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Review:

Simultaneously transmitting and reflecting (STAR) RISs for 6G: fundamentals, recent advances, and future directions*

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Abstract: Simultaneously transmitting and reflecting reconfigurable intelligent surfaces (STAR-RISs) have been attracting significant attention in both academia and industry for their advantages of achieving 360° coverage and enhanced degrees-of-freedom. This article first identifies the fundamentals of STAR-RIS, by discussing the hardware models, channel models, and signal models. Then, three representative categorizing approaches for STAR-RISs are introduced from the phase-shift, directional, and energy consumption perspectives. Furthermore, the beamforming design of STAR-RISs is investigated for both independent and coupled phase-shift cases. As a recent advance, a general optimization framework, which has high compatibility and provable optimality regardless of the application scenarios, is proposed. As a further advance, several promising applications are discussed to demonstrate the potential benefits of applying STAR-RISs in sixth-generation wireless communication. Lastly, a few future directions and research opportunities are highlighted.

Key words: Sixth-generation wireless communication (6G); Reconfigurable intelligent surface (RIS); Smart radio environment; Simultaneous transmission and reflection

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1 Introduction

Reconfigurable intelligent surfaces (RISs), consisting of a large number of low-cost and low-power electromagnetic elements, have emerged as a promising technology for sixth-generation wireless communication (6G) and thus have received significant research interest from both academia and industry (di Renzo et al., 2020; Huang et al., 2020; Wu QQ

and Zhang, 2020a; Liu YW et al., 2021a). By deploying RISs in existing wireless environments, the phase shift and amplitude of the wireless signal incident upon each RIS element can be adjusted. Thus, the propagation of the reflected wireless signal can be changed for satisfying specific requirements (di Renzo et al., 2020; Liu YW et al., 2021a). In contrast to wireless networks from the previous first-generation to the current fifth-generation networks, in which the wireless technologies were generally developed to combat the random radio environment (e.g., fadings and blockages), RISs achieve the so-called “smart radio environment” for realizing flexible and sustainable 6G (di Renzo et al., 2020). More

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importantly, their two-dimensional (2D) form factors and nearly passive working modes make RISs highly compatible with existing wireless technologies. The superiority of RISs has been extensively studied for achieving different objectives, e.g., enhancement of spectral/energy efficiency (Huang et al., 2019; Guo et al., 2020; Zhang SW and Zhang, 2020) and transmit power reduction (Wu QQ and Zhang, 2019; Zheng et al., 2020; Yu et al., 2021), and in diversified communication scenarios, e.g., multi-cell communications (Pan et al., 2020b; Xie et al., 2021), simultaneous wireless information and power transfer (SWIPT) (Pan et al., 2020a; Tang et al., 2020; Wu QQ and Zhang, 2020b), physical layer security (PLS) (Cui et al., 2019; Shen et al., 2019; Yu et al., 2020), and unmanned aerial vehicles (UAVs) (Zhang QQ et al., 2019; Li et al., 2020; Liu X et al., 2021). Moreover, various recent studies have demonstrated the extraordinary functionalities of RISs in future-generation wireless communication networks (Alexandropoulos et al., 2022; Jian et al., 2022; Xu JD et al., 2023).

1.1 The road to simultaneously transmitting and reflecting (STAR) RISs

Note that most of the existing research contributions on RISs have focused on the category of single-functional RISs, i.e., either transmitting or reflecting incident wireless signals. This inevitably leads to a 180° smart radio environment. Therefore, wireless devices located on one side of a reflecting/transmitting-only RIS can merely benefit from the facilitated smart radio environment, while the other side of the RIS remains ineffective or possibly even worse than the conventional radio environment. As a remedy, a novel STAR-RIS technology was first proposed by Xu JQ et al. (2021). As illustrated in Fig. 1, STAR-RIS integrates both transmission and reflection (T&R) functions. Notably, the wireless signal incident upon STAR-RIS can be transmitted and reflected into both sides of STAR-RIS with reconfigured propagation. For example, as illustrated, the incident signal can be steered into a given direction in both T&R space. As a result, a 360° smart radio environment can be realized by STAR-RISs. Compared to conventional reflecting/transmitting-only RISs, there are two key benefits of STAR-RISs:

1. Full space coverage: The realized 360°

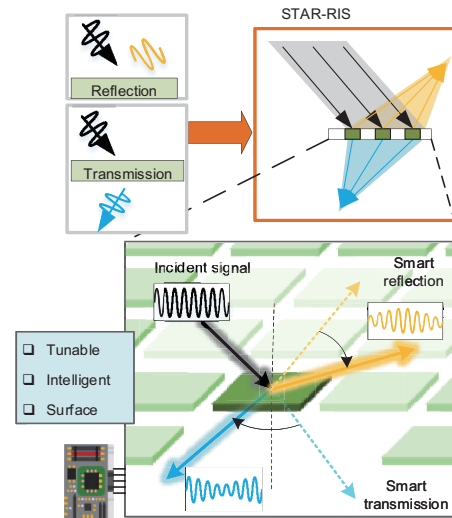


Fig. 1 Illustration of the STAR-RIS and the facilitated 360° smart radio environment

smart radio environment allows wireless nodes to receive the beneficially reconfigured wireless signals regardless of their locations with respect to STAR-RIS. Therefore, no additional topological constraints have to be satisfied as in conventional reflecting/transmitting-only RISs. STAR-RISs contribute to ubiquitous coverage for 6G with high flexibility.

2. Enhanced degrees-of-freedom (DoFs): As illustrated in Fig. 1, desired propagation can be achieved on both sides via the T&R coefficients provided by STAR-RISs. Compared to conventional reflecting/transmitting-only RISs, more DoFs can be exploited in STAR-RIS-assisted communications.

1.2 Overview of research contributions on STAR-RISs

Motivated by the uniqueness of STAR-RISs, extensive research efforts have been devoted to them. Table 1 summarizes the recent research contributions in terms of hardware and channel modeling, performance analysis, and beamforming optimization of STAR-RISs.

1.2.1 Hardware and channel modeling

Since there are various types of STAR-RISs, existing works have proposed different hardware and signal models. Zhang SH et al. (2020, 2021) proposed an initial signal model for STAR-RISs where the T&R phase shifts are considered to be the same.

Table 1 Summary of recent research contributions on STAR-RISs

Topic	Reference	Title	Brief description
Hardware and channel modeling	Zhang SH et al. (2020)	Beyond intelligent reflecting surfaces: reflective-transmissive metasurface aided communications for full-dimensional coverage extension	The paper studied an IOS-assisted downlink communication system that uses both reflective and transmissive capabilities of an intelligent surface to improve the link quality and extend wireless coverage.
	Zhang SH et al. (2021)	Intelligent omni-surface: ubiquitous wireless transmission by reflective-transmissive metasurface	The paper introduced the concept of an IOS as an extension of RISs enabling wireless communication coverage on both sides of the surface through reflective and transmissive channels, achieved by joint beamforming between a multi-antenna small BS and the IOS.
	Xu JQ et al. (2021)	STAR-RISs: simultaneous transmitting and reflecting reconfigurable intelligent surfaces	This paper proposed the concept of STAR-RIS and presented the basic hardware model. It further proposed channel models for near-field and far-field scenarios for STAR-RISs, and analyzed the diversity gain compared to conventional RISs, showing that full diversity order can be achieved on both sides of STAR-RISs.
	Bao et al. (2021)	Programmable reflection-transmission shared-aperture metasurface for real-time control of electromagnetic waves in full space	This paper presented a “Janus” digital coding metasurface that enables simultaneous programming of various electromagnetic functions in both reflected and transmitted waves by incorporating PIN diodes to independently control the phase of each wave, demonstrating proof-of-concept implementations such as anomalous deflections, beam focusing, and scattering reduction, with potential applications in stealth technologies, imaging systems, and next-generation wireless communications.
	Xu JQ et al. (2022a)	Simultaneously transmitting and reflecting intelligent omni-surfaces: modeling and implementation	The paper presented four practical hardware implementations, three hardware modeling methods, and five channel modeling methods, providing a categorization of existing smart surface technologies and physics-compliant models for further research on STAR-RISs.
	Wang TX et al. (2022b)	Performance analysis of IOS-assisted NOMA system with channel correlation and phase errors	This paper unveiled the channel hardening effect caused by correlated channels and phase errors in STAR-RIS-assisted NOMA systems. It was demonstrated that in the considered system, NOMA may not always outperform OMA as STAR-RISs can configure the channel in each time slot of OMA.
Performance analysis	Zhang C et al. (2022)	STAR-IOS aided NOMA networks: channel model approximation and performance analysis	This paper derived three approximations of channels in STAR-RIS-aided systems: central limit model, M -fold convolution model, and curve fitting model. The outage probability and diversity order of STAR-RIS-aided NOMA systems were derived.
	Nguyen and Nguyen (2022)	On performance of STAR-RIS-enabled multiple two-way full-duplex D2D communication systems	This paper provided a performance analysis of STAR-RIS-enabled multiple two-way full-duplex D2D communication systems. Closed-form outage probability, sum throughput, and ergodic capacity were derived, and insights on diversity order and ergodic slope were obtained.
	Zhang ZH et al. (2023)	Ergodic capacity of intelligent omni-surface-aided communication systems with phase quantization errors and outdated CSI	This paper considered the impact of phase quantization errors and outdated CSI on STAR-RIS-aided systems. It was shown that (1) the ergodic capacity of the considered system is saturated in high-SNR regime due to outdated CSI and (2) a few quantization bits are sufficient.
	Wang TX et al. (2022a)	Outage probability analysis of STAR-RIS assisted NOMA network with correlated channels	This paper evaluated the impact of channel correlation on the performance of STAR-RIS-assisted NOMA systems. Analytical results showed that channel correlation reduces the outage performance of the considered system.

To be continued

Table 1

Topic	Reference	Title	Brief description
Performance analysis	Papazafeiropoulos et al. (2022)	Coverage probability of STAR-RIS-assisted massive MIMO systems with correlation and phase errors	This paper studied the coverage probability of STAR-RIS-aided massive MIMO systems. Based on the derived coverage probability, the passive beamforming at STAR-RIS was optimized based on statistical CSI, which reduced the optimization overhead.
	Cai et al. (2021)	Joint beamforming designs for intelligent omni surface assisted wireless communication systems	This paper jointly optimized the active beamforming at the BS and the passive beamforming at STAR-RIS to minimize the power in a two-user system. An alternating optimization algorithm was proposed to solve the resulting optimization problem.
	Lin YM et al. (2023)	Simultaneous transmission and reflection beamforming design for RIS-aided MU-MISO	This paper studied the joint beamforming design of the STAR-RIS-aided multi-user systems. The resulting power minimization problem was addressed based on alternating optimization and semidefinite relaxation.
Beamforming optimization	Mu et al. (2022)	Simultaneously transmitting and reflecting (STAR) RIS aided wireless communications	This paper proposed three practical operating protocols of STAR-RISs: energy splitting, mode switching, and time switching. A novel joint optimization algorithm was proposed to minimize the power consumption of the STAR-RIS-aided multi-user system, which guarantees theoretical convergence.
	Niu et al. (2022)	Weighted sum rate optimization for STAR-RIS-assisted MIMO system	This paper investigated the joint beamforming design for maximizing the weighted sum rate of the STAR-RIS-aided two-user system and proposed a block coordinate descent algorithm to solve the corresponding problem.
	Liu YW et al. (2022b)	Simultaneously transmitting and reflecting (STAR)-RISs: a coupled phase-shift model	This paper considered a joint beamforming design of the STAR-RIS-aided systems under a coupled phase-shift assumption. A low-complexity element-wise algorithm was proposed to solve coupled phase shifts for a system with a single-antenna BS and two communication users.
	Niu and Liang (2023)	Weighted sum-rate maximization for STAR-RISs-aided networks with coupled phase-shifters	This paper studied the optimization of the coupled phase shift of STAR-RISs in a system with a multi-antenna BS and multiple users on both sides of the surface, aimed at maximizing the weighted sum rate. An alternating optimization algorithm was proposed to obtain a sub-optimal solution.
	Wang ZL et al. (2023a)	Coupled phase-shift STAR-RISs: a general optimization framework	This paper proposed a general optimization framework for coupled phase-shift STAR-RISs by exploiting penalty dual decomposition. This framework addresses the coupled phase-shift constraint regardless of the objective function.
	Zhong et al. (2022)	Hybrid reinforcement learning for STAR-RISs: a coupled phase-shift model based beamformer	This paper proposed a pair of hybrid reinforcement learning algorithms to facilitate coupled phase-shift beamforming of STAR-RIS, where a long-term beamforming problem was solved.

BS, base station; CSI, channel state information; D2D, device-to-device; IOS, intelligent omni-surface; MIMO, multiple-input multiple-output; MU-MISO, multi-user multiple-input single-output; NOMA, non-orthogonal multiple access; OMA, orthogonal multiple access; PIN, positive-intrinsic-negative; RIS, reconfigurable intelligent surface; SNR, signal-to-noise ratio; STAR, simultaneously transmitting and reflecting

Xu JQ et al. (2021) proposed a hardware model and near/far-field channel models for independent T&R phase-shift STAR-RISs. Bao et al. (2021) proposed a hardware implementation for metasurface-based STAR-RIS to achieve independent control of T&R phase shifts. Xu JQ et al. (2022a) discussed different hardware implementations, hardware models, and channel models for STAR-RISs. Yang et al. (2023) introduced a variant concept of STAR-RIS, the reconfigurable intelligent computational surfaces (RICSs). RICSs address the limitations of conventional RISs by integrating wave-based calculations and signal processing, offering a promising solution for the integration of communication and computing.

1.2.2 Performance analysis

Some other works investigated STAR-RISs from the performance analysis perspective. Wang TX et al. (2022b) studied the performance of STAR-RIS-aided non-orthogonal multiple access (NOMA) networks with phase quantization errors and channel estimation errors. Zhang C et al. (2022) investigated the performance of STAR-RIS-aided downlink NOMA networks with randomly deployed users. Nguyen and Nguyen (2022) investigated the performance of STAR-RIS-enabled multiple two-way full-duplex device-to-device (D2D) communication systems over Rayleigh fading channels. Zhang ZH et al. (2023) studied the performance of a STAR-RIS-aided communication system considering the impacts of actual phase quantization errors and outdated channel state information (CSI). Wang TX et al. (2022a) studied the outage probability of a STAR-RIS-assisted downlink NOMA network over spatially correlated channels. Papazafeiropoulos et al. (2022) investigated the coverage probability of a STAR-RIS-assisted massive multiple-input multiple-output (mMIMO) system.

1.2.3 Beamforming optimization

To fully leverage the benefits of STAR-RIS, it is essential to conduct a proper optimization of the T&R coefficients, which has attracted substantial research interest. Cai et al. (2021) considered a two-user system, where the active beamforming, the phase shifts of T&R coefficients, and the energy splitting ratios of the T&R coefficients were optimized to minimize the transmit power. Following this line

of work, Lin YM et al. (2023) studied the beamforming design of STAR-RIS-aided communication systems in a more general multi-user scenario. Mu et al. (2022) made novel contributions by proposing three practical operating protocols for STAR-RIS, namely energy splitting, mode switching, and time switching. Subsequently, joint optimization (JO) schemes were developed for these protocols to minimize transmit power. From a different perspective, Niu et al. (2022) maximized the weighted sum rate under the three operating protocols of STAR-RISs. The aforementioned studies assumed that the phase shifts of the T&R coefficients of STAR-RISs can be adjusted independently. However, in practical scenarios, those phase shifts may be coupled, thereby motivating recent investigations on beamforming design for the coupled phase-shift STAR-RISs. Specifically, Liu YW et al. (2022b) developed a low-complexity element-wise algorithm for the coupled phase-shift STAR-RIS that served two communication users. Niu and Liang (2023) considered a more general multi-user system, where the coupled phase shifts were optimized through alternating optimization (AO). As a novel contribution, Wang ZL et al. (2023a) proposed a generalized optimization framework for the coupled phase-shift STAR-RIS, which has provable optimality under mild conditions. Zhong et al. (2022) applied hybrid reinforcement learning techniques to obtain the T&R coefficients that comply with the coupled phase-shift constraints.

1.3 Motivations and organizations

As can be observed, STAR-RIS is a prominent member of the RIS family, and the research contributions on STAR-RISs keep rapidly growing. However, the development of STAR-RISs has been extensively researched in various application scenarios, perspectives, and assumptions without much coordination. There is an urgent need to categorize the existing studies, which provides the main motivation for this paper. This paper intends to consolidate and advance the research on STAR-RISs via summarizing the fundamentals of STAR-RISs, overviewing the recent state-of-the-art research results on STAR-RISs, and highlighting promising applications and open problems for STAR-RISs.

The remainder of this paper is structured as follows: Section 2 introduces the fundamentals of STAR-RISs covering hardware models, channel

models, and signal models. Section 3 discusses three representative categorizing approaches for STAR-RISs from the phase-shift, directional, and energy consumption perspectives. Section 4 discusses the STAR beamforming design for the independent and coupled phase-shift models, and proposes a generalized optimization framework for STAR-RISs. Section 5 highlights several promising STAR-RIS-enabled wireless technologies for 6G and provides numerical results demonstrating their effectiveness. Conclusions are drawn and some future directions for investigating STAR-RISs are identified in Section 6.

2 Fundamentals of STAR-RISs

In this section, we discuss the fundamentals of STAR-RIS in terms of hardware models, channel models, and signal models. First, hardware modeling studies how STAR-RIS interacts with wireless signals. Thus, relations between physical parameters and the T&R coefficients for each element can be obtained. Second, through channel modeling, we study the channels between STAR-RISs and receivers so that end-to-end channel gains can be obtained. Finally, signal models can be established for determining the signals reconfigured by STAR-RISs.

2.1 Hardware models

The hardware implementations of STAR-RISs can be broadly classified into two categories, namely patch-array-based STAR-RISs and metasurface-based STAR-RISs (Xu JQ et al., 2022a). Since STAR-RISs have a spatially periodic structure, the key difference between these two categories is that patch-array-based and metasurface-based STAR-RISs have significantly different period sizes.

Patch-array-based STAR-RISs (Zhang SH et al., 2020): They consist of periodic elements having sizes on the order of a few centimeters. As a result, the phase-shift profile of these STAR-RISs is spatially discrete.

Metasurface-based STAR-RISs (NTT DO-COMO, 2020): They have periodic cells on the order of a few millimeters down to molecular sizes. As a result, metasurface-based STAR-RISs are able to achieve the spatially continuous configuration of incident waves.

In terms of hardware modeling, these two categories of STAR-RIS hardware implementations re-

quire different modeling methods. Specifically, the load impedance model is suitable for patch-array-based STAR-RISs and the generalized sheet transition condition (GSTC) model is suitable for modeling metasurface-based STAR-RISs. For the load impedance model, each element of a STAR-RIS can be treated as a lumped circuit with electric and magnetic impedances of Y_m and Z_m , respectively. By configuring the values of two complex-valued impedances, the T&R coefficients of the m^{th} element can be controlled through the relations $T_m = \frac{2-\eta_0 Y_m}{2+\eta_0 Y_m} - R_m$ and $R_m = -\frac{2(\eta_0^2 Y_m - Z_m)}{(2+\eta_0 Y_m)(2\eta_0 + Z_m)}$, where η_0 is the impedance of free space (Xu JQ et al., 2021). For the GSTC model, metasurface-based STAR-RISs are characterized by electric and magnetic susceptibilities as functions of position (di Renzo et al., 2020). The discontinuity of electric and magnetic fields on the two sides of the metasurface can be obtained through these susceptibilities. Compared with the load impedance model, the GSTC model is able to obtain more detailed results for the distribution of the transmitted and reflected signals.

2.2 Channel models

For STAR-RIS, different channel modeling methods are required for communication in far-field and near-field regions. A wireless receiver is regarded to locate in the far-field region of a STAR-RIS if the communication distance satisfies $d > 2L^2/\lambda$, where L is the largest dimension of STAR-RIS and λ is the carrier wavelength (di Renzo et al., 2020).

2.2.1 Far-field channel models

Within the far-field region, the Friis formula is valid for free-space transmission and the received power falls off with $d_1^{-2}d_2^{-2}$, where d_1 is the communication distance between the transmitter and STAR-RIS and d_2 is the distance between STAR-RIS and a receiver. Specifically, considering the line-of-sight (LOS) link between STAR-RIS and a MIMO receiver, the far-field channel can be expressed as the product of transmit and receive array response vectors:

$$\mathbf{H}_{\text{far}} = \beta \mathbf{a}_{\text{STAR}}(\theta, \phi) (\mathbf{a}_{\text{R}}(\theta, \phi))^T, \quad (1)$$

where β is the complex channel gain, \mathbf{a}_{STAR} and \mathbf{a}_{R} are the array response vectors for STAR-RIS and the receiver respectively, and θ and ϕ denote

the azimuth and elevation angles respectively. The overall channel between a transmitter and a receiver through STAR-RIS is a cascaded link, wherein the link through each element is scaled with the corresponding T&R coefficients. In the presence of scatterers, the STAR-RIS-aided far-field channel can be modeled by exploiting the Rician distribution.

2.2.2 Near-field channel models

Near-field channel models involve not only distance d_2 , but also all the distances between each STAR-RIS element and a receiver. Specifically, considering the LOS channel between a STAR-RIS and a MIMO receiver, the near-field channel matrix cannot be factorized into the product form as in Eq. (1). In contrast, the $(m, n)^{\text{th}}$ entry of the channel matrix can be expressed as follows:

$$[\mathbf{H}_{\text{near}}]_{m,n} = \beta e^{-j\frac{2\pi}{\lambda} \|\mathbf{p}_m - \mathbf{q}_n\|}, \quad (2)$$

where \mathbf{p}_m and \mathbf{q}_n are the m^{th} receive antenna and the n^{th} element of the STAR-RIS, respectively. Thus, the near-field channel can be formulated as the sum of all these individual links with different path-lengths. In addition, for metasurface-based STAR-RISs, the near-field channels are modeled through the Huygens–Fresnel principle based integration (Xu JQ et al., 2021). For these cases, the near-field channel is an integral over the surface area of the STAR-RIS, where the contributions of each unit area are proportional to its size, amplitude, leaning factor, and reciprocal distance to the receiver.

2.3 Signal models

Here, we provide basic signal models for STAR-RISs. In most cases, the wireless signals incident on a given element of the STAR-RIS are divided into transmitted and reflected signals. Let s_m denote the signal incident on one side of the m^{th} STAR element. Thus, the transmitted signals and the reflected signals can be modeled as $t_m = (\sqrt{\beta_m^t} e^{j\phi_m^t}) s_m$ and $r_m = (\sqrt{\beta_m^r} e^{j\phi_m^r}) s_m$, respectively, where $\sqrt{\beta_m^t}, \sqrt{\beta_m^r} \in [0, 1]$ and $\phi_m^t, \phi_m^r \in [0, 2\pi)$ denote the amplitude and phase shift of the T&R coefficients, respectively. For different categories of STAR-RISs, there are, in general, additional constraints on the amplitude and phase shift of the T&R coefficients, which are further discussed in the next section. For example, if the STAR element is considered to be lossless, energy conservation

dictates the following: $|t_m|^2 + |r_m|^2 = |s_m|^2$. Equivalently, the amplitudes of the T&R coefficients should satisfy $\beta_m^r + \beta_m^t = 1$.

3 Representative categorizing approaches of STAR-RISs

In this section, we distinguish representative categorizing approaches of STAR-RISs from three perspectives. We also reveal the key differences between these STAR-RIS categories in terms of signal models.

3.1 Phase-shift perspective: independent versus coupled phase shift

As discussed in Section 2.3, in the basic STAR-RIS signal model, the T&R phase shifts involved can take values ranging from 0 to 2π . In the literature, there are two main categories for T&R phase-shift reconfiguration, namely the independent phase-shift model and the coupled phase-shift model.

3.1.1 Independent phase-shift model

The transmission phase shift (ϕ_m^t) and the reflection phase shift (ϕ_m^r) can be adjusted independent of each other. This independent phase-shift control is achieved by tuning the surface electric and magnetic impedances. Recall that in Section 2.1, T&R phase shifts are determined through two complex-valued impedances, namely Y_m and Z_m . In other words, each STAR element has four real-valued configurable DoFs which correspond to $\beta_m^t, \beta_m^r, \phi_m^t$, and ϕ_m^r . However, the independent phase-shift model is challenging to realize in practice, especially for passive STAR-RISs. This is because if STAR-RISs are made of passive materials, the corresponding electric impedance and magnetic impedance cannot be arbitrary values.

3.1.2 Coupled phase-shift model

As pointed out by Zhu et al. (2014), for STAR-RISs using passive lossless materials, the corresponding electric impedance and magnetic impedance should be purely imaginary numbers. Under this constraint, transmission phase shift (ϕ_m^t) and reflection phase shift (ϕ_m^r) are coupled subject to specific values of phase-shift differences (Zhu et al., 2014; Xu

JQ et al., 2022b):

$$\phi_m^r - \phi_m^t = \frac{\pi}{2} + \nu_m \pi, \nu_m = 0 \text{ or } 1, \quad \forall m = 1, 2, \dots, M, \quad (3)$$

where ν_m is referred to as the auxiliary bit and can take on only two values, 0 or 1. In other words, the phase differences ϕ_m^r and ϕ_m^t are either $\pi/2$ or $3\pi/2$.

3.2 Directional perspective: single-sided versus dual-sided STAR-RISs

The basic signal model for STAR-RISs given in Section 2.3 considers only signals incident on one side of the surface. In practice, wireless signals may be incident upon both sides of STAR-RISs simultaneously. However, it is not yet clear how these signals can be simultaneously manipulated. To address this issue, Xu JQ et al. (2023c) proposed a signal model for dual-sided STAR-RISs. As illustrated in Fig. 2, under dual-sided incidence, each STAR element has four T&R coefficients, i.e., \tilde{r}_m^A , \tilde{r}_m^B , \tilde{t}_m^{AB} , and \tilde{t}_m^{BA} . These four coefficients transform the incident signals to the output signals of each STAR element. The relationship between the incident and the output signals is given by

$$\begin{pmatrix} y_m^A \\ y_m^B \end{pmatrix} = \begin{pmatrix} \tilde{r}_m^A & \tilde{t}_m^{AB} \\ \tilde{t}_m^{BA} & \tilde{r}_m^B \end{pmatrix} \begin{pmatrix} s_m^A \\ s_m^B \end{pmatrix}, \quad (4)$$

or equivalently, $\mathbf{y}_m = \mathbf{\Xi}_m \mathbf{s}_m$, where $\mathbf{\Xi}_m$ is the T&R matrix of the m^{th} STAR element. In terms of reciprocity, a STAR-RIS can be either reciprocal or non-reciprocal. A STAR element is reciprocal if the T&R matrix $\mathbf{\Xi}_m$ is symmetrical, i.e., $\tilde{t}_m^{AB} = \tilde{t}_m^{BA}$. For a nonreciprocal STAR matrix, we have $\tilde{t}_m^{AB} \neq \tilde{t}_m^{BA}$. For application scenarios where all users under service are located on one side of the STAR-RIS (e.g., side A), signal power is lost if $\tilde{t}_m^{BA} \neq 0$ even if all STAR elements might be lossless. A nonreciprocal STAR element is ideal in these scenarios to avoid power leakage from side A to side B.

3.3 Energy consumption perspective: passive versus active STAR-RISs

In terms of energy consumption, a patch-array-based STAR-RIS can be either passive or active.

3.3.1 Passive STAR-RISs

Since STAR-RISs generally do not require active components, most STAR-RIS implementations can

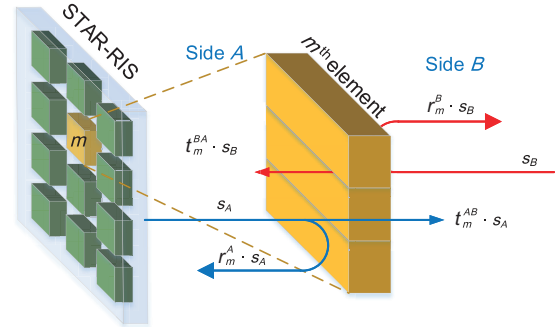


Fig. 2 A general signal model for dual-sided STAR-RISs

be regarded as passive. A STAR element is passive lossless if $\mathbf{\Xi}_m$ is unitary, i.e., $\mathbf{\Xi}_m^H \mathbf{\Xi}_m = \mathbf{I}_2$, where \mathbf{I}_2 denotes the 2×2 identity matrix. For passive lossless STAR elements, there is no energy loss so that the sum of the reflected and transmitted energies is equal to the energy of the incident signal. For the passive lossy STAR element, a portion of the incident energy is dissipated as heat, so that $\mathbf{\Xi}_m^H \mathbf{\Xi}_m \prec \mathbf{I}_2$.

3.3.2 Active STAR-RISs

For an active STAR element, we have $\mathbf{\Xi}_m^H \mathbf{\Xi}_m \succ \mathbf{I}_2$ (Pozar, 2011). In terms of the T&R coefficients, the key difference between active and passive STAR-RISs is that for active STAR-RISs, the amplitudes of their T&R coefficients can be greater than one, i.e., $\beta_m^r > 1$ and $\beta_m^t > 1$. This removes the amplitude constraint introduced for passive lossless STAR-RIS in Section 2.3. As proposed by Xu JQ et al. (2023a), active STAR-RISs can be achieved by exploiting reflection-type amplifiers and quadrature hybrid couplers. In addition, the performance gain of active STAR-RISs over passive ones is more significant when the number of STAR elements is small and the transmit signal-to-noise ratio (SNR) is low.

4 Beamforming design for STAR-RISs: from independent to coupled phase-shift models

When deploying STAR-RISs to assist communication systems, it is essential to carefully design the T&R coefficients of each element, namely STAR beamforming design, for facilitating the desired signal propagation. In this section, we first introduce

three practical operating protocols proposed for using STAR-RISs. Then, we discuss the STAR beamforming approaches developed for both independent and coupled phase-shift models and summarize their respective advantages and disadvantages. Finally, we propose a generalized optimization framework for STAR beamforming design, which has high compatibility and provable optimality.

4.1 Operating protocols

As discussed previously, there is a fundamental energy conservation constraint among the incident signal, the transmitted signal, and the reflected signal of each STAR element. As a result, each STAR can work in the intermediate mode, i.e., simultaneous T&R mode, and in the two extreme states, i.e., transmission-only and reflection-only modes. By exploiting this feature, three practical operating protocols were proposed by Liu YW et al. (2021b), namely energy splitting, mode switching, and time switching.

4.1.1 Energy splitting

All STAR elements work in the simultaneous T&R mode. Therefore, the signal incident upon each STAR element is generally split into transmitted and reflected signals toward different spaces. It can be observed that energy-splitting STAR-RISs can exploit the maximum DoFs since the T&R coefficients of each element can be optimized. This, however, leads to potentially high complexity in communication design and channel estimation given the resulting large dimension of optimization variables. Moreover, if the coupled phase-shift model is used, the energy-splitting STAR beamforming design is more challenging than the case with the independent phase-shift mode.

4.1.2 Mode switching

All STAR elements work in either the transmission-only mode or the reflection-only mode. Note that since each element of mode-switching STAR-RISs is able to work only in the single mode, the constraint caused by the coupled phase-shift model becomes a dummy. Therefore, the binary working mode reduces the total number of optimization variables and alleviates the overhead burden for controlling STAR-RISs, which is friendly for practi-

cal implementation. However, the maximum performance gain achieved by mode-switching STAR-RISs is degraded due to the reduced DoFs.

4.1.3 Time switching

All STAR elements periodically work in the transmission-only mode and reflection-only mode over different time slots. This leads to two independent T&R coefficient designs, in which the impact of the coupled phase-shift model vanishes. Note that compared to mode-switching STAR-RISs, the maximum array gain for T&R reserves in time-switching STAR-RISs. However, note that time-switching STAR-RISs have to frequently change the working modes of all elements, which leads to severe overhead and high implementation complexity.

4.2 STAR beamforming design under independent and coupled phase-shift models

After introducing the operating protocols of STAR-RISs, we focus our attention on the fundamental STAR beamforming design. It can be observed that different operating protocols impose different constraints on the STAR beamforming design problem. As discussed before, compared to mode- and time-switching STAR-RISs, the beamforming design in energy-splitting STAR-RISs is much more challenging. The case becomes even worse when considering the coupled phase-shift model. In the following, we first consider the energy-splitting STAR beamforming design under the independent phase-shift model, where a JO-based optimization approach is introduced. Then, we consider the more challenging energy-splitting STAR beamforming design under the coupled phase-shift model, in which an effective element-wise optimization approach is introduced. Note that the effectiveness of the beamforming design is closely tied to the accuracy of channel estimation. In comparison to conventional RISs (An et al., 2022), the channel estimation process for STAR-RISs involves estimating both the transmission and the reflection channels. Additionally, the channel estimation results can be significantly influenced by the operating protocols used by STAR-RISs (Wu CY et al., 2022). For the following beamforming design, we assume that the channels have been estimated through the approaches proposed by Wu CY et al. (2022).

4.2.1 JO-based STAR beamforming design under the independent phase-shift model

For energy-splitting STAR-RIS-assisted communication systems with the independent phase-shift model, the coupling between STAR beamforming exists only in the energy conservation constraint, which is or can be transformed into a convex constraint. Then, the main challenge lies in the coupling between the newly introduced STAR beamforming and the existing variables, e.g., base station (BS) beamforming and power allocation. As investigated in many RIS works, one straightforward way is to apply AO, which decomposes the original joint BS and RIS beamforming problem into two subproblems and alternately optimizes one beamforming with the other being fixed. The advantage of AO is that compared to the original problem, the two decomposed subproblems are less complicated and easy to resolve. However, the main drawbacks of AO are that its convergence and optimality might not be guaranteed (Yu et al., 2021). To address this issue, Mu et al. (2022) proposed an efficient JO-based beamforming approach for minimizing the BS power consumption in a STAR-RIS-assisted multiple-input single-output (MISO) multi-user communication system. As shown in Fig. 3, the BS beamforming and STAR beamforming in the proposed JO-based approach can be simultaneously optimized in each iteration, thus guaranteeing convergence and resulting in a locally optimal solution.

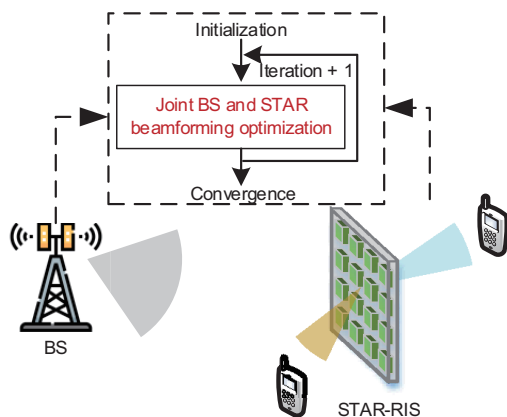


Fig. 3 Joint optimization based STAR beamforming design

4.2.2 Element-wise optimization based STAR beamforming design under the coupled phase-shift model

For energy splitting STAR-RIS assisted communication systems with the coupled phase-shift model, the STAR beamforming design becomes quite challenging. This is because, for each STAR element, T&R phase shifts are coupled, which leads to non-convex constraints. To overcome this obstacle, Liu YW et al. (2022b) proposed an efficient element-wise optimization based STAR beamforming approach for minimizing the BS power consumption in a STAR-RIS assisted single-input single-output (SISO) two-user communication system. As shown in Fig. 4, the salient feature is that the phase-shift and amplitude coefficients of each STAR element are optimized one by one, i.e., in an element-wise manner. The advantage is that the computational complexity only linearly scales with the number of STAR elements, which renders it promising to be used in practice since the size of STAR-RISs is usually large. Nevertheless, the limitations of the proposed element-wise optimization based approach are that it can be used only in the two-user communication system and there is no knowledge of the optimality of the obtained solution.

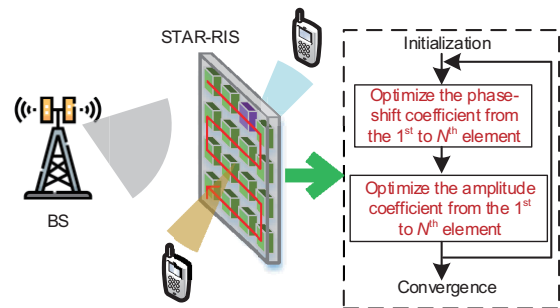


Fig. 4 Element-wise optimization based STAR beamforming design

4.3 Generalized optimization framework for STAR beamforming design

Having introduced two representative STAR beamforming approaches, we can observe that they still have the following two common drawbacks: (1) These approaches are in general developed for specific objective functions (e.g., power consumption and sum rate) and/or communication scenarios (e.g., MISO, SISO, and two-user cases). Their applicability to other use cases is limited. (2) The convergence

of these approaches and the optimality of their solutions might not be always stable, especially for the coupled phase-shift case.

To fill in this gap, Wang ZL et al. (2023a) proposed a generalized penalty-based optimization framework for STAR beamforming. The beauty of the proposed framework can be summarized as follows:

High compatibility: The applications of the proposed framework are not restricted by objective functions and communication scenarios. More importantly, it can be regarded as an “add-on” approach to state-of-the-art approaches, thus being applicable to diversified STAR-RIS-assisted communication scenarios.

Provable optimality: The solutions obtained by the proposed framework can be proved to be Karush–Kuhn–Tucker (KKT) optimal under some mild conditions, such as the Robinson condition or the Mangasarian–Fromovitz constraint qualification (MFCQ) condition.

Guaranteed convergence: The convergence of the proposed framework can always be achieved regardless of the optimality of the obtained solutions.

The characteristics of the JO-based approach, the element-wise optimization based approach, and the generalized optimization framework for STAR beamforming design are summarized in Table 2. The simulation codes for these approaches are available at <https://github.com/STAR-Yuanwei-Liu/Optimization-for-wireless-communications>.

To further illustrate the efficacy of the generalized optimization framework in addressing STAR beamforming design problems, we present a case study involving a spectral efficiency maximization problem (Fig. 5). As illustrated in Fig. 5a, the phase-shift differences between ϕ_m^r and ϕ_m^t for each element eventually converge to either $\frac{\pi}{2}$ or $\frac{3\pi}{2}$, thereby satisfying the coupled phase-shift constraint. Furthermore, as evidenced in Fig. 5b, the proposed framework achieves performance comparable to that of the independent phase-shift STAR-RIS approach and outperforms the baseline scheme based on alternating optimization (Niu and Liang, 2023), which confirms the optimality of the proposed framework.

Note that the design of T&R beamforming can also be influenced by the rotation and location of STAR-RIS. Previous research has demonstrated that

optimizing the rotation and location of conventional RISs can significantly improve communication performance (Cheng et al., 2022). However, the optimization of rotation and location for conventional RISs is limited by hardware constraints, requiring the BS and the user to be situated on the same side of the surface. By leveraging STAR-RISs, this limitation is overcome, as the BS and user can be located on different sides of the surface. However, a new challenge arises when optimizing the rotation and location of STAR-RISs, which is referred to as transmission–reflection switching. For instance, a user initially relying on reflection may transition to a transmission user after rotating STAR-RIS. How to effectively address or leverage this transmission–reflection switching remains an open research question.

5 STAR-RIS-enabled promising wireless technologies toward 6G

In this section, we continue to discuss recent advances in applying STAR-RIS to improve the performance of other 6G technologies, including NOMA, integrated sensing and communication (ISAC), terahertz (THz) communications, PLS, and near-field communications. Numerical results are provided to demonstrate the great potential of STAR-RISs in 6G.

5.1 Non-orthogonal multiple access

RISs are capable of enhancing the performance of NOMA networks by providing distinct channel conditions for NOMA users (Liu YW et al., 2022a). Nevertheless, for RIS-aided NOMA networks, all the users have to be set in the reflection space. As a result, the channel conditions of users in the reflected space are generally similar, which renders it not easy to fully exploit the benefits of NOMA. STAR-RISs can properly solve this issue. Particularly, a pair of users at the transmission and the reflection sides can be grouped to facilitate NOMA. As a result, asymmetric channel conditions among transmitted and reflected users can be realized and thus high-performance gain over orthogonal multiple access (OMA) can be achieved by adopting flexible resource allocation.

Zuo et al. (2023) first proposed the framework for applying NOMA to STAR-RIS networks. The cluster-based beamforming design was adopted in

Table 2 Summary of beamforming algorithms for STAR-RISs

Algorithm	Exploited method	Suitable scenario	Optimality
Joint optimization based algorithm (Mu et al., 2022)	Successive convex approximation, semidefinite relaxation	Independent phase shifts, power minimization	Locally optimal solution
Element-wise optimization based algorithm (Liu YW et al., 2022b)	Successive convex approximation, block coordinate descent	Coupled phase shifts, power minimization, single-antenna BS, two users	–
General optimization framework (Wang ZL et al., 2023a)	Penalty dual decomposition	Independent and coupled phase shifts, any objective function	KKT optimal solution under mild conditions

BS, base station; KKT, Karush–Kuhn–Tucker

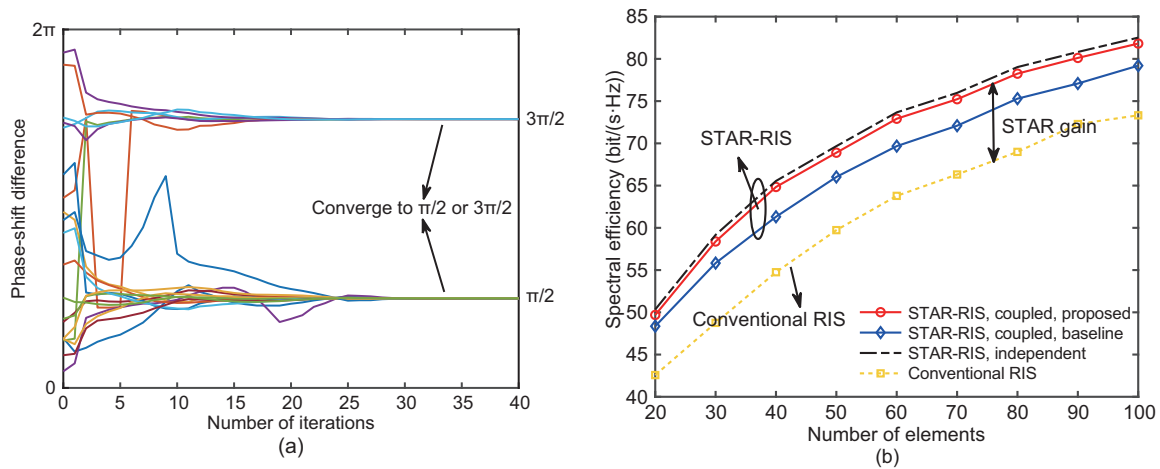


Fig. 5 Performance of the proposed generalized penalty based optimization framework for maximizing the system spectral efficiency: (a) convergence performance of the phase-shift difference between the transmission and reflection coefficients of each element of STAR-RIS; (b) performance of the proposed framework in terms of spectral efficiency maximization, where the phrase “STAR-RIS, coupled, baseline” refers to the alternating optimization scheme (Niu and Liang, 2023). The detailed simulation setup can be found in Wang ZL et al. (2023a)

the proposed framework by jointly optimizing the decoding order, power allocation coefficients, and beamforming at both the BS side and the STAR-RIS side. The advantages of the proposed STAR-RIS-NOMA framework, compared to RIS-NOMA, were illustrated via simulation results. There are still several research opportunities and challenges in STAR-RIS-NOMA design based on this proposed framework. For example, the appearance of STAR-RIS makes the joint user assignment and beamforming design challenging; how to efficiently align and allocate different NOMA users into suitable beams and to provide proper optimization for mitigating intra-cluster and inter-cluster interference requires further study. Another unsolved problem is facilitating coupled phase-shift design in the proposed STAR-RIS-NOMA framework. Note that with the aid of the proposed general optimization framework in Wang

ZL et al. (2023a), this issue can be solved in a proper way.

5.2 Integrated sensing and communications

ISAC is a technology that serves the dual purpose of sensing and communication through a shared hardware platform and waveform. Typically, ISAC relies on the LOS channel to facilitate the sensing function between the ISAC transceiver and the desired targets. Carrying out target sensing without LOS links presents a significant challenge. However, RIS can overcome this issue by establishing virtual LOS links between RIS and the desired targets. This capability enhances the sensing coverage and resolution. Compared to conventional reflecting-only RIS, STAR-RIS offers several advantages for ISAC. First, as shown in Fig. 6a, STAR-RIS can enable full-space sensing and communication, which is a

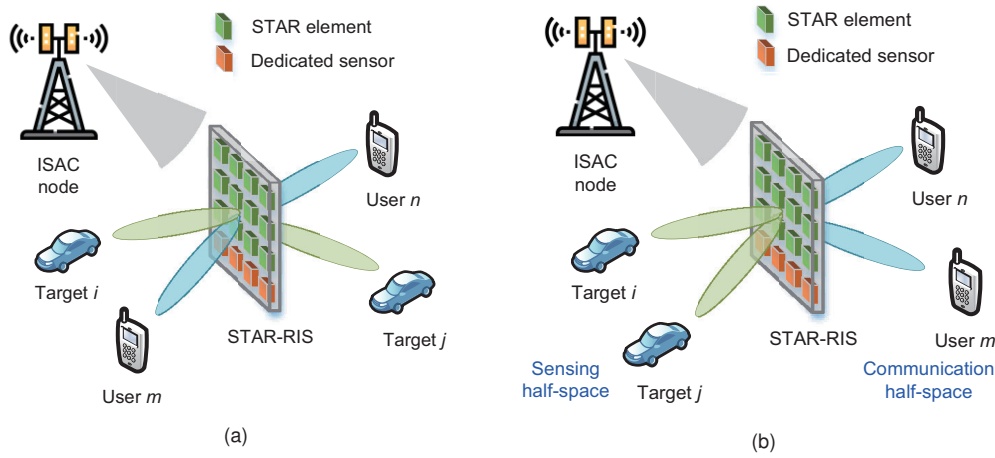


Fig. 6 Illustration of the STAR-RIS-ISAC system for full-space (a) and half-space (b) sensing and communication (ISAC, integrated sensing and communication)

straightforward benefit. Second, STAR-RIS opens up new possibilities for carrying out sensing and communication in physically separated spaces using a shared hardware platform and waveform (Wang ZL et al., 2023c), as illustrated in Fig. 6b. Specifically, STAR-RIS can divide the full space into two halves: sensing half-space and communication half-space. The ISAC node transmits a joint signal, which is then split by STAR-RIS into two separate signals, for carrying out sensing and communication in the respective half-spaces.

Nevertheless, STAR-RIS poses new challenges. The T&R properties of STAR-RIS can result in mixed echo signals from the two half-spaces in the link between STAR-RIS and the ISAC node, making it difficult to identify the signals. Additionally, the multiple hops of the echo signal and energy splitting at STAR-RIS can result in a lower sensing SNR, leading to low sensing accuracy. To address these challenges, Wang ZL et al. (2023c) proposed to install dedicated sensing elements at STAR-RIS, which is referred to as the sensing-at-STAR-RIS structure. Target sensing is carried out at these dedicated sensing elements instead of at the ISAC node. Such a structure avoids mixing of the echo signals in a single link and establishes a one-hop echo link, resulting in improved sensing accuracy.

In Fig. 7, we evaluate the effectiveness of the sensing-at-STAR-RIS structure, where the entire space is divided into the sensing half-space and the communication half-space by STAR-RIS. The root Cramér–Rao bound (CRB) achieved for tar-

get sensing under varying communication signal-to-interference-plus-noise ratio (SINR) requirements is depicted in Fig. 7a. CRB represents a fundamental lower bound for the mean-squared error (MSE) achievable by any unbiased estimator. It is evident from the results that both independent and coupled phase-shift STAR-RISs exhibit superior performance compared to the conventional RIS in the ISAC system. The significance of STAR-RIS in this context is further supported by practical estimation outcomes, as presented in Fig. 7b. Specifically, the estimation results obtained by STAR-RIS exhibit a much smaller bright region than those obtained by the conventional RIS, thereby indicating a higher level of estimation accuracy.

5.3 THz communications

The vast bandwidth resources available in the THz band, which can reach tens of gigahertz (GHz), make THz communication a promising technique to support peak data rates of terabits per second in 6G. However, THz signals experience significant propagation loss and high susceptibility to blockage due to their very high frequency. RIS can mitigate these issues by establishing additional LOS paths, but their reflecting-only property limits design flexibility. In contrast, the 360° coverage capability of STAR-RIS technology makes it easier to address signal blockage. Furthermore, STAR-RIS can bridge physically separated spaces, such as indoor and outdoor areas, which is not possible with reflecting-only RIS.

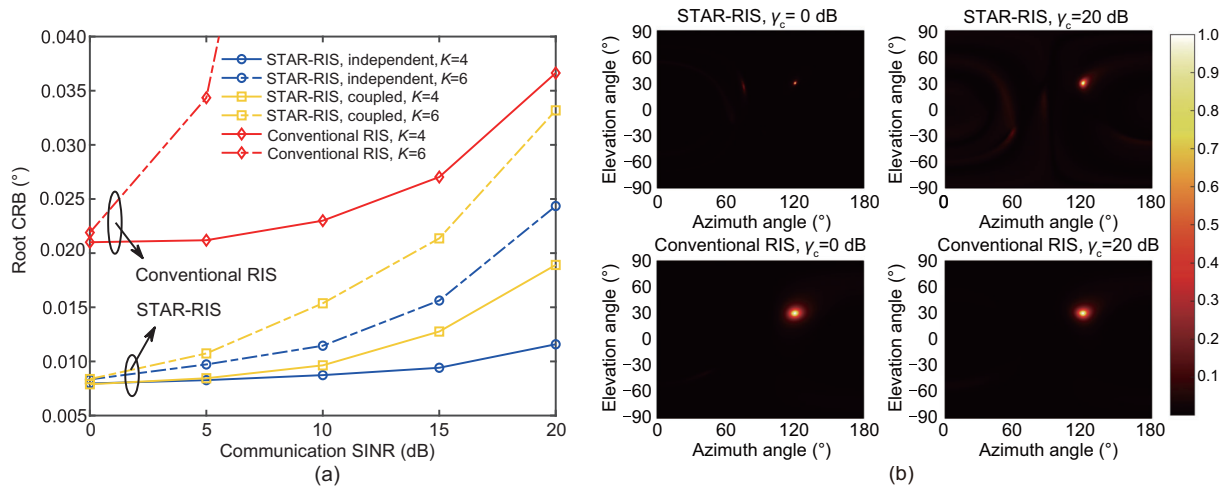


Fig. 7 Performance of the STAR-RIS-ISAC system with the sensing-at-STAR-RIS structure: (a) achieved root CRB of target sensing under different communication SINR requirements, γ_c , where K denotes the number of communication users; (b) sensing results obtained by MLE, where the brightest part represents the estimated location of the target. The detailed simulation setup can be found in Wang ZL et al. (2023c). CRB: Cramér–Rao bound; ISAC, integrated sensing and communication; MLE, maximum likelihood estimation; SINR, signal-to-interference-plus-noise ratio

To effectively exploit the bandwidth resources available in the THz band, it is imperative to consider the wideband STAR-RIS-THz system. However, the wireless channel can be significantly frequency-dependent, owing to the large array of STAR-RIS and the very high carrier frequency used. This can induce a beam split effect, resulting in an array gain loss in the wideband STAR-RIS-THz system. The beam split effect can be directly caused by either phase-shifter (PS) based analog beamforming at BS (Gao et al., 2021) or passive beamforming at STAR-RIS (Yan et al., 2023) due to their frequency-independent property. Recent research contributions have demonstrated that the beam split effect at RIS depends on the size and shape of RIS (Yan et al., 2023). Therefore, it is possible that the two sides of STAR-RIS experience varying degrees of the beam split effect, especially when applying the mode-switching protocol. To mitigate the beam split effect in the wideband STAR-RIS-THz system, Wang ZL et al. (2023b) introduced a time-delay (TD) network into the conventional hybrid beamforming structure. Since the TD is frequency-dependent, such a TD-based hybrid beamforming can effectively reduce the beam split effect.

The performances of the wideband STAR-RIS-THz system in terms of maximum spectral efficiency and maximum energy efficiency via different beam-

forming structures are presented in Fig. 8. The results indicate a substantial performance improvement achieved by STAR-RIS over the conventional RIS in both cases. As depicted in Fig. 8a, the conventional hybrid beamforming structure leads to a significant spectral efficiency loss due to the beam split effect. The introduction of a TD network enables the achievement of comparable spectral efficiency to that achieved through fully digital beamforming. The relatively low power consumption of the TD network helps enhance the energy efficiency of the wideband STAR-RIS THz system, as depicted in Fig. 8b.

5.4 Physical layer security

Compared to the reflecting-only RIS, the appearance of STAR-RIS provides extended coverage from 180° to 360° . Nevertheless, such changes inevitably result in full-space wiretapping. As a result, the PLS issue needs to be re-investigated. As the basic model of STAR-RIS consists of both transmitted and reflected users, we can broadly classify the PLS problems into a couple of categories, namely external eavesdropper case and internal eavesdropper case: (1) For the external eavesdropper case, as shown in Fig. 9a, a few eavesdroppers try to eavesdrop on both transmitted and reflected users. Zhang Z et al. (2023) proposed a secure beamforming

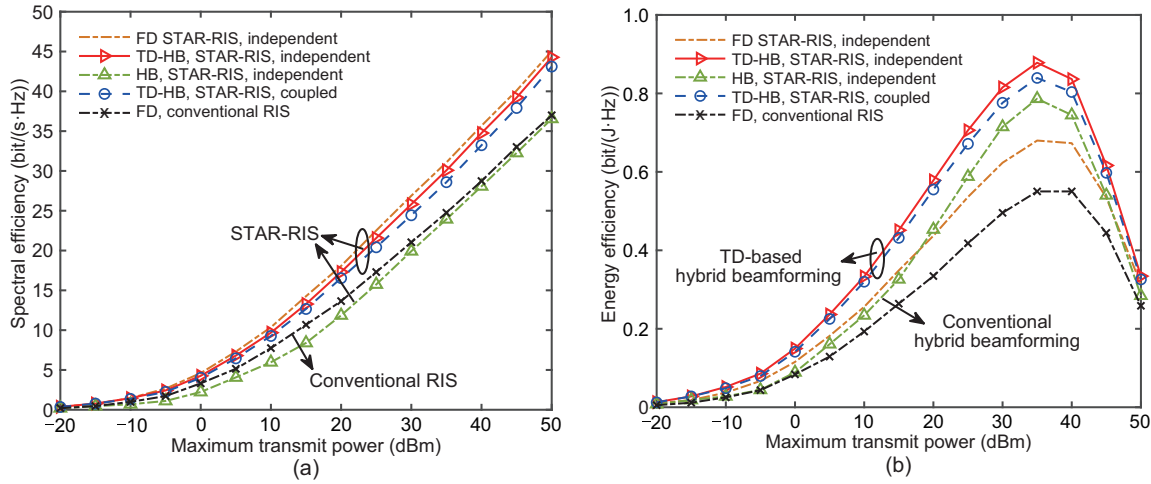


Fig. 8 Performance of the wideband STAR-RIS-THz system achieved by different beamforming structures in terms of maximum spectral efficiency (a) and maximum energy efficiency (b). FD, TD-HB, and HB represent fully digital beamforming, time delay based hybrid beamforming, and conventional hybrid beamforming, respectively. The detailed simulation setup can be found in Wang ZL et al. (2023b)

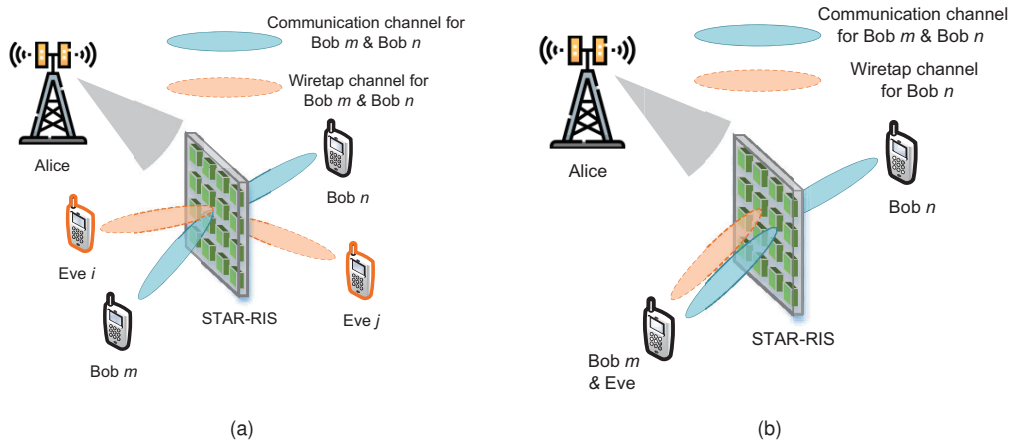


Fig. 9 Illustration of physical layer security of STAR-RIS with external (a) or internal (b) eavesdropper

design for the coupled-phase-shift STAR-RIS networks by maximizing the security capacity. They demonstrated the security performance advantages of their proposed design over conventional RIS, by using only a few discrete phase-shifters. (2) For the internal eavesdropper case, due to the multi-user nature of STAR-RIS, internal eavesdropping may exist. Particularly, for a pair of transmitted and reflected users, one transmitted/reflected user may wiretap the other reflected/transmitted user’s confidential information, which is regarded as STAR-RIS networks in the presence of an untrusted user, as shown in Fig. 9b. Such cases pose new challenges for the PLS in STAR-RIS networks and therefore deserve further research efforts. How to invoke artificial noise

to further enhance the PLS for both external and internal eavesdropping cases is another promising direction to carry out research.

5.5 Near-field communications

To meet the demanding criteria for spectral efficiency, energy efficiency, latency, coverage, and other performance metrics in 6G, STAR-RISs follow two major developmental trends. The first trend involves the utilization of extremely large surfaces, while the second focuses on the use of high-frequency bands, such as millimeter-wave (mmWave) and THz bands. These two trends will inevitably cause the near-field effect. Particularly, the Rayleigh distance, which is

known as the boundary between the near field and the far field, is proportional to the aperture of the antenna array and the operating frequency. An illustrative example of the challenges posed by the near-field effect can be observed in the case of a surface with a dimension of 0.5 m operating at a frequency of 60 GHz. In this scenario, the near-field region can extend up to 100 m, signifying that the impact of the near-field effect cannot be disregarded.

However, the near-field region has distinct characteristics that are significantly different from those of the far-field region. To study the performance of STAR-RISs in near-field communication, Xu JQ et al. (2023b) proposed a Green function method based near-field channel model for STAR-RISs. Exploiting the Green function, the near-field channel gains of both patch-array-based and metasurface-based STAR-RISs are derived. More importantly, in contrast to the far-field LoS channel, the near-field LoS channel potentially has a high number of DoFs. This is because the near-field STAR-RIS cascaded channels have non-linear phase shift. In addition, in comparison to the conventional reflecting-only RIS, which features a fixed near-field region due to the fixed size and shape of the surface, STAR-RIS offers a novel approach to dynamically adjust the near-field region through the allocation of distinct elements for T&R. Hence, it is imperative to consider the impact of the near-field effect in the development of advanced STAR-RIS-aided systems.

6 Conclusions and future directions

This article provided a comprehensive overview of STAR-RISs for future 6G. Particularly, we began by identifying three different models as the fundamentals of STAR-RISs. We then summarized three representative categorizing approaches of STAR-RISs. Moreover, we investigated both independent and coupled phase-shift beamforming designs of STAR-RISs. We demonstrated that our proposed generalized optimization framework can be exploited as an “add-on” approach to achieve near-optimal performance. This is followed by the discussion of several promising applications of STAR-RISs in future 6G. There are still numerous open research directions in this area, some of which are listed as follows:

1. Caching at STAR-RISs. Recently, the de-

sign of multi-functional STAR-RISs has become a promising research direction. In addition to the aforementioned active STAR-RISs and ISAC-STAR-RISs, caching at STAR-RISs can be a promising attempt. Particularly, in contrast to conventional edge caching, caching at STAR-RISs is capable of improving network efficiency and achieving enhanced diversity. By caching frequently accessed information at STAR-RISs, information can be quickly retrieved by nearby users without having to travel all the way to the central server or edge nodes. STAR-RISs adaptively transmit signals based on network caching information; by doing so, information from both BS and STAR-RIS may be obtained at the receivers to achieve enhanced diversity. Nevertheless, the design of caching at STAR-RIS requires additional active elements/relays to be deployed on STAR-RIS, which brings about increased hardware costs. Moreover, as the caching processes consist of both information pushing and information delivery phases, proposing efficient protocols to coordinate a proper design for different phases among a BS, active elements/relays, and STAR-RISs is a non-trivial problem, which requires further research efforts.

2. Stochastic geometry for STAR-RIS-assisted networks. Stochastic geometry is recognized as a powerful mathematical tool to capture the spatial randomness of wireless networks. It can be used to evaluate the average performance of one particular area. For example, we can invoke stochastic geometry to evaluate how many STAR-RISs we need in a cafe, a campus, or even in a city. For the conventional reflecting-only or transmitting-only RIS, we may need to use Poisson hardcore processes to capture the characteristics of spatial deployment. This is because only half-space points can be active. This assumption is not technically friendly for stochastic geometry. Such an issue can be fully avoided by a STAR-RIS due to its nature of providing 360° full-space coverage. As a result, various point processes can be invoked to provide spatial analysis, which can significantly simplify the mathematical analysis. This characteristic brings in new research opportunities for STAR-RIS networks. Of course, advanced and suitable point processes need to be further investigated, for providing accurate and efficient analysis.

3. Machine learning empowered STAR-RIS-assisted communications. Although STAR-RISs provide enhanced DoFs, the resulting communication

design problems are generally complicated and challenging. To this end, advanced machine learning tools come to the rescue, which is efficient in dynamic user scheduling, long-term resource allocation, large-dimensional STAR beamforming design, and CSI estimation in STAR-RIS-assisted communications. More importantly, practical communication designs of STAR-RISs may involve multiple objectives (e.g., power consumption, data rate, and latency). In this case, machine learning tools can be used to derive the Pareto-optimal solution and thus strike a good trade-off among different performance metrics, which constitutes an interesting future research topic.

Contributors

Yuanwei LIU (lead), Jiaqi XU, Zhaolin WANG, and Xidong MU drafted the paper. Jianhua ZHANG and Ping ZHANG revised and finalized the paper.

Compliance with ethics guidelines

Jianhua ZHANG and Ping ZHANG are executive associate editor-in-chief and associate editor-in-chief of *Frontiers of Information Technology & Electronic Engineering* respectively, and they were not involved with the peer review process of this paper. All the authors declare that they have no conflict of interest.

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