation phase quantization error, such as 1- and 2-bit quantizations (Li QC et al., 2023a), (2) deviation calibration, involving processing deviation, calibration, aging, environmental impact, and calibration for system drift measurements, and (3) CSI feedback quantization error and time delay.

4.4 Standard and protocol design

The standardization design of RIS involves mainly the following aspects:

1. The access procedure of UE: The access procedure design includes measurement, discovery,

random access, transmission, target signal identification and regulation, and measurement.

2. Resource management and scheduling procedure: This includes mainly the management and scheduling of RIS resources, such as the selection of RIS channels and NB–UE direct channels and the scheduling/selection of RIS in multiple RIS scenarios.

3. The impact of the introduction of RIS on the handover procedure (i.e., mobility management): This includes switching between different RISs and different frequency bands.

4. Side control information interaction between NB and RIS: This includes beamforming information, timing information to align transmission, information on uplink–downlink (UL–DL) time division duplexing (TDD) configuration, and ON–OFF information.

5 Conclusions

This paper primarily examines the practical engineering applications of RIS. It provides a summary of the engineering applications of RIS, discusses the technical challenges encountered, and proposes potential solutions. Furthermore, future trends and challenges in RIS engineering applications are addressed. In conclusion, while there are numerous challenges in the engineering applications of RIS, viable solutions exist to overcome them.

Compliance with ethics guidelines

Yajun ZHAO declares that he has no conflict of interest.

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