A Survey on STAR-RIS: Use Cases, Recent Advances, and Future Research Challenges

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Abstract

The recent development of metasurfaces, which may enable several use cases by modifying the propagation environment, is anticipated to have a substantial effect on the performance of 6G wireless communications. Metasurface elements can produce essentially passive sub-wavelength scattering to enable a smart radio environment. STAR-RIS, which refers to reconfigurable intelligent surfaces (RIS) that can transmit and reflect concurrently (STAR), is gaining popularity. In contrast to the widely studied RIS, which can only reflect the wireless signal and serve users on the same side as the transmitter, the STAR-RIS can both reflect and refract (transmit), enabling 360-degree wireless coverage, thus serving users on both sides of the transmitter. This paper presents a comprehensive review of the STAR-RIS, with a focus on the most recent schemes for diverse use cases in 6G networks, resource allocation, and performance evaluation.

We begin by laying the foundation for RIS (passive, active, STAR-RIS), and then discuss the STAR-RIS protocols, advantages, and applications. In addition, we categorize the approaches within the domain of use scenarios, which includes increasing coverage, enhancing physical layer security (PLS), maximizing sum rate, improving energy efficiency (EE), and reducing interference. Next, we will discuss the various strategies for resource allocation and measures for performance evaluation. We aimed to elaborate, compare, and evaluate the literature in terms of setup, channel characteristics, methodology, and objectives. In conclusion, we examine the open research problems and potential future prospects in this field.

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***Index Terms*—Reconfigurable intelligent surfaces, STAR-RIS, active RIS, intelligent omni-surfaces, smart radio environment.**

I. INTRODUCTION

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Research on beyond 5G (B5G) and the sixth-generation (6G) wireless communication networks is underway in anticipation of the stricter criteria that these generations are likely to impose, such as energy-efficiency and high spectrum, microsecond latency, and full-dimensional network coverage [1], [2]. Improved communication methods, such as ultra-massive multiple-input multiple-output (UM-MIMO), ultra-dense networks (UDN), and terahertz (THz) communication, have been explored to achieve these aims. However, expanding antennas/base stations (BS) and using extremely high carrier frequencies would result in excessive energy consumption and hardware expenses due to the increased need for power-hungry and expensive RF chains for signal conversion. Multiple active components running at high frequencies may not necessarily be beneficial in wireless networks due to inter-user/cell interference, pilot contamination, and severe hardware limits. Therefore, there is an immediate need for the creation of novel techniques/approaches and technologies for wireless communication systems to overcome the aforementioned constraints.

Metasurfaces and their production processes are rapidly advancing, making reconfigurable intelligent surfaces (RIS) and their many forms promising technology for 6G wireless networks [3], [4]. RIS is typically 2D structures made up of many inexpensively reconfigurable elements. By integrating a smart controller into the RIS, it is possible to change the phase and amplitude of these reconfigurable elements in useful ways, reconfiguring the propagation of incident wireless signals and creating a smart radio environment (SRE) [3]. Since RISs don't employ RF chains, they are more economical and less harmful to the environment than the standard family of multi-antenna and relaying technologies [5]. Because of its many benefits, RISs have been the subject of much study in both the industry and academia. These studies have focused on a wide range of topics, from the energy-efficient communication design [6] to the use of artificial intelligence in implementation [7] to the elimination of barriers to mmWave and terahertz (THz) transmissions [8].

Industry and academia have done considerable theoretical and field testing, and regional standards developing bodies (SDOs) have started standardization. At the October 2020 radio communication sector summit hosted by the International Telecommunication Union (ITU), it was emphasized

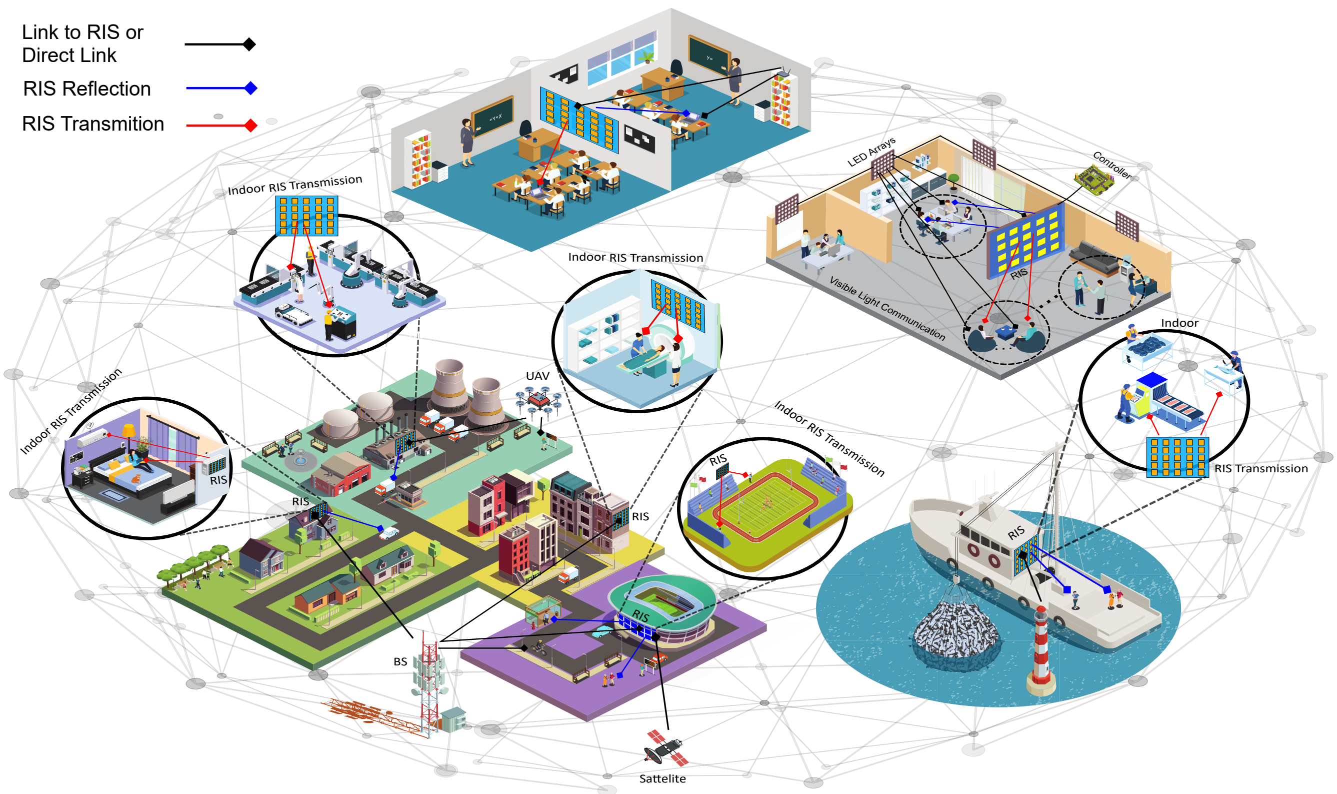

Fig. 1: Application scenarios of STAR-RIS networks

how important RIS is to the physical layer of future generation networks [9] The 3rd Generation Partnership Project (3GPP) began receiving RIS suggestions during the conference in March 2021 [10], and more industrial stakeholders joined to promote the RIS as it became a crucial part of future wireless networks [11]. European Telecommunications Standards Institute (ETSI), in June 2021, also set up a new RIS industry specification group [12]. Moreover, the China Communications Standards Association (CCSA), an official SDO developing normative standards, has authorized a request to establish a research item on RIS [13], with a technical report expected in 2022.

However, the consensus amongst published research is that RIS can at most only reflect the incident signal. Therefore, when the transmitter and receiver are on opposite sides of the RIS, the communication system cannot make use of the RIS. Researchers have proposed employing STAR-RIS, which stands for simultaneously transmitting and reflecting RIS (STAR-RIS), to overcome this limitation [14]. Unlike traditional passive RIS, each STAR-RIS element can simultaneously refract and reflect the incident signal, which eliminates the need to limit deployment to certain geographic areas and allows for full-space coverage, hence also known as intelligent omni-surfaces (IOS) as shown in Fig. 1. When it comes to improving the efficiency of wireless networks, STAR-RIS can provide SRE with more versatility thanks to the ability to tune transmission and reflection coefficients (TARCs).

A. *Motivation and Contribution*

Previous research articles have provided in-depth tutorials or surveys relevant to RIS from distinct viewpoints as shown in Table I. However, the subject of the present paper is quite distinct. Particularly, the authors of [15] examined how RISs can be utilized as reflectors and compared them to backscatter communications and reflecting relays. In contrast, the focus of the paper [17] was on the emerging use cases of RISs. Smart cities idea is investigating through RIS in [18] and emphasizing possible benefits of RIS implementation along with exciting research prospects. The authors of [19] and [20] researched channel characteristics and address main challenges for RIS-assisted wireless communications.The authors of [21] provided useful scenarios, and important performance measures along with new signal model, hardware architecture, and competitive advantages while in [22] possible future use cases, deployment techniques, and design considerations for RIS devices in underground IoT, underwater IoT, Industry 4.0 were examined and explored future research challenges. When analyzing the difficulty of incorporating RISs into wireless networks, the authors of [23] mentioned three issues: channel state information acquisition, low-complexity phase shift optimization, and passive information transfer. The authors of the article [24] analyzed machine learning and resource allocation algorithms for RIS-assisted wireless communications. In [25], they gave a tutorial on RIS-enhanced wireless sensing and localization. In [26], the authors investigated RIS-enhanced wireless

TABLE I: Comparison of STAR-RIS related survey papers

RIS Types	Ref	Year	Publisher	Main Contributions
Reflective RIS	[15]	2019	Journal of Communications and Information Networks	RIS performance gains, hardware implementations, and application are discussed and compared with backscatter communications and reflecting relays.
	[16]	2019	EURASIP Journal on Wireless Communications and Networking	Presented the concept of RIS as a means to facilitate SRE, delved into the many features of RIS, and surveyed the state of the art in SRE studies.
	[3]	2020	IEEE Journal on Selected Areas in Communications	This article provided a communication-theoretic overview of technologies necessary to support RIS-enabled wireless networks and discussed the most significant research issues in this domain.
	[17]	2020	IEEE Communications Surveys & Tutorials	Presented a literature review on recent applications and design aspects of RISs in wireless networks, and discussed emerging use cases of RISs
	[18]	2020	IEEE Open Journal of the Communications Society	Presented a smart cities idea for future communication networks by investigating new application scenarios and use cases while emphasizing possible benefits of RIS implementation along with exciting research prospects.
	[19]	2020	IEEE Transactions on Cognitive Communications and Networking	Presented different hardware implementations to achieve SRE, analyzed the channel characteristics, and other challenges and opportunities in RIS-aided wireless networks
	[20]	2021	IEEE Transactions on Communications	A tutorial on RIS-enhanced wireless communications was offered to address several main technical challenges from a communication point of view.
	[21]	2021	Journal of Communications and Information Networks	An overview of IRS-aided wireless communications was provided, including the vision, useful scenarios, and important performance measures. The new signal model, hardware architecture, and competitive advantages are then introduced. RIS's possible applications are also examined, as are RIS's future challenges and deployment.
	[22]	2021	IEEE Access	Possible future use cases, deployment techniques, and design considerations for RIS devices in underground IoT, underwater IoT, Industry 4.0, and emergency networks were examined. Provide a potential hardware architecture and evaluate the anticipated signal quality improvements as the number of RIS elements increases, as well as future research challenges.
	[23]	2021	IEEE Wireless Communications	The state-of-the-art solutions to three physical layer challenges after integrating RIS into wireless networks are presented. These include channel state information (CSI) acquisition, passive information transfer, and low-complexity phase shift optimization.
	[24]	2021	IEEE Communications Surveys & Tutorials	Provided a survey on the performance analysis, resource management, as well as machine learning techniques for RIS-aided wireless communications and outlined potential applications
	[25]	2022	Proceedings of the IEEE	Presented the prototype together with the experimental outcomes, and gave a tutorial on RIS-aided sensing and localization to tackle the main technical challenges.
	[26]	2022	IEEE Signal Processing Magazine	An overview of the RIS fundamentals and up-to-date research efforts from a signal processing standpoint, including communication, localization, and sensing
	[27]	2022	IEEE Communications Surveys & Tutorials	Provided a comprehensive survey on RIS-aided wireless communications, with an emphasis on the promising solutions to tackle practical design issues of channel estimation and beamforming design
	[28]	2022	ArXiv	Discussed indoor VLC systems with RIS technology, especially how RIS overcome line-of-sight (LoS) blockage and device orientation issues in VLC systems
STAR-RIS	[29]	2022	IEEE Communications Magazine	Introduced the notion of intelligent omni-surface, which enables full-dimensional communications by servicing users on both sides of the surface. A new hybrid beamforming approach is proposed for wireless communications based on IOS.
	[30]	2022	IEEE Communications Surveys and & Tutorials	A comprehensive IOS review is conducted considering future cellular network applications and design principles, which include beamforming, channel modeling, experimental implementation, and measurements.
	Our Survey			This paper reviews STAR-RIS, focusing on recent approaches for 6G networks, resource allocation, and performance evaluation. After outlining STAR-RIS preliminaries, protocols, benefits, and applications, we classify the techniques according to use case scenarios, such as boosting coverage, improving PLS, maximising sum rate, enhancing EE, and reducing interference. Followed by the various resource allocation strategies and performance evaluation metrics. Our goal was to further explain, contrast, and assess the literature in terms of setup, channel characteristics, methodology, and objectives. In the end, we look at the open research questions and potential directions for this discipline.

Ref-Reference

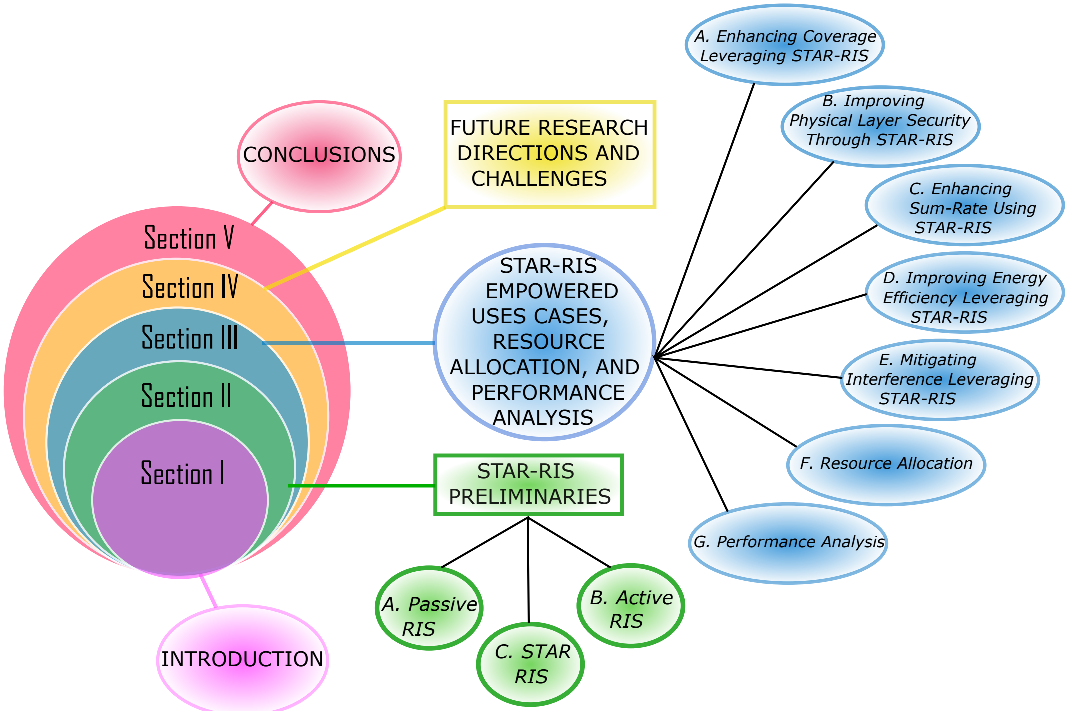

Fig. 2: Taxonomy of STAR-RIS comprises of 5 Sections

communications from a signal processing perspective,while [27] examined channel estimation approaches. In [28], the authors focused primarily on the applications of RISs in visible light communication (VLC) systems.

Latest papers [29], [30] have primarily focused on IOS, as opposed to the aforementioned works, which focuses on reflecting surfaces exclusively. In [29], the authors introduced the notion of intelligent omni-surface, which enables full-dimensional communications by servicing users on both sides of the surface. A new hybrid beamforming approach is proposed for wireless communications based on IOS. The authors of [30] conducted a comprehensive IOS review considering future cellular network applications and design principles, which include beamforming, channel modeling, experimental implementation, and measurements. This study presents the first full overview of a more general category of RIS, STAR-RIS, and their applications in wireless networking.

Following are our review's key contributions:

- We built on the STAR-RIS existing literature and systematized an up-to-date complete survey of state-of-the-art schemes enabling a smart radio environment. For deeper comprehension, we highlight the fundamentals of several RIS kinds, such as passive, active, and STAR-RIS. Additionally, we examine the STAR-RIS operating protocols before going over its various B5G and 6G applications and their benefits.
- We organize all possible schemes that harness STAR-RIS, based on use cases, resource allocation, and performance assessment. Additionally, we provide an overview and further divide the STAR-RIS use cases category into sub-categories based on coverage, PLS, sum rate, EE, and interference. Then, we investigate the techniques used for STAR-RIS resource allocation and performance evaluation.
- Furthermore, at the conclusion of each subcategory, summary tables are provided so that the reader can gain a better understanding of the rational association between the various schemes, taking into account crucial factors such as system model in different scenarios, direct, reflective, and refractive channel characteristics, and proposed solutions.
- We list some of the open problems and interesting new directions for future study in this dynamic field. This survey, we believe, can benefit researchers of all levels, from novice to seasoned. As a result, new opportunities for significant advancements in the underlying field can be explored.

The remaining sections of the survey are arranged as follows. Section II provides an explanation of RIS and its various forms, such as passive RIS, active RIS, and STAR-RIS. The advantages, applications, and operational procedures of STAR-RIS are also covered. We categorize the approaches in Section III in accordance with the use case scenarios, which include expanding coverage more effectively, bolstering PLS, maximizing sum rate, improving EE, and reducing interference. We'll then discuss various methods for allocating resources and measuring performance. We list some open issues and suggested future research opportunities in Section IV. Section V of the article wraps up the STAR-RIS review. Taxonomy of our survey is shown in Fig. 2 and, the Table II includes a list of all abbreviations associated to the topic.

II. STAR-RIS PRELIMINARIES

Reconfigurable Intelligent Surfaces (RIS) are also known as intelligent reflecting surfaces (IRS) and large intelligent metasurfaces (LIM) [31] [32]. By reconfiguring the propagation environment of electromagnetic (EM) waves, RIS is expected to reduce wireless network power consumption and improve system efficiency. An RIS can be regarded of as a programmable cluster with many scatterers, each of which comprises of many subwavelength and conductive parts. Like a signal processing system, a RIS has inputs, outputs, and many parallel subsystems with reconfigurable transfer functions. According to their research, there are three different types of RIS: passive RIS, active RIS, and Simultaneous Transmission and Reflection (STAR) RIS as shown in Fig. 3.

A. Passive RIS

EM materials are used to construct the passive RIS. Due to their low cost, RIS can be integrated into several compositions, including building facades, reconfigurable walls, high-altitude platforms, roadside billboards, highway polls, glasses, and pedestrian clothing [24]. The RIS can alter the environment for wireless transmission by accounting for long-distance power losses. BS and MU can generate virtual LoS lines by passively reflecting the received signals. Unlike typical relay systems such as AF and DF [33], Instead of needing a power amplifier, RIS can modify the input signal by controlling the phase shift of each reflector. This means that deploying RIS is much more eco-friendly and efficient than deploying conventional AF and DF Relay systems. Due to the fact that EM waves are only reflected, RIS also allows full duplex and full-band transmission.

Although passive RIS provides a reliable reflection link for signal transmission alongside the direct link. This reflection link always has a double fading effect, which means that signals received over this link have twice as much large-scale fading. In many situations where the direct link is robust, passive RISs can only contribute a small amount of capacity [34]. In contrast to a direct link, a transmitter-RIS-receiver link's equivalent path loss is the product (as opposed to the sum of path losses) [34]. Furthermore, signals from the comparatively long reflection link affects more than those from the shorter direct link in terms of power loss if the fading coefficient is high. This means that a system with RIS is only slightly better than one without it. To avoid "double fading" or "multiplicative fading," [35], [36], and [37] have developed active RIS.

B. Active RIS

The "multiplicative fading" effect of passive RIS is a major performance bottleneck, and the concept of active RIS was introduced as a possible solution [35]. Active RIS, similar to passive RIS, can reflect incident signals with adjustable phase shifts. Active RIS can further amplify the reflected signals, in contrast to passive RIS which merely reflect incident signals. Active RIS, in contrast to passive RIS, has a different hardware architecture [38]. Phase shift circuits and reflection-type amplifiers are used to boost the signal strength in an active RIS. It is not possible to ignore the power requirements of active RIS because they may be comparable to those of the BS amplifiers. Due to the fact that the overall power consumption of active RIS-assisted systems may be much higher than that of passive RIS-assisted systems [39].

Thus, active RIS changes the multiplicative channel loss of passive RISs into an additive form and adds an amplification gain, making it more effective than specular reflection alone. Using active and passive RIS components in a hybrid architecture could improve analysis and optimization. For RIS that is not connected to the power grid, the power consumption of active RIS components could be an issue. Future research should carefully examine these challenges. An active RIS is a promising research topic because we expect it to surpass an AF relay in cost and efficiency [21].

C. Simultaneously Transmitting and Reflecting RIS (STAR-RIS)

In order for a traditional RIS to function, its transmitter and receiver must always be on the same side, as it can only reflect incident wireless signals. This results in the exploitation of a half-space SRE. [40] [41] [42]. Frequently, users are placed on both sides of a RIS, which drastically limits its adaptability and effectiveness. To overcome this issue, [29] and [14] suggested innovative way of simultaneously reflecting and transmitting of signals leveraging STAR-RIS. The surface of STAR-RIS separates incoming signals into two distinct components. To achieve 360-degree coverage, a portion of the signal is reflected in the reflection region and the rest is transmitted. RIS were originally conceived as wall-mounted or building-front-mounted devices. RIS can be positioned inside a wall or in the centre of a communication area to receive and transmit signals using a variety of techniques. From a signal processing standpoint, this RIS fits the profile of a 'single-input, dual-output' system.

In contrast, the system communication protocol must consider a range of factors, which include energy, mode, and time. Other considerations include the sophisticated hardware composition and perhaps antique appearance of such RISs, which may be the cost of obtaining 360-degree wireless coverage. Moreover, these types of surfaces can enhance coverage from one room to another and from the outdoors to the inside of a building. Coverage on both sides of the RIS could be reduced due to the multiplicative path-loss effect, which is why STAR-RIS design is still a concern. In this setting, the development of an active STAR-RIS might be a crucial step toward attaining comprehensive coverage. Table III is given for comparison of passive RIS,

TABLE II: Summary of Important Acronyms

Acronym	Definition	Acronym	Definition
AN	Artificial noise	AP	Access point
AO	Alternating optimization	BS	Base station
BER	Bit erorr rate	CoMP	Coordinated multi-point transmission
CSI	Channel state information	EM	Electromagnetic
Eve	Eavesdropper	ER	Ergodic rate
EE	Energy efficiency	DoF	Degrees of freedom
FD	Full-duplex	HD	Half-duplex
IOS	Intelligent omni-surface	IRS	Intelligent reflecting surface
LoS	Line of sight	NLoS	Non line of sight
MISO	Multiple-input single-output	MIMO	Multiple-input multiple-output
mmWave	Millimeter wave	TARCs	Transmission and Reflection Coefficients
NOMA	Non-orthogonal multiple access	OMA	Orthogonal multiple access
PLS	Physical layer security	RIS	Reconfigurable intelligent surface
SIC	Successive interference cancellation	SNR	Signal-to-noise-ratio
SNIR	Signal-to-interference-plus-noise ratio	SR	Secrecy rate
SR	Secrecy rate	SNIR	Signal-to-interference-plus-noise Ratio
SEE	Secure energy efficiency	SE	spectral efficiency
SOP	Secrecy outage probability	STAR-RIS	Simultaneously Transmitting and Reflecting RIS
SCA	Successive convex approximation	SDR	Semi definite relaxation
OP	Outage probability	QoS	Quality of service
UAV	Unmanned Aerial vehicle	UE	User equipment

active RIS, and STAR-RIS.

1) STAR-RIS Protocols : STAR-RIS can function in three distinct ways, according to the following protocols: mode switching (MS), energy splitting (ES), and time switching (TS).

- Mode switching: MS separates STAR-RIS into modes, i.e., transmitting (T) and receiving (R). MS STAR-RIS can be viewed as a combination of a standard RIS that only reflects or transmits. For both transmission and reflection, this protocol optimizes mode choice and phase shift coefficients element-by-element. MS functionality is enabled using "on/off" protocols (transmission or reflection). Since just a fraction of elements are used for transmission and reflection in MS, it cannot match with the gains made by ES.
- Energy Splitting: All STAR-RIS elements are deemed to be functioning in transmission and reflection (T and R) mode for the purposes of ES. As a result of this configuration, the signal energy is split between the transmitted and reflected signals. As the TARCs of each ES element are adjustable, communication system designers have a significant level of design flexibility. On the other hand, the enormous number of design variables puts a significant overhead on the transfer of configuration information between the BS and STAR-RIS.
- Time Switching: TS uses the time domain in contrast to ES and MS and alternately switches all elements between T mode and R mode at orthogonal time intervals. The TARCs for TS are easier to handle since they are not connected due to the use of the time domain, unlike the ES and MS protocols. However, strict temporal synchronization requirements are imposed by the frequent component changeover, which increases the complexity of hardware implementation.

2) Benefits of STAR RIS: Due to its unique features, following are the benefits of STAR-RIS:

- A major advantage of STAR-RIS is its ability to transmit and reflect incident signals, allowing them to cover the entire space and service both sides with a single RIS.
- Since STAR-RISs provide additional degrees of freedom (DoF) for modifying signal propagation, the design's flexibility is increased, allowing it to meet even the most rigorous communication requirements.
- With its optical transparency, STAR-RIS may be used in windows and has a pleasant aesthetic, both of which are important for real-world applications.

3) Application of STAR RIS: Following a review of STAR-RIS benefits, we examine various prospective wireless communication network applications [29]. STAR-RIS can improve wireless network coverage and quality by overcoming obstacles like buildings, trees along roads, automobiles, etc.

- Improving communication reliability and coverage for outdoor, outdoor to indoor, and indoor scenarios: Similar to passive RIS, STAR-RIS may be mounted on buildings and road signs to give an extra outdoor communications link. STAR-RISs can also be mounted in the windows of moving cars to boost the quality and range of satellite and BS signals (including automobiles, aircraft, and cruise ships). Building barriers significantly decrease the reach of outside BSs for outdoor-to-indoor communications, especially for mmWave and THz communications. STAR-RIS constructs an effective indoor-to-outdoor bridge. In terms of indoor communications, STAR-RISs are preferable to passive RISs. Because ordinary passive RISs only

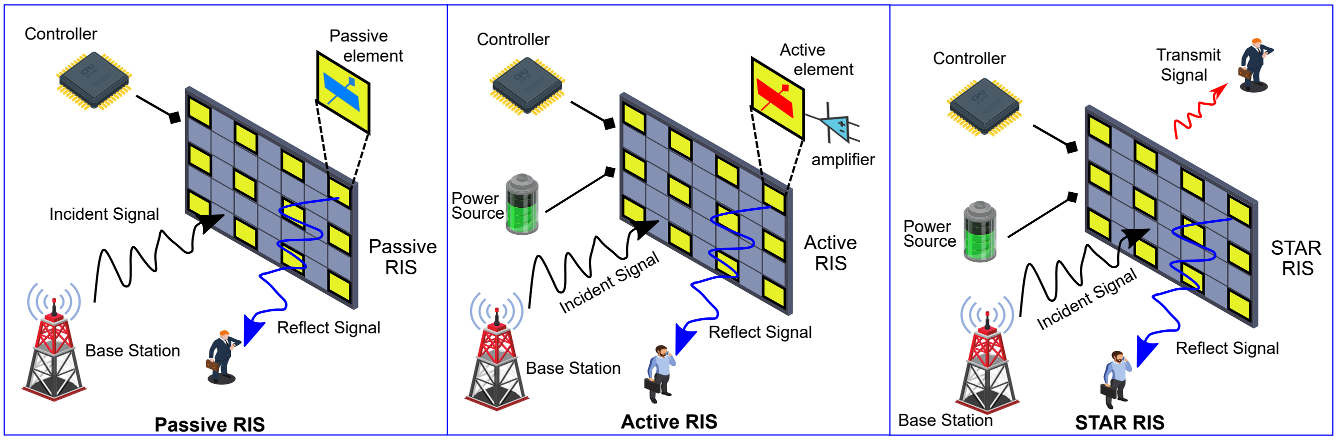

Fig. 3: Types of RISs are illustrated including, passive, active, STAR-RIS (which can be active or passive).

TABLE III: Comparison of Passive, Active and STAR-RIS

Items	Passive RIS	Active RIS	STAR-RIS
Coverage	180	180	360
Elements	Passive	Active	Passive / Active
Hardware Design	Simple	Complicated	Complex with MS, ES, and TS operation modes
Working	Reflect Signal	Reflect Signal	Reflect and Transmit Signal
Path loss	Multiplcative	Additive	Multiplicative / Additive

cover half-space, access point (AP) signals may require multipath hops to reach the intended user. Full-space coverage can shorten propagation distance and increase received signal strength by utilizing transmission and reflection. In addition, STAR-RIS only requires one hop, whereas passive RISs typically require two. In terms of design, STAR-RISs outperform typical passive RISs due to their larger transmission capacity.

- STAR-RIS-NOMA: NOMA is an excellent alternative for the next generation since it permits variable spectrum efficiency, flexible resource distribution, and huge connection. Users with diverse channel conditions must be paired in order for NOMA to attain considerable performance advantage over OMA. The advantages of NOMA may not be completely realized for passive RIS due to the users' comparable channel conditions in the local reflected region. Exploiting STAR-RIS allows transmission-reflection NOMA, a better communication structure that pairs transmission and reflection-oriented users. Boosting NOMA gain by tweaking the TARCs of the ES or MS protocol could result in varying transmitted and reflected channel conditions.
- STAR's Coordinated Multipoint (CoMP) Communication: The performance of cell edge users cannot be guaranteed in multi-cell communication networks due to high inter-cell interference. CoMP reduces interference between cells. Several multiple-antenna BSs support a cell edge user called CoMP. Each BS also supports a non-CoMP user, commonly known as a non-CoMP cell center user. With a STAR-RIS installed, the transmission half space is occupied by the CoMP user, while the reflection half space is used by the non-CoMP user. It is possible to improve the SINR of the CoMP-received user by designing all STAR-RIS cooperative transmission coefficients. However, non-CoMP users' exposure to cell edge user-generated interference can be reduced by increasing the reflection coefficients of each STAR-RIS.
- Secure communication: RISs can also enhance physical layer security (PLS) by decreasing the signal propagation of eavesdropper's (Eve) channels. While this may be the case in theory, in practice it is not necessarily the case that authorized users and Eves are on the same side of the RIS, which is the assumption made in traditional passive RIS-based secure communication. Eventually, STAR-RIS arrive to provide support. PLS can be increased independently of the location of an Eve using full-space STAR-RIS propagation.
- Indoor Localization and Sensing: STAR-RIS can enhance the localization and sensing capabilities of wireless networks, especially in confined spaces like buildings, by overcoming signal barriers and providing full-space coverage. Moreover, mobile robot location and data transfer speed can be enhanced with the aid of STAR-RISs in intelligent factories.

III. STAR-RIS Empowered Uses Cases, Resource Allocation, and Performance Analysis

In this section, we will first focus how the STAR-RIS influences the communication performance based on different use cases. Specifically, we categorize the available literature for different use cases, which include enhancing coverage, improving PLS, enhancing sum-rate,improving EE, and mitigating interference. Following that we will review the available literature on STAR-RIS resource allocation and performance analysis.

A. Enhancing Coverage Leveraging STAR-RIS

As mentioned before, a STAR-RIS can serve users on its both sides. Therefore, expanding the range of cellular network coverage is one of the most important applications for the STAR-RIS as shown in Fig. 4. A STAR-RIS deployed near the cell edge, for instance, can enhance the performance of users within cell coverage and provide service to users outside of cell coverage. This sub-section investigates the state-of-the-art strategies for increasing the wireless communication coverage leveraging STAR-RIS for different scenarios, and it is supplemented by summary Table IV to enable readers to comprehend the primary principles and have a more thorough intuition about the associated technology.

Reflecting and transmissive signals may have distinct channel models and power, making IOS-assisted communication challenging. In such a situation, IOS-assisted communications cannot easily be applied to reflective IRS-assisted communications studies. Furthermore, the BS-user link and IOS-assisted communication system's reflecting and transmissive links can coexist. Therefore, IOS phase shift design should consider multiple communication connection superposition. In this article [43], the authors examine an IOS-assisted downlink communication system that improves the mobile user (MU) link quality by introducing an IOS phase shift configuration. IOS, unlike IRS in the vast majority of existing systems, can transmit or reflect signals to the MU, thereby, boosting wireless coverage. To maximise MU downlink spectral efficiency (SE), an IOS phase shift optimization problem is provided along with a branch-and-bound technique for constructing the best IOS phase shift within a finite set. Simulations have proven that the IOS-assisted system is capable of signal transmission across a wider area than the IRS-assisted system.

Papazafeiropoulos *et al.* [44] investigated STAR-RIS as a means of enabling mMIMO. The coverage capability of a STAR-RIS-mMIMO system was characterized by closed-form expressions that take into account phase-shift errors and correlated fading. Intriguingly, phase setting occurs by enhancing the probability of coverage for every few synchronization gaps because it requires statistical CSI in massive data sets. Consequently, in the case of STAR-RIS networks with rapid CSI, they were able to construct passive beamforming with fewer complications but at a higher cost. The numerical results highlight characteristics such as the effect of RIS element influence and phase errors and confirm the superiority of STAR-RIS over RIS. Future research could focus on Ricean channels and possibly millimeter-wave transmission.

To ensure complete coverage in all directions, Zhang *et al.* [45] analyzed a downlink NOMA network that included STAR-RIS support and randomly deployed users. The authors designed two STAR-RIS-assisted channel models, one

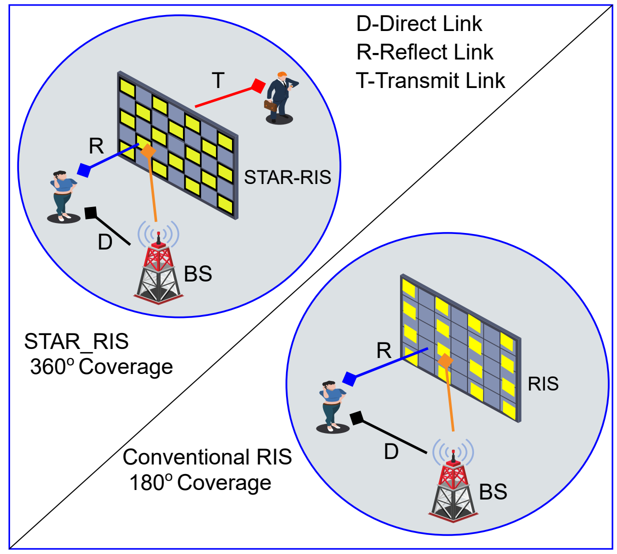

Fig. 4: Illustration of STAR-RIS for coverage extension

for situations with a large number of RIS elements (i.e., the Central limit) and one for settings with multiple cells (i.e., the curve fitting). A Gamma distribution can be used to closely approximate the curve fitting model, and closed-form expressions can be used to construct the error functions of the Central limit model. Additionally, closed-form outage probability expressions have been obtained for NOMA users. Numerical results show that the Central limit model is an upper bound and the curve-fitting model is a lower bound for the N-pairs with no error bound. Moreover, the two-channel models reach boundaries in regions with high SNR and match simulation findings well in parts with low SNR.

When it comes to smart radio environments, STAR-RIS can span the full-space coverage. Xie *et al.* [46] considered downlink NOMA multi-cell network with STAR-RIS, where incident signals at STAR-RISs are separated into two halves for transmitting and reflecting. The authors leverage the controllable Gamma distribution to approximate composite small-scale fading power. The location of RIS, BSs, and UEs is then provided using a unified mathematical method based on stochastic geometry. Moreover, this method calculates the typical UE and connected UE coverage probability and ergodic rate (ER). For the coverage probability under interference-limited situations, closed-form equations are derived and also generated theoretical expressions in typical RIS-aided networks for comparison. Analysis indicates that there are optimal STAR-RIS energy splitting coefficient values that maximise both system coverage and ER. The numerical findings show that STAR-RIS can manage UEs on both sides and provide higher coverage and throughput than typical RIS with proper energy splitting coefficients.

Wu *et al.* [47] investigated STAR-RIS for OMA and NOMA and modeled a sum coverage range maximization problem. Individually, the resource allocation at the AP and the TARCs at STAR-RIS were optimized to meet the communication requirements of consumers. NOMA, a

TABLE IV: A summary of schemes leveraging STAR-RIS for enhancing coverage in different scenarios

Ref	Year	Scenario	Channel Characteristics		Methods	Proposed Solution
			Direct	Reflective-Refractive		
[43]	2020	DL OMA, BS (SA), STAR-RIS (1), Single UE (SA)	Rician fading	Rician fading	Branch and bound based algorithm	Enhancing the SE of the UE by optimizing the phase shift of the IOS.
[44]	2022	DL, mMIMO BS (MA), STAR-RIS (1) , Two users (SA)	Blocked	Correlated Rayleigh fading	Theoretical analysis	Both the reflection and refraction beamforming matrices are improved using statistical CSI, decreasing the amount of unnecessary overhead.
[45]	2021	DL NOMA, BS, STAR-RIS (1), Users (Paired)	Blocked	Rician fading	Central Limit and Curve Fitting	To determine the OP in a downlink NOMA system that is enabled by STAR-RIS
[46]	2022	DL NOMA, BS (SA), STAR-RISs , UEs (SA)	Blocked	Double-Rician fading	Stochastic Geometry	To enhance the system's ergodic performance and coverage.
[47]	2021	DL OMA and NOMA, AP (SA), STAR-RIS (1), Two users (SA)	Blocked	Rician fading	One dimensional search based algorithm	To address the communication demands of users, a sum coverage range maximization is proposed,

DL-Downlink, Ref-Reference, SA-Single Antenna, MA-Multi-Antenna, UE-User equipment

nonconvex decoding order constraint, was transformed into a linear constraint, thereby transforming the problem into a convex one that can be solved in the most efficient manner. Initially, it was demonstrated that the OMA optimization problem was convex for a specified frequency/time resource allocation. Then, for the best results, the fundamental search-based method was chosen. In comparison to conventional RISs, STAR-RIS can significantly increase coverage, according to the research.

B. *Improving Physical Layer Security Through STAR-RIS*

Without resorting to higher-layer encryption, PLS is a reliable means of transmitting secret messages over a wireless channel while Eves are present [48]. The basic idea behind is to limit the amount of data an unauthorised receiver can extract by taking advantage of the randomness of noise and fading channels [49]. STAR-RIS can help boost PLS performance, e.g., a user on one side of the STAR-RIS can pick up signals coming from a transmitter on the other side, bu this user's secret transmissions cannot be directed toward Eves on the same side as the user [50]. Therefore, the STAR-RIS channel enables secure communications as shown in Fig. 5.

Despite this, STAR-RIS-enhanced PLS poses new research challenges. When a STAR-RIS is present, wireless channels become configurable. This generally necessitates a reevaluation of the PLS paradigm in light of the new design constraints that permit the input distribution of a system to be altered in response to the system's own states [51], [52]. Having prior knowledge of the Eves in the context of PLS is typically difficult. Therefore, optimizing the STAR-RIS to guarantee the required level of security is challenging. Multiple users may share a single STAR-RIS in a multi-user system, and optimizing user competitiveness is a significant research problem. This sub-section investigates the state-of-the-art strategies for improving PLS utilising STAR-RIS considering single and multiple Eves. It is also supported by the summary Table V for enabling readers to grasp the

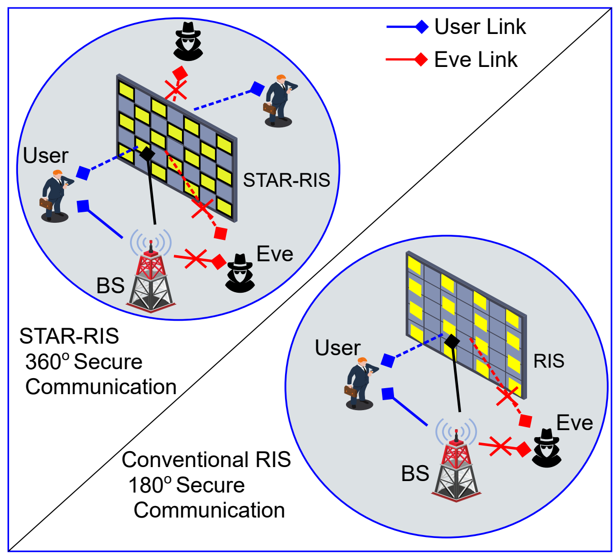

Fig. 5: Illustration of STAR-RIS for secure communication

primary techniques and get better intuition about the STAR-RIS based PLS.

1) STAR-RIS Assisted PLS For Single Eve Scenario: Combining NOMA with STAR-RIS, as Han *et al.* [53] claims, is a win-win strategy that can greatly improve coverage performance. To address the issue and improve the secrecy rate, a secure communication technique with artificial noise (AN) support was proposed. To find the best AN model and RIS settings, an AO-based technique was presented. Methods of semidefinite relaxation (SDR) and successive convex approximation (SCA) are used in this algorithm. The proposed scheme performs better than the benchmark approaches in terms of secrecy while requiring less AN power. By increasing the number of RIS elements, the AN's power can be further lessened. Furthermore, increasing the number of transmit antennas decreases the AN power when the Eve is close to the transmitter, but increases it when the Eve is far away. While Han *et al.* [53] concentrated on the downlink scenario, Zhang *et al.* [54] looked at secure transmission in the uplink NOMA system with STAR-RIS assistance, wherein authorised users proactively change the electromagnetic propagation environment to transmit confidential messages to the BS. The accessibility of the eavesdropping CSI was attributed to both the statistical CSI and the full CSI. Using an adaptive-rate wiretap code, they are able to maximizing minimum secrecy capacity under SIC decoding order for the full eavesdropping CSI scenario. The authors then introduced the alternating hybrid beamforming (AHB) algorithm to optimise transmit power, reflection/transmission coefficients, and receive beamforming. In the statistical eavesdropping CSI state, constant-rate wiretap code was used to minimize the maximum SOP, subject to the QoS limits of legitimate users. Next, develop a better AHB algorithm for the joint secrecy beamforming design and use constant-rate coding to derive a precise SOP expression. The simulation results demonstrate that the proposed strategy is effective.

In contract to NOMA based works in [53], [54], Fang *et al.* [55] investigated the performance of IOS in the context of PLS across MIMO based communication networks. In the presence of a multiantenna Eve, the IOS focuses on a specific case to improve the receiver's secrecy performance. Using AN-assisted beamforming increased additional security robustness even further. In order to reduce the complexity of the AN-assisted beamforming design, the block coordinate descent (BCD) optimization technique and the Lagrangian dual method were chosen. Using quadratically constrained quadratic programming (QCQP), the problem of frequency changes efficiency was resolved. Simulation validate IOS's superiority over RIS and validate the method's efficacy.

2) STAR-RIS Assisted PLS For Multi-Eve Scenario: STAR-RIS-assisted communication, according to Xu *et al.* [56], is an exciting topic of study since it can satisfy the strict requirements for increased spectrum, efficiency, and coverage quality. The downlink STAR-RIS-NOMA system, which improves transmission quality between users and a multiple-antenna BS, was the main focus of this study. Two NOMA users positioned on either side of the projected STAR-RIS are served via the ES protocol. Each reconfigurable element can function simultaneously in transmission and reflection modes based on the ES protocol. Initially, the closed form of SOP was established to evaluate the STAR-RIS-NOMA system's secrecy performance. The performance of the generated SOP was then evaluated asymptotically. Additional insights might be extracted thanks to the secrecy diversity order (SDO), which was created by the asymptotic approximation in the high signal-to-noise ratio (SNR) and main-to-eavesdropper ratio (MER) regimes. A subsequent advancement was the optimization of the system's parameters to lower the SOP. The analysis's findings showed that the multiple-antenna BS had no effect on SDO for the NOMA system supported by STAR-RIS. Theoretical findings and simulation results closely complement each other, and the SOP of the STAR-RIS-enhanced NOMA system was lower than that of the OMA system, according to simulations. Future research, however, will take the channel estimation error into account.

Different from the NOMA-based work in [56], Niu *et al.* [57] employs a STAR-RIS to increase security in a multiple-input single-output (MISO) network by studying the three protocols, i.e., TS, ES, and MS. By jointly designing TARCs and BF coefficients, weighted sum secrecy rate (WSSR) is maximized. At first, a path-following technique was created to transform the non-convex problem into a convex one, and then the TARCs and BF were constructed in a way that allowed for flexibility. Using the penalty concave-convex procedure (PCCP), the TARCs for the ES scheme were then solved. In addition, resolving a mixed-integer problem for MS and proposing a two-layer optimization strategy for the TS. Finally, the results of the simulation confirm STAR-superiority.

Wang *et al.* [58], using the STAR-RIS system, looked into the problems of transferring e-health data quickly and safely via the Internet of Medical Things (IoMT) network. Patients' telemedicine transmissions were secured using the STAR-RIS to prevent eavesdropping. To maximise secrecy energy efficiency (SEE) while taking into account the imperfect CSI of all channels, a joint active and passive beamforming approach was created. In order to estimate the semi-infinite inequality constraints, the reformulated problem was solved using an alternating optimization (AO) framework that made use of the S-procedure and general sign certainty. In places with low downlink power, the TS mode of STAR-RIS was favoured, whereas the ES mode provided the highest performance in regions with sufficient downlink power. Without CSI evaluation's accuracy and bit resolution power usage, STAR-RIS's aids could not be acquired. The simulation findings show that STAR-RIS can inncrease SEE for IoMT networks far more than RIS can. In another work, Wang *et al.* [59] proposed a novel IOS-enhanced air secure unloading method to prevent security breaches, improve authentic receiving quality, and increase the safety installation area of unmanned aerial vehicles (UAVs). By assigning computing frequency, determining offloading strategy, controlling transmit power, designing phase shifts, and organising UAV locations, a non-convex resource allocation problem was constructed to maximise the SEE of the system. The interconnectedness of the variables made it hard to find a simple solution to the problem. Therefore, the original problem was divided into sub-problems, and an iterative technique with low complexity was used to optimise the computation and communication settings. The findings proved that IOS could make full use of UAVs' deployability flexibility, which in turn made for secure offloading. The SEE of the IOS-enhanced air secure offloading method significantly outperforms that of the conventional systems. Unexplored were a few intriguing aspects including multi-

TABLE V: A summary of schemes leveraging STAR-RIS for improving PLS in different scenarios

Ref	Year	Scenario	Channel Characteristics		Methods	Proposed Solution
			Direct	Reflective-Refractive		
[53]	2022	DL NOMA, BS (MA) STAR-RIS (1) Users (SA) Eve (SA)	Rayleigh fading	Rician fading	SCA and SDR	To maximize the SR, an AN assisted secure communication technique is proposed.
[54]	2022	UL NOMA, BS (MA) STAR-RIS (1) Users (SA) Eve (SA)	Blocked	Rayleigh fading	Alternating hybrid beamforming (AHB)	The adaptive rate wiretap code design is used to maximize minimal secrecy capacity under SIC decoding order constraints.
[55]	2022	DL MIMO, BS (MA) IOS (1) User (SA) Eve (MA)	Rayleigh fading	Rician fading	Lagrangian dual and QCQP	Maximized the SR of an IOS-aided MIMO by jointly optimizing BF, AN vectors at BS, and reflecting and refracting phase shifts at IOS.
[56]	2022	DL NOMA, BS (MA) STAR-RIS (1) Users (SA) Two Eves (SA)	Rayleigh fading	Rayleigh fading	Numerical analysis	SOP as closed form expression for STAR-RIS assisted NOMA system is derived.
[57]	2021	DL MISO, BS (MA) STAR-RIS (1) Two Users (SA) Two Eves (SA)	Blocked	Rician fading	Path-following based technique	To maximize WSSR by jointly designing BF, and TARCs.
[58]	2022	DL OMA, BS (MA) STAR-RIS (1) Two Users (SA) Two Eves (SA)	Rician fading	Rician fading	SCA, AO and penalty CCP methods.	Taking imperfect CSI of all channels, the joint active and passive BF is designed to maximize the SEE.
[59]	2022	UAV based setup, BS (SA), IOS (1), Eves (SA), multiple UAVs	Rician fading	Rician fading	AO Algorithms	IOS-enabled aerial secure offloading mechanism is presented with several Eves on the ground.

Ref-Reference, DL-Downlink, UL-Uplink, SA-Single Antenna, MA-Multi-Antenna, UE-User equipment, Eve-Eavesdropper

functional metasurface, CSI acquisition and resilient design, as well as the optimization and deployment of various IOSs.

C. Enhancing Sum-Rate Using STAR-RIS

NOMA is capable of satisfying the huge connection demands and high spectral efficiency of the future generation networks [60]. NOMA permits several users to share a single resource block (RB) in the code or power domain, as opposed to OMA, which serves users via orthogonal time/frequency RBs [61], [62]. At the transmitter, user signals are combined using power-domain NOMA and recovered using successive interference cancellation (SIC). When users have distinct channels, NOMA outperforms OMA as shown in Fig. 6. STAR-RIS assisted NOMA systems can further maximise NOMA gain by reconfiguring wireless channels [63].

The state-of-the-art methods for increasing the sum rate using STAR-RIS are examined in this subsection. These methods are further classified into OMA, NOMA multi-antenna/full-duplex/vehicular domains. Additionally, the summary in Table VI is included to help readers understand the key concepts and gain a better insight of the STAR-RIS technology.

1) STAR-RIS-OMA based Sum-Rate Maximization: Wu *et al.* [64] stated that IOS as a component of RIS gained more attention due to its ability to continuously serve user equipment (UE) on both sides of the metasurface. Therefore, reflection and refraction signals must share the IOS's phase shift, resulting in the inevitable pairing of refraction and reflection beams. They suggested that bilayer-IOS (BIOS) offers flexible reflection and refraction beamforming (BF) as a solution to this issue. BIOs can completely control the refraction and reflection beam for UEs on both sides due to the proximity of two IOSs. With MISO, a BIOS was implemented in a multi-user system. In order to maximise spectral efficiency while utilising AO, the authors jointly optimise BS precoding and BIOS passive beamforming. Future research into the capabilities of BIOS in more com-

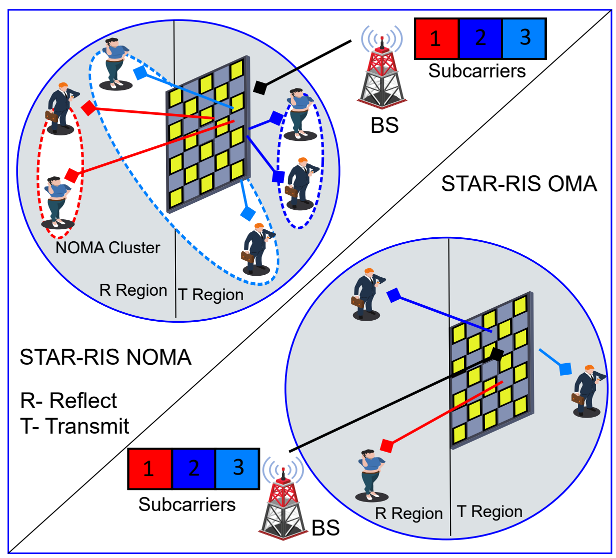

Fig. 6: Illustration of STAR-RIS for enhancing capacity

plex situations, such as MIMO, wideband, and multi-layer IOS, would be quite intriguing. In another work, Niu *et al.* [65] simultaneously design base frequencies and TARCs to maximize the weighted sum rate for many users under the discrete coefficient restriction. To address the nonconvex objective function, an approach based on irregular optimization was created. When TARCs are fixed through element-wise optimization, the BF can be derived in closed form through the bisection approach. Similarly, Mohamed *et al.* [66] presented an algorithm for simultaneously optimizing the covariance matrix at the BS, TARC matrix, and power level that is reflected and refracted by the IOS. The unique aspect of this study is that it investigates the interdependence of an IOS's transmission and reflection capabilities. Simulation results were used to show the convergence of the suggested strategy and the advantages of employing surfaces with continuous reflection and refraction capabilities.

Different from the works in [64]–[66], Liu *et al.* [67] investigates the issue of improvement for downlink unmanned aerial vehicle-assisted IOS (UAV-IOS). Despite RIS, IOS can transmit and reflect signals instantaneously, thereby enhancing the rate in all dimensions. Combining the UAV trajectory with IOS's phase shift helped identify the rate enhancement problem. Although its non-convexity makes it difficult, they devised a method for generating a superior suboptimal solution. Comparing UAV-IOS communications to other standard methods, computational results indicate that UAV-IOS communications are capable of achieving higher rates. This demonstrates IOS's capacity to provide comprehensive telecom coverage in forthcoming 6G networks.

Zhang *et al.* [68] implemented IOS-assisted networking to expand wireless communication system coverage and provide mobile users (MUs) with reflective and refractive service. A multi-antenna SBS and an IOS collaborate to execute beamforming via various reflective/refractive paths in order to boost the received power of multiple MUs on either sides of the IOS. The authors defined an optimization problem for both SBS beamforming and IOS phase shift and presented an iterative solution for sum rate optimization. According to theoretical analysis, IOS expands SBS coverage and rate in comparison to IRS. In another work, Zhang *et al.* [69] proposed IOS to achieve full-dimensional communications and determine the optimal beamforming technique for IOS because obtaining the ideal CSI presented challenges. Then beamforming was designed at the BS and IOS, employing beam training with codebooks. It was proposed that the cross-beam training system conduct beam training for users concurrently, thus decreasing training costs. The simulation findings show that their proposed strategy achieves a greater data rate than most advanced beam training methods and performs nearly as well as the ideal CSI scenario. Similarly, Perera *et al.* [72] studied FD communication system assisted by STAR-RIS to maximize the system's weighted sum rate by enhancing STAR-RIS elements for ES and MS protocols. The authors utilize SCA and proposed suboptimal solution. At the STAR-RIS, maximum average weighted sum rate and related factors were quantified. Then the performance of the proposed system design was evaluated through simulations compared to half-duplex equivalents and conventional RISs. STAR-RIS has been found to enhance the performance of FD systems.

IRS's capacity to dynamically regulate the phase shift of replicated EM waves to create an optimal broadcast environment led to its widespread adoption. The revolutionary concept of IOS allows for the modification of both signal reflection and transmission, whereas IRS focuses solely on signal reflection. Consequently, IOS represents a novel paradigm for establishing ubiquitous wireless technology. Cai *et al.* [70] presented IOS with a MU-MISO scheme that makes use of IOS's reflecting and transmissive properties to enhance MU-MISO broadcast. Using the Riemannian manifold, weighted minimum mean square error (WMMSE), second-order cone programming (SOCP), and block coordinate descent (BCD) algorithms, both the power minimization and sum-rate maximization problems were solved. Simulation results validated the utility of the associated joint beamforming design technique and the improvements of the anticipated IOS based wireless networks. In addition, several IOS based system issues, such as hardware flaws, quick channel estimation, realistic transmission protocols, the creation of more complex procedures, learning-based methods, etc., should be examined in future research. Unlike the MU-MISO based work in [70], Niu *et al.* [71] investigated MIMO using STAR-RIS support. Utilizing the ES scheme predominantly, the authors seek to optimize the weighted sum rate of the system under consideration. A sub-optimal BCD method was developed to construct the precoding matrix and the TARCs to maximize the weighted sum based primarily on ES to solve this optimization problem. Precoding matricenlike the were solved using the Lagrange dual method, and TARCs were produced using the constrained concave-convex process (CCCP). The results demonstrate that STAR-RIS is superior to RIS. Furthermore, the TS strategy outperforms the MS and ES strategies in single-hop interactions. In contrast, the ES strategy in broadcast communication is superior to the TS and MS strategies.

2) STAR-RIS-NOMA based Sum-Rate Maximization: Zuo *et al.* [73] proposed a STAR-RIS-NOMA system in which active beamforming, power allocation coefficients, transmission beamforming, and reflection beamforming enhance the possible sum rate by improving each other's decoding order. The authors framed a non-convex problem with interconnected variables. To address this issue, a sub-optimal two-layer iterative technique was presented. In the inner layer iteration, for instance, the power allocation coefficients, active beamforming, transmission beamforming, and reflection beamforming were alternately tuned for a specific decoding order. During the outer layer iteration, the solutions were disclosed while the inner layer iteration was used to modify the decoding order of NOMA users for each cluster. Simulation results indicated that the proposed system outperforms

TABLE VI: A summary of STAR-RIS based schemes for maximizing sum rate in different scenarios

Ref	Year	Scenario	Channel Characteristics		Methods	Proposed Solution
			Direct	Reflective-Refractive		
[64]	2022	DL OMA, BS (MA), Bilayer-IOS (BIOS) UEs (SA)	Blocked	Rician fading	AO Algorithm	To obtain flexible reflection and refraction BF, a novel bilayer IOS (BIOS) structure is proposed.
[65]	2022	DL OMA-MISO, Tx (MA), STAR-RIS (1), Several Users (SA).	Blocked	Rician fading	AO Algorithm.	WSR is maximized subject to the discrete coefficient constraint.
[66]	2022	DL OMA-MIMO, BS (MA), IOS (1), Users (MA).	Rician fading	Rician fading	AO algorithm	To maximize sum rate in IOS-assisted MIMO broadcast channels, transmitter covariance matrices, IOS TARCs, and reflected/refracted power ratio are optimized.
[67]	2022	UAV based setup, Ground Node (1) (SA), IOS (1), UAV (SA)	Rician fading	Rician fading	AO algorithm	To increase the average achievable rate by employing a reflective transmissive IOS.
[68]	2022	DL OMA, Small-cell BS (MA), IOS (1), Users (SA).	Rayleigh fading	Rician fading	Iterative algorithm	To maximize the system's sum rate, a joint IOS analog BF and Small BS digital BF problem is optimized.
[69]	2022	DL OMA, BS (MA), IOS (1) Users (SA)	Blocked	Saleh Valenzuela	Beam training with codebooks	An IOS aided system is considered where the BF scheme is designed via beam training with codebooks at the BS, the IOS, and users to obtain maximum sum rate.
[70]	2022	DL OMA-MISO, BS (MA), IOS (1), Users (SA).	Blocked	Rayleigh fading	SOCP, WMMSE and BCD	To minimize power and maximize sum rate with the help of IOS
[71]	2022	DL OMA-MIMO, Tx (MA), STAR-RIS (1), Users (MA).	Blocked	Rician fading	BCD & constrained concave-convex procedure (CCCP) algorithms	An ES strategy is used to maximize weighted sum rate.
[72]	2022	FD, AP (MA), STAR-RIS (1), Users (SA).	Nakagami-m	Nakagami-m	SCA and Penalty Based Iterative Algorithm	To maximize the system's WSR, TARCs of STAR-RIS elements are optimised for the ES and MS protocols.
[73]	2021	DL NOMA, BS (MA), STAR-RIS (1), Users (SA).	Blocked	Rician fading	Two-layer iterative algorithm	Jointly optimization problem to maximize the achievable sum rate.
[74]	2022	DL NOMA, BS (SA), STAR-RIS (1), Users (SA).	Nakagami-m fading	Nakagami-m fading	Numerical Analysis	Performance analysis for effective capacity is obtained considering two NOMA users.
[75]	2022	DL NOMA, BS (MA), STAR-RIS (1), Users (SA)	Blocked	Nakagami-m fading	Numerical Analysis	Ergodic rate analysis is performed and closed-form expressions are derived under high SNR for edge users.
[76]	2022	DL NOMA, BS (MA), STAR-RIS (1), Users (SA).	Blocked	Rician fading	Blocked Coordinate descent (BCD), SCA and Iterative method	To maximize the per-slot queue WSR of users, the long-term stability oriented issue is reformulated by jointly optimize the active & passive BF in each time slot.
[77]	2022	DL NOMA, BS (SA), STAR-RIS (1), Users (SA).	Rayleigh fading	Rician fading	Penalty-based iterative and low-complexity algorithm	Two efficient two-timescale (TTS) transmission protocols called beamforming-then-estimate (BTE), and partition then-estimate (PTE) are proposed for distinct channel settings to maximize the respective average achievable sum rate
[78]	2022	DL NOMA mmWave, BS (MA), STAR-RIS (1), Users (SA).	Blocked	Saleh-Valenzuela geometry	AO algorithm	A downlink STAR-RIS-based MU-MISO Hybrid NOMA wireless network with a sum-rate maximization problem.

Ref-Reference, DL-Downlink, UL-Uplink, SA-Single Antenna, MA-Multi-Antenna, UE-User equipment, FD-Full-duplex

traditional RIS-assisted systems. In another work, Liu *et al.* [74] investigated the performance of the NOMA networks that STAR-RIS supported for ultra-reliable low-latency communications. Effective capacity (EC) was employed to assess the delay requirements of NOMA customers. Specific analytical expressions of the EC were derived for the network with two NOMA users on different STAR-RIS edges. The asymptotic analysis of the ECs at high SNR was also provided using the high SNR slope and high SNR power balance. As a result, STAR-RIS-NOMA networks had superior EC compared to STAR-RIS-OMA and conventional RIS networks. Furthermore, tight delay constraints result in inferior ECs. Additionally, as the number of elements in STAR-RIS increases, so does the geographic variety and ECs. Therefore, the given analytical technique will help the STAR-RIS-NOMA networks theoretically.

Zhao *et al.* [75] assessed the ERs of a STAR-RIS-NOMA system in which STAR-RIS provides LoS links to these cell-edge users. Due to obstructions, direct links between the BS and these cell-edge users were not LoS. The merged channel power gain distribution was fitted to a gamma distribution to obtain closed-form expressions of ERs and high SNR slopes for cell edge users. According to numerical results, the ERs of proposed systems are greater than those of conventional RIS-NOMA systems, and the slopes of the high SNR are constant.

Zhang *et al.* [76] examined the system stability of the STAR-RIS NOMA system with queue awareness. The continuing stability oriented issue was rewritten as a queue weighted sum rate (QWSR) maximization problem in respective time slots, leveraging the Lyapunov drift theory to address the case of the indefinite periods required for stability. The BS maintained the data queue length, and transmission to each user was awaited. Active beamforming coefficients (ABCs) at the BS, NOMA decoding order, and passive TARCs at STAR-RIS were jointly optimized to maximize the QWSR. ES, MS, and TS three STAR-RIS operating protocols were considered. For ES, the BCD and SCA were used to iteratively and alternatively optimize problems to manage the highly coupled and non-convex problems. The defined issue was divided into two sub issues for TS. B both of them can be handled in the same way that ES is. To solve the binary amplitude limited problem for MS, the proposed iterative method was expanded into a penalty-based two-loop procedure. The simulation results indicated that the queue would remain stable under the revised QWSR maximization problem. In addition, the proposed STAR-RIS NOMA communication system performance surpasses conventional systems. Simulations demonstrated that, regarding QWSR and average queue length, the TS protocol was superior to the other two protocols.

Wu *et al.* [77] stated that STAR-RISs have emerged as a potential technique for modifying the radio propagation environment throughout the entire universe. Prior research on STAR-RISs has concentrated primarily on the energy-splitting operation protocol, which has a high level of hardware complexity. In addition, the passive beamforming design of STAR-RIS always assumes the availability of complete and rapid CSI, which is practically difficult due to the large number of STAR-RIS components. Observing the STAR-RIS MS design and STAR-RIS-NOMA communication system issues. Effective two-timescale (TTS) broadcast methods have been developed in order to increase the average sum rate for each channel configuration. Specifically for LoS-dominant channels, short-term power provision at the BS was designed based on all users' evaluated effective fading channels. Simultaneously, the long-term transmission and reflection factors for STAR-RIS were optimized using only the statistical CSI. For dense scattering environments, partition-the-estimate (PTE) is recommended. BS determines the long-term STAR-RIS surface-partitioning strategy based solely on path-loss information, assigning each subsurface to a single user. Accordingly, BS designs its power allocation and STAR-RIS Phase-shift. In addition, efficient algorithms for solving short-term and long-term optimization issues were proposed. Similarly, both proposed transmission protocols reduce the channel estimation overhead significantly.

Abrar *et al.* [78] stated that STAR-RIS has recently become a well-known technique that utilizes the transmissive nature of RIS to overcome the half-space exposure limit of traditional RIS operating on mmWave. In a downlink STAR-RIS-based MU-MISO mmWave hybrid NOMA (H-NOMA) wireless system, they proposed a sum-rate maximization problem. The paper then suggests a framework based on alternating optimization (AO) for solving passive and active beamforming subproblems. Channel strength-based and Channel connection-based methods were recommended for a specific instance of two-user optimal clustering and decoding order assignment, and numerical calculations were derived for combining time and power allocation for H-NOMA. Simulation results demonstrate that H-NOMA outperforms OMA and NOMA in terms of maximizing the achievable sum rate and the number of clusters that can support the specified design constraints. In addition, STAR-RIS can significantly reduce the number of elements compared to RIS while maintaining the same service quality (QoS). The deployment techniques of STAR-RISs to enhance current networks in light of stochastic geometry can be incorporated into future extensions, despite the fact that a number of publications have studied the optimal placements of RIS.

D. Improving Energy Efficiency Leveraging STAR-RIS

A smart controller in STAR-RIS can segregate the incident signal into the transmission and reflection sectors to give 360-degree coverage. The top features of STAR-RIS, aside from optical transparency and attractiveness and suitability for usage with windows, are that it can transmit and reflect incident signals simulataneously, it enables the full space SRE, and it can set dynamic power ratios for STAR-RIS elements. One part of the incident signal is reflected into the reflection space while the other is transmitted in the opposite direction (i.e., the transmission space). Controlling a STAR-RIS element's electric and magnetic currents allows the TARCs to reconfigure signals. By designing the STAR-RIS TARCs, system performance can be increased. This subsection examines the latest methods for enabling energy-efficient solutions using STAR-RIS, supported by the summary in Table VII to assist readers in comprehending the innovative approaches.

Guo *et al.* [79] examined the NOMA-assisted STAR-RIS downlink network's EE maximization issue. Due to the EE's fractional nature, it was challenging to maximize it using conventional convex optimization methods. To maximize the EE, transmission beamforming vectors at the BS, and the coefficient matrices at the STAR-RIS were optimized using a deep deterministic policy gradient (DDPG) based technique. The simulation findings suggested that recommended approach can successfully maximize system EE while taking into account channels that vary over time. In another work, Zuo *et al.* [80] recommended using the uplink NOMA communication technology with STAR-RIS, which is different from downlink scenario in [79]. By optimizing user transmit power concurrently, the BS receives beamforming vectors, STAR-RIS, STAR beamforming vectors, and time slots, hence posing the problem of minimizing total power usage. Here, transmission and reflection beamforming of STAR beams via STAR-RIS are introduced. To reduce the total power consumption problem, a penalty-based alternating optimization (P-AltOp) strategy was proposed. The effectiveness of the proposed plan has been proven by simulation results, which also demonstrated that alternative system configurations affect total energy consumption and the system has already been tested by simulation results, which also revealed the many system configurations that influence total energy consumption.

TABLE VII: A summary of STAR-RIS based approaches for improving energy efficiency in different setups

Ref	Year	Scenario	Channel Characteristics		Methods	Proposed Solution
			Direct	Reflective-Refractive		
[79]	2021	DL NOMA, BS (MA), STAR-RIS, Multiple Users (SA)	Blocked	Rician fading	DDPG	EE is maximized by jointly optimizing BS beamforming vectors and STAR-RIS coefficient matrices.
[80]	2021	UL NOMA, BS (MA), STAR-RIS (1), Multiple Users (SA).	Blocked	Rician fading	Penalty-based AO algorithm	Overall power consumption is minimized by optimizing user transmit power, recieve BF vectors at BS, BF vectors of STAR at STAR-RIS and time slots.
[81]	2021	DL OMA, BS (MA), STAR-RIS (1), Users (SA).	Blocked	Rician fading	Iterative algorithm	Jointly optimized active and passive BF problem to decrease the power usage of the BS while meeting user QoS needs.
[82]	2022	DL OMA, BS (MA), STAR-RIS (1), Users (SA).	Blocked	Rician fading	Penalty-based Iterative algorithm and SCA	Power minimization problem is framed to jointly optimize BF for BS and STAR-RIS leveraging iterative algorithm for solution exploiting the penalty method and SCA.
[83]	2022	DL MISO, AP (MA), STAR-RIS (1), Users (SA).	Rayleigh fading	Rayleigh fading	Hybrid DDPG and DDPG-DQN	Reducing long-term transmission power usage subject to phase shift and data rate constraints.
[84]	2022	FD, BS Tx(SA) Rx(SA), STAR-RIS (1), UL user (SA) R region, DL user (SA) T region.	Heavy shadowing	Rician fading	AO algorithm	To achieve the maximum possible EE for the system while also satisfying the requirements for the UL and DL minimum rates.

Ref-Reference, DL-Downlink, UL-Uplink, SA-Single Antenna, MA-Multi-Antenna, FD-Full-duplex

In contract to NOMA based radio access technology works in [79], [80], Mu *et al.* [81] considered OMA network and investigated an innovative STAR-RIS concept where a power consumption minimization issue was developed to optimize active beamforming at the BS and passive broadcast and reflection beamforming at the STAR-RIS under user-imposed communication frequency constraints. The resulting strongly connected non-convex optimization problem was addressed using an iterative method involving the penalized method and sequential convex approximation. Calculated results revealed that, compared to RIS, STAR-RIS can drastically reduce BS power consumption. Moreover, it was revealed that element-wise amplitude control performed better than group-wise amplitude control for STAR-RIS. Similarly, Mu *et al.* [82] conducted research on the unique concept of STAR-RIS. On the basis of the 'STAR' signal model development, three realistic working protocols for STAR-RIS, MS, TS, and ES were proposed. A STAR-RIS-assisted downlink communication system that transmits information to users on both sides of the STAR-RIS was also considered. A challenge was presented for the best allocation of active beamforming at the BS and passive transmission and reflection beamforming at the STAR-RIS, subject to user-imposed communication rate limits for each of the proposed operational protocols. Using an iterative strategy based on successive convex approximation and the penalty method, ES's resulting highly linked non-convex optimization problem was resolved. The optimization problem for MS involving mixed-integer non-convexity was solved by extending the proposed penalty-based iterative technique. Using convex optimization approaches and cutting-edge algorithms, the optimization issue for TS was divided into two manageable subproblems. In addition, numerical findings reveal that the proposed approach substantially reduces the required power and that the TS and ES operating protocols are frequently selected for unicast and multicast transmission, respectively.

Zhong *et al.* [83] investigated the STAR-RIS MISO scenario and considered a coupled phase-shift model. By defining a joint passive and active beamforming optimization problem, the power consumption for long-term broadcasting was minimized under the coupled phase-shift restriction and the least data rate constraint. By employing a hybrid continuous and discrete phase-shift control policy, despite the coupled nature of the phase-shift model, the formulated issue was handled. This realization led to the creation of two hybrid RL algorithms, namely the joint DDPG and deep-Q network-based algorithm and the hybrid deep deterministic policy gradient algorithm. In accordance with the hybrid action mapping, the hybrid DDPG technique manages the associated high-dimensional continuous and discrete actions. The combined DDPG-DQN algorithm provides a joint hybrid control by generating two Markov decision processes (MDPs) dependent on the outer and inner environment. The results of the simulation demonstrate that the STAR-RIS uses less energy than other RISs. Moreover, the joint DDPG-DQN algorithm achieves enhanced performance despite having a higher computational complexity than any of the presented approaches, which both surpass the original DDPG algorithm.

Wang *et al.* [84] claimed that RIS was a technique with the potential to enhance the functionality of future wireless networks. Then, an innovative STAR-RIS has been proposed to facilitate communication. Using a sophisticated controller to alter the EM properties of the STAR-RIS components, the incident signal can be split into reflected and transmitted signals, allowing for 360-degree coverage. In their work, the authors demonstrated the efficacy of a FD communication system with STAR-RIS support, in which an FD-BS simultaneously communicates with a UL and DL user across the same time frequency domain. The objective was to maintain a minimal data rate while decreasing the total transmit power. Using the AO paradigm, the original issue was subdivided into power optimization and STAR-RIS passive beamforming issues. Using the SDP and SCA method, each iteration obtained the closed form expression for the ideal power plan and solved the passive beamforming optimization subproblem. The simulation findings demonstrated that STAR-RIS was more successful than conventional RIS. In cases with higher data rates and lower SI, STAR-RIS-assisted FD schemes would also perform better than HD options.

E. Mitigating Interference Leveraging STAR-RIS

In future cellular networks, it is projected that the coverage of densely deployed small cells would overlap, hence increasing the likelihood of multi-cell interference. In this context, one of the most important uses of STAR-RIS technology is the decrease of interference in wireless networks caused by many cell scenarios. For instance, the STAR-RIS might be designed for signal refraction and reflection towards the desired edge users in a given cell, while concurrently suppressing the signals aimed at the undesired users as shown in Fig. 7.

Coordination among small-cells is an intricate and ongoing research problem since multiple small-cells may share the same STAR-RIS. While in practice, a BS in a small-cell only gets the CSI of its own linked users, the analogue beamforming at the STAR-RIS has an effect on all users in the near vicinity. As a result, methods are required to coordinate the small-cell BSs efficiently. In this setting, machine learning can be utilised to coordinate multiple small-cells in challenging wireless environments. This subsection examines cutting-edge methods for mitigating interference using STAR-RIS for various scenarios. It is complemented by a summary in Table VIIIto help readers understand the fundamental ideas and develop a deeper understanding of the key technologies.

In the article [85], Hou *et al.* presented a novel simultaneous-signal-enhancement-and-cancellation-based (SSECB) design based on signal-cancellation-based (SCB) designs and signal enhancement-based (SEB) designs (SEB). This permits the inter-cell differences and preferred signals to be removed and improved in parallel. In addition, the simulation analysis revealed that numerous RIS elements may be used to perfectly eliminate inter-cell interference while optimizing the needed signals, and how the recommended SSECB design is superior to the conventional SCB and SEB schemes. In future investigations, the passive beamforming, active beamforming, and detection vectors should be designed cooperatively to increase RA and TA at the base station and for users. Combining stochastic geometry approaches with the evaluation of the consequences of unpredictability in user location is a potential future development. In another work, Zhang *et al.* [86] investigated an IOS that enables simultaneous signal transmission and reflection, thereby benefiting users on both sides. To eliminate inter-cell interference, they developed an IOS-enhanced indoor communication structure

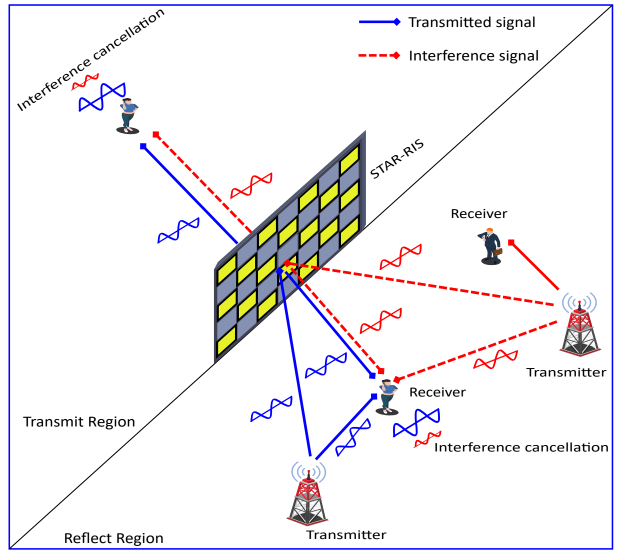

Fig. 7: Illustration of STAR-RIS for mitigating interference

consisting of an IOS installed between two autonomous APs. To increase the total rate without sending CSI between APs, they devised a remote hybrid beamforming system that combines digital beamforming at the AP level with IOS-based analogue beamforming. In terms of sum rate performance, simulation findings reveal that the proposed system surpasses existing schemes and closely matches the performance of an optimal centralized scheme.

Full-duplex (FD) transmission provides more bandwidth than half-duplex (HD) transmission, according to Fang *et al.* [87]; nonetheless, self-interference (SI) is the largest issue. This study, however, differs from those in [85], [86], which focused on inter-cell interference. Initially, IOS-FD-MISO was recommended to address the intensity problem, whereas ES-IOS and MS-IOS were presented to increase the data rate and lower SI power, respectively. These obstacles were difficult to address directly. Consequently, they designed a revolutionary optimization method. Specifically, the amplitudes and phase shifts of the ES-IOS and MS-IOS were optimised using quadratic constraint quadratic programming (QCQP). Due to the complexity of binary IOS variables, they apply SDR and the Gaussian randomization technique to solve the problem. The findings demonstrate that both IOSs effectively reduce SI compared to the lack of an IOS, proving the usefulness of the suggested techniques.

F. Resource Allocation

The motivation for this research is the realisation that, unlike conventional reflecting-only RISs, STAR-RIS utilised in wireless systems can accomplish a full-space SRE. It is crucial to develop a resource allocation policy for STAR-RIS with the primary goal of optimising system performance in order to reach its full potential. However, the optimization factors are highly interdependent on one another (such as transmit power, channel assignment, TARCs, and factor of time allocation/decoding order). Since the user-grouping

TABLE VIII: A summary of STAR-RIS based schemes for mitigating interference in different scenarios

Ref	Year	Scenario	Channel Characteristics		Methods	Proposed Solution
			Direct	Reflective-Refractive		
[85]	2022	DL NOMA-CoMP, BS (MA), STAR-RIS (2) Users (SA)	Rayleigh fading	Rician fading	SSECB design	SSECB approach is proposed to boost desired signal and cancel inter-cell interferences simultaneously.
[86]	2022	DL MIMO, AP (2) (MA), IOS (1), Users (SA).	Rician fading	Rician fading	Distributed hybrid beamforming design algorithm	Digital BF at APs and IOS assisted analog BF are proposed to enhance sum rate
[87]	2022	FD MISO, Tx (MA), IOS (1), User (SA).	Rician fading	Rician fading	AO algorithm.	By optimizing ES-IOS beamforming vectors, phase shifts, amplitudes, and the mode selection and phase shifts for the MS-IOS to minimize SI power and maximize data rate.

Ref-Reference, DL-Downlink, UL-Uplink, AP- Access point, SA-Single Antenna, MA-Multi-Antenna, FD-Full-duplex, Tx-Transmitter

problem appears in multi-carrier transmission, allocating resources is not a simple task. In view of this, it is crucial to create effective algorithms for STAR-RIS-based wireless communication systems. This section adds to the STAR-RIS research by looking at how resources are allocated in OMA and NOMA communication networks. Moreover, a summary in Table IX of resource allocation based schemes is also enclosed for comparative analysis.

Two significant issues for RIS-aided vehicular communications are the cascaded links encountering double fading and the CSI acquisition imposed by high mobility. By simultaneously sending and amplifying the incident signals instead of only reflecting them, Chen *et al.* in [88] presented RIOS as a novel type of RIS to address these issues. Active RIOS is installed on the automobile window to improve transmission for both passengers and nearby drivers. Their objective was to simultaneously optimise the broadcast precoding matrix at the BS and RIOS coefficient matrices to minimise the BS's transmit power despite having a limited comprehension of the large-scale CSI. With limited understanding of the large-scale CSI, their goal was to concurrently optimize the broadcast precoding matrix at the BS and RIOS coefficient matrices to reduce the BS's transmit power. To decrease the frequency of network various trends, an effective transmission protocol was proposed to use high active RIOS beamforming gain with minimal network training overhead by skillfully adjusting the timing of CSI collection. Constrained stochastic sequential convex approximation (CSSCA) and Alternating optimization (AO) techniques were used to approach the examined resource allocation problem. Simulation results validate active RIOS's considerable performance boost and the correctness and durability of their suggested algorithms compared to standard systems.

In contrast to the studies in [88], which only investigated vehicular OMA downlink network, Yang *et al.* [89], studied a NOMA system assisted by STAR-RIS. They presented discrete amplitude allocation and joint power techniques that can lessen the burden associated with channel approximation and the difficulty of the hardware. To certify the QoS requirements of the reflected user, the Beaulieu series over Nagakami-m fading was created to appraise the performance of the suggested method. Then, closed-from terminologies were discovered for the various order of the reflected user and outage probability (OP). Additionally, a lower bound of the communicated user's outage possibility was examined due to the integrated network statistic of the communicated user. Numerical findings showed that the suggested technique significantly enhances the appearance of the affected user and produces a higher output.

Unlike the work in [89], which focused on downlink scenario, Ni *et al.* [90] considered uplink and combined over-the-air federated learning (AirFL) with NOMA through concurrent broadcasts in a scalable and unified model. The signal processing order was modified in a particular way to make use of STAR-RIS for effective interference reduction and Omni directional service improvement. To observe the effects of non-ideal wireless communication on AirFL, a closed-form equation was derived for the optimality gap over a certain communication circles to examine effects of non-ideal wireless communication on AirFL. These findings showed that the allocating resource mechanism and channel interference significantly influence learning performance. To reduce the obtained optimality gap, an MINLP problem was framed by concurrently designing the communication power at the users' side and configuration mode provided by STAR-RIS. Based on the results, using the STAR-RIS helps in boosting training process in sense of test accuracy and learning loss.

Wu *et al.* [91] studied the issue of resource distribution in multi-carrier communication networks aided STAR-RIS. To maximise the system sum rate, a shared optimization problem involving power allocation, channel assignment, reflection, and transmission beamforming at the STAR-RIS for OMA was designed. They established a channel task scheme based on matching theory and iteratively improved the beamforming vectors and resource allocation approach using the AO-based method. The authors then investigated the optimization of the sum rate for NOMA with adjustable decoding orders. Initially, a location-based matching algorithm that groups a transmitted and reflected user on a subchannel was presented to effectively address the issue. Semidefinite programming, convex upper bound approximation, and geometry programming were proposed as a three-stage process to carry out this reflection and transmission sub-channel task plan. Numerical results show

TABLE IX: A summary of STAR-RIS based approaches under different resources allocation

Ref	Year	Scenario	Channel Characteristics		Methods	Proposed Solution
			Direct	Reflective-Refractive		
[88]	2022	DL vehicular, BS (MA), Active-RIOS (1), UEs (SA).	Rician Fading	Quasi static and nearly LoS dominant	AO and a constrained stochastic (CSSCA) based algorithm	The BS's transmit power was reduced by jointly optimizing the transmit precoding matrix at the BS and RIOS coefficient matrices.
[89]	2022	DL NOMA, BS (SA), STAR-RIS (1), Two Users (SA).	Nakagami-m fading	Nakagami-m fading	Beaulieu series	Minimizing channel estimate cost and hardware complexity by joint power and discrete amplitude allocation scheme
[90]	2021	UL NOMA, BS (SA), STAR-RIS (1), Multiple Users.	Rician fading	Rician fading	AO algorithm	STAR-RIS aided heterogeneous networks serve NOMA and AirFL users non orthogonally by sharing temporal and spectral resources.
[91]	2022	DL OMA and NOMA, AP (SA), STAR-RIS (1), Users (SA).	Blocked	Rician fading	Matching theory and AO algorithm	The RA problem of STAR-RIS is formulated for both OMA and NOMA to enhanced sum rate.

Ref-Reference, DL-Downlink, UL-Uplink, AP-Access point, SA-Single Antenna, MA-Multi-Antenna, FD-Full-duplex, Tx-Transmitter

that same-side user pairing for channel assignment in a generic design is superior to OMA. In contrast, the projected reflection and transmission system performs the exhaustive search-based NOMA algorithm. In addition, the STAR-RIS-NOMA network outperforms typical RIS and OMA networks. Analytical modelling of the STAR-RIS coefficients' interactions was crucial. The resource allocation will become significantly more difficult, considering the practical models, as numerous new limitations are added. So, the questions about how to deal with the constraints by simplifying the model and using more effective methods need to be looked at in more depth.

G. Performance Analysis

The use of STAR-RIS is a potential way for generating a flexible wireless broadcast environment. Incident signals can be transmitted and reflected back to users at different surface edges in the most recent STAR-RIS design. Thus, each STAR-RIS component required the setup of two coefficients. The first is set to change the phase shifts and amplitudes of the transmit signal, and the second is set for the reflect signal. In difficult locations with insufficient direct AP-user connectivity, in order to boost signal STAR-RIS can be used.

In this section, we'll examine the studies that have been conducted to assess STAR-RIS performance in relation to OMA and NOMA. Outage probabilities are calculated for a variety of wireless network configurations, including perfect and imperfect SICs, varying channel conditions, and phase shift configuration strategies, all of which are relevant to evaluating the efficacy of STAR-RISs under different access technologies. Additionally, the STAR-RIS channel estimation and bit error rate (BER) performance are evaluated considering several users spread out on surface sides using a NOMA-based approach. A Table X summarizing the performance evaluation based works is given for better understanding the scenarios, channel characteristics, techniques, and evaluation strategies of each scheme.

1) Performanance Analysis for OMA based STAR-RIS : In contrast to RIS, the coverage of STAR-RIS is increased to 360 degrees. Xu *et al.* [92] proposed a generic hardware model for STAR-RIS. The diversity gain of STAR-RIS was compared to that of conventional RISs by simulating channels and then projecting the results for both far-field and near-field conditions. Analytical results are corroborated by numerical simulations, which show that full diversity order can be achieved across both sides of the STAR-RIS. Different from [92], Wu *et al.* [93] looked into a STAR-RIS-aided uplink channel estimation design for a two-user communication system. They first evaluated the STAR-RIS TS protocol and then devised a workable method for estimating the channels of two users using a transmission/reflection training pattern. Then, the authors considered the realistic coupled phase-shift model and came up with a novel approach to simultaneously estimate the channels of both users when evaluating the ES protocol for STAR-RIS. The authors demonstrated an effective way for generating a high-quality solution by simultaneously creating the pilot sequences, training patterns, and power-splitting ratio. However, reducing the channel estimation error that resulted from using the ES protocol was a significant obstacle to overcome. Estimates of the uplink channel show that TS is more cost-effective than ES. Downlink channel estimations and resilient beamforming in the presence of imperfect CSI may be the focus of future research.

2) Performanance Analysis for NOMA based STAR-RIS : Wang *et al.* [94] evaluated the OP in a STAR-RIS-assisted NOMA wide network by analysing the spatial correlations between channels. The authors use a moment-matching technique to initially approximate the distribution of the composite channel gain as a gamma random variable in order to study the effects of channel correlations on system performance. Following that, the author presents closed-form expressions of OP for two NOMA users. The theoretical method is validated by numerical results, which also exhibit performance loss due to channel correlations. in another work, Yue *et al.* [95] examined the OP and ER of networks over Rician channels and provided an in-depth analysis of STAR-RIS-NOMA. The corresponding probability of outages for users "n" and "m". The diversity rankings of the users' "n" and "m" are determined using asymptotic results. It has been shown that STAR-RIS-NOMA is more likely to have outages than STAR-RIS-OMA. In addition, the theoretical formulations of the ER for users "n" and "m" with pSIC were meticulously reported along with their corresponding high SNR slopes. According to numerical results, the ER of user "n" with pSIC outperforms orthogonal users at high SNRs. The NOMA-based STAR-RIS system's throughput was also measured in both delay-limited and delay-tolerant configurations. STAR-RIS-NOMA has the potential to achieve stricter QoS demands in practical use cases, where "n" and "m" users may be high and low bitrate video streaming clients, respectively. For NOMA-based STAR-RIS networks, perfect CSI configuration may result in overstated performance promises. Future studies may examine the effects of inaccurate CSI and look for efficient channel estimate techniques.

STAR-IOS regulates NOMA based SIC by dividing energy or altering active elements. Zhang *et al.* [96] examines STAR-IOS-assisted NOMA's benefits with randomly distributed users. and proposed three tractable channel models including Central limit, curve fitting, and M-fold convolution. Curve fitting analyses multi-cell networks, whereas central limit modelling fits massive STAR-IOS scenarios. Both categories cannot organise variation. M-fold convolution organises diversity. STAR-IOS uses ES, TS, and MS. NOMA users get analytical closed-form OP from ES protocol-based central limit and curve fitting models. M-fold convolution and 3 protocols calculate NOMA user diversity gains. NOMA users diversified like STAR-IOS. The central limit model gives an upper bound and the curve fitting model provides a lower bound in regions of high SNR ratio; the TS protocol performs best but demands more time blocks than other protocols; and the ES protocol outperforms the MS protocol due to its larger diversity gains. Similarly, the BER performance of STAR-RIS in NOMA networks was studied by Aldababsa *et al.* [97]. Multiple NOMA users in the analysed network are served by a STAR-RIS adopting MS protocol. The BER equations for both the perfect and imperfect SIC instances are derived. To further investigate the BER's behaviour at high SNR, an asymptotic analysis is also conducted. The authors theoretical investigation is supported by Monte Carlo simulations. When compared to traditional NOMA, STAR-RIS-NOMA delivers superior BER performance, implying that it could be a NOMA 2.0 option.

In contrast to [94]–[97], which focused on dowlink NOMA-based systems, Sheng *et al.* [98] examined STAR-RIS for uplink that enables several users to communicate in a power-domain NOMA environment while sharing the same time-frequency resources. Though users have nearly the same spread power and distance from the AP as they approach the cell boundary, system performance degrades at this point. To actively address this issue, only elements that can enhance the channel for the targeted users were selected. Therefore, the entire cascade channel is adjusted to provide an optimum environment for NOMA transmission. Simulation findings reveal that the improved performance of SIC at the receiver can lead to a reduction in BER.

3) Performanance Analysis for both OMA and NOMA based STAR-RIS : Xu *et al.* [99] investigated STAR-RIS and concentrated on transmission and reflection phase shifts that were linked. By presenting the design for diversity preservation, the authors demonstrate how to acquire complete diversity on both sides. For OMA and NOMA, a STAR-RIS-assisted two-user downlink communication system is explored. Upper and lower performance limitations are compared with OP, diversity order, and power scaling rules. It has been established through simulations that the proposed diversity-preserving phase-shift strategy for the STAR-RIS provides the same diversity order as independent phase shift of STAR-RIS and obtains a comparable power scaling law with only a 4 dB power drop.

Xu *et al.* [100] examined OMA and NOMA utilizing a two-user downlink communication system aided by STAR-RIS in their article. To evaluate the impact of the connected broadcast and reflection phase-shift model on communication performance, the diversity-preserving phase shift configuration (DP-PSC), the primary-secondary phase shift configuration (PS-PSC), and the T/R-group phase-shift configuration (TR-PSC) were designed. According to the findings, the proposed DP-PSC technique simultaneously satisfies all guidelines for users on both sides of STAR-RIS. In addition, scaling rules for power were developed for the random phase-shift configuration and the three proposed techniques. Using NOMA rather than OMA on each side of the STAR-RIS improved performance, according to numerical simulations. In addition, it was demonstrated that the proposed DP-PSC technique achieves the same variety order as STAR-RIS under the independent phase shift model and a similar power scaling law with just a 4 dB decrease in received power.

IV. FUTURE RESEARCH DIRECTIONS AND CHALLENGES

QoS has improved with each generation of wireless networks. Concurrently with the deployment of 5G networks, 6G network research is being conducted. The RISs are among the competitive 6G components [19], [24], [101]. They improve mmWave communications [102], energy-efficient communication [6], and propagation for edge users. RISs can do more than just signal boosting and can perform functions like estimating channels [103], users' localization [104], and integrated sensing and reflecting [105].

In this section, we examine where the field of STAR-RIS-assisted wireless networks is headed and what future challenges it may face. We briefly discuss STAR-RIS challenges and potential future directions of research. Additional intriguing applications of STAR-RISs in 6G networks include STAR-RIS-assisted simultaneous wireless information and power transfer (SWIPT), STAR-RIS-assisted visible light

TABLE X: A summary of performance analysis for STAR-RIS based scenarios

Ref	Year	Scenario	Channel Characteristics		Methods	Proposed Solution
			Direct	Reflective-Refractive		
[92]	2021	DL OMA, Tx (SA), STAR-RIS (1), Rxs (SA).	Rician fading	Rician fading	OP	To assess the performance of STAR-RISs, the asymptotic behavior of the OP was expressed.
[93]	2022	UL OMA, BS (SA), STAR-RIS (1) Two Users (SA)	Rician fading	Rician fading	Channel Estimation	Consider the TS protocol first for STAR-RIS, then suggested a technique to estimate the two users' channels separately using an optimal training (transmission/reflection) pattern. Next, analyze ES protocol under the coupled phase shift model and suggested a technique to estimate both users' channels simultaneously .
[94]	2022	DL NOMA, Tx (SA), STAR-RIS (1), Users (SA).	Blocked	Small scale fading	moment matching method	Outage Probability analysis performance loss caused by channel correlations.
[95]	2022	DL NOMA, BS (SA), STAR-RIS (1), Users (SA)	Rayleigh fading	Rician fading	OP and ER	To measure performance, OP and ER were developed for a pair of users.
[96]	2022	DL NOMA, BS, STAR-RIS (1), Randomly Users	Blocked	Rician fading	Central limit mode, curve fitting model, and M-fold convolution model	Three STAR-IOS channel models are provided, and the NOMA outage performance framework is analyzed with scattered users.
[97]	2022	DL NOMA, BS (SA), STAR-RIS (1), Users (SA).	Blocked	Rayleigh fading	BER Analysis	BER performance analysis.
[98]	2022	UL NOMA, AP (SA), STAR-RIS (1), Users (SA).	Blocked	Rician fading	Element selection method	Only elements that help the user's channel are enabled. As a consequence, the entire cascade channel is reconfigured for NOMA transmission to offer the best propagation environment.
[99]	2022	DL OMA and NOMA, BS (SA), STAR-RIS (1), 2 Users (SA).	Blocked	Rician fading	Phase-shift design	Analysis and comparison of the upper and lower performance with the power scaling laws, diversity orders, and the OP are performed.
[100]	2022	DL OMA and NOMA, BS (SA), STAR-RIS (1), Users (SA).	Rician fading	Rician fading	Phase shift configuration strategies	The performance achieved by STAR-RIS were evaluated and compared with different Phase shift configuration strategies.

Ref-Reference, DL-Downlink, UL-Uplink, AP- Access point, SA-Single Antenna, MA-Multi-Antenna, FD-Full-duplex, Tx-Transmitter

communications (VLC), and STAR-RIS-enhanced robotic communications. These applications hold promise for future research.

Open Issues and Future Research Direction

Moreover, the implementation of the STAR-RIS presents a number of novel challenges and complications, including the following:

- To expand coverage, the analog beamforming and digital beamforming at the RIS and BS, respectively, must be designed jointly. Practical constraints, such as discrete phase changes, necessitate efficient algorithms. How to achieve a balance between performance on the two sides of STAR-RIS is a daunting challenge to investigate.
- At STAR-RIS, the effectiveness of analogue beamforming is heavily reliant on the accuracy of the CSI [4]. Since these channels of STAR-RIS' sides are interconnected, the CSI of users on both sides of the surface must be jointly estimated.
- Evaluating the efficacy of multi-user NOMA networks aided by STAR-RIS with defective SIC and CSI is an additional challenging future research topic.
- A STAR-RIS performance depends on its proximity to the transmitter and users. The optimal deployment of a STAR-RIS by balancing its reflecting and transmitter capabilities is an unanswered research question.
- While STAR-RISs have certain advantages, developing their corresponding TARCs can be difficult. When it comes to the STAR-RIS, first, transmission-reflection beamforming is a far more advanced option than reflection-only beamforming. Because electric and magnetic impedance depend on the electromagnetic properties of the STAR components, STAR-RISs cannot independently affect TARCs. Coupled transmit and reflect coefficients necessitate a hybrid continuous and discrete control scheme for phase-shift design. Given the aforementioned obstacles and the fact that current convex optimization and machine learning techniques only permit continuous or discrete control, it is challenging to solve the transmission and reflection beamforming problem for STAR-RISs. In such cases, attention should be given to hybrid algorithms for small action dimensions.
- The performance of wireless communication systems depends on efficient resource use. Phase shift and beamforming of passive elements are optimized in STAR-RIS-enhanced communication to increase coverage and boost PLS-based security over traditional communication systems. RIS and resource allocation—for example, sub-carrier, power distribution, and trajectory design in the case of UAV integration—are frequently related, making design optimization difficult and resulting in suboptimal designs. Differences between optimal and suboptimal performance, however, are not apparent. Therefore, to optimize RIS-enhanced communication in a wide range of applications, appropriate strategies must balance computational complexity and system

performance.

- The resource allocation for wireless communication systems involving STAR-RIS for OMA and NOMA system resource allocation including power allocation, channel assignment, reflection and transmission beamforming at the STAR-RIS for OMA. It is difficult to optimize large-scale STAR-RIS-enhanced wireless communications, particularly when UAVs are involved and placed in an environment that is partially unknown. Due to nonlinear models, it is particularly difficult to create an optimal UAV trajectory, RIS reflecting elements, and network resource optimization. Thus, it is complicated to design approaches with low complexity and efficient system performance. Approaches based on AI and machine learning are formidable tools for developing and optimizing such networks. These techniques are rapidly evolving and offer powerful and promising tools for planning and optimizing complex situations. Moreover, the complex system can be analyzed using hybrid models, data-driven approaches, and hybrid offline and online methods to improve system performance.
- There are three main obstacles to overcome while developing and deploying active STAR-RIS for high-mobility applications like vehicular communication networks. To begin with, the active STAR-RIS will always increase the noises, leading to even more noises at the receiver, which could reduce the system's efficiency. As a result, optimally setting the coefficients of the active STAR-RIS elements is essential for striking a balance between the competing demands of maximizing the received signal strength while simultaneously reducing the noise impact. Second, beamforming precision is highly dependent on CSI acquisition precision. As the predicted CSI quickly becomes out of date in cases with highly dynamic channels, there will always be noticeable CSI discrepancies due to Doppler shifts. This means that in a dynamic environment, the beamformed transmission calls for strong beamforming techniques that are specially designed to the unique requirements of the transmission. Third, it is challenging to keep track of the instantaneous CSI in practice due to continuous changing mobile channels. Moreover, significant signaling overheads are associated with the frequent feedback of fading information. These challenges are made worse by the large number of cascaded channel coefficients introduced by active STAR-RIS. Therefore, there is need of further research in highly mobile scenarios considering the aforementioned open challenges in active STAR-RIS.
- For sensing and localization, RF signals are increasingly used because they are inexpensive and maintain confidentiality. RF sensing and localization is reliant on exploiting the environment-dependent features of wireless signals. To attain a high level of precision, it is imperative that the signals captured at two distinct sites are as diverse as possible. STAR-RIS is a deemed effective for RF sensing and localization in this scenario because it can alter propagation channels to make them more distinct from one another. Additionally, the STAR-RIS's ability to communicate in all dimensions can reduce the number of uncovered areas effectively.
- Nonetheless, the implementation of sensing and localization through STAR-RIS must overcome a number of challenges. Optimizing the STAR-RIS analog beamforming to reduce errors while sensing and localization is one of them. Compressed sensing techniques can be used in a variety of situations when signals are limited in specific areas. The signals can also be sorted according to the presence of things and users' locations using machine learning techniques.
- Future IoT networks may feature simultaneous wireless information and power transfer (SWIPT). Energy harvesting (EH) makes it possible for IoT devices to draw power from ambient EM sources or from purpose-built EH sources, such as those that emit EM waves simultaneously [106]. Low EH efficiency makes it hard to use SWIPT systems in the real world [107]. Implementing a STAR-RIS for SWIPT system is one approach that shows promise for addressing this issue. To be more precise, the STAR-RIS is able to concentrate EM waves, resulting in an increase in the efficiency of energy harvesting.

V. Conclusion

This survey provides a detailed review of the STAR-RIS, with a particular emphasis on the most recent schemes for distinct use cases in 6G networks, resource allocation, and performance evaluation. We begin with an overview of RIS (passive, active, and STAR-RIS), followed by a discussion of the STAR-RIS protocols, their benefits, and their applications. In addition, we grouped the schemes according to their use cases, which include improving coverage, PLS, sum rate, EE, and mitigating interference. Then, we examine several resource allocation strategies and performance evaluation criteria. We endeavored to elucidate, compare, and evaluate the literature in terms of settings, techniques, and objectives. Finally, we discuss outstanding research challenges and probable new research directions in this field.

References

[1] W. Saad, M. Bennis, and M. Chen, "A vision of 6g wireless systems: Applications, trends, technologies, and open research problems," *IEEE network*, vol. 34, no. 3, pp. 134–142, Oct, 2019.

[2] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G. K. Karagiannidis, and P. Fan, "6g wireless networks: Vision, requirements, architecture, and key technologies," *IEEE Vehicular Technology Magazine*, vol. 14, no. 3, pp. 28–41, Jul, 2019.

[3] M. Di Renzo, A. Zappone, M. Debbah, M.-S. Alouini, C. Yuen, J. De Rosny, and S. Tretyakov, "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead," *IEEE journal on selected areas in communications*, vol. 38, no. 11, pp. 2450–2525, Jul, 2020.

[4] C. Huang, S. Hu, G. C. Alexandropoulos, A. Zappone, C. Yuen, R. Zhang, M. D. Renzo, and M. Debbah, "Holographic mimo surfaces for 6g wireless networks: Opportunities, challenges, and trends," *IEEE Wireless Communications*, vol. 27, no. 5, pp. 118–125, Jul, 2020.

[5] W. U. Khan, E. Lagunas, Z. Ali, M. A. Javed, M. Ahmed, S. Chatzinotas, B. Ottersten, and P. Popovski, "Opportunities for physical layer security in UAV communication enhanced with intelligent reflective surfaces," *arXiv preprint arXiv:2203.16907*, 2022.

[6] C. Huang, A. Zappone, G. C. Alexandropoulos, M. Debbah, and C. Yuen, "Reconfigurable intelligent surfaces for energy efficiency in wireless communication," *IEEE Transactions on Wireless Communications*, vol. 18, no. 8, pp. 4157–4170, Jun, 2019.

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

[8] I. F. Akyildiz, C. Han, and S. Nie, "Combating the distance problem in the millimeter wave and terahertz frequency bands," *IEEE Communications Magazine*, vol. 56, no. 6, pp. 102–108, Jun, 2018.

[9] ITU-R, "Future technology trends of terrestrial imt systems towards 2030 and beyond,," https://www.itu.int/md/R19-WP5D-210607-TD-0400,, Jun. 2021.

[10] ZTE-Corporation, "Support of reconfigurable intelligent surface for 5g advanced,," https://www.3gpp.org/ftp/TSGRAN/TSGRAN/TSGR91e/Docs/RP-210618.zip,[, Mar. 2021.

[11] Sony-Europe, "Reconfigurable intelligent surfaces and smart repeaters for 5g-advanced,," https://www.3gpp.org/ftp/TSGRAN/TSGRAN/TSGR93e/Docs/RP-212166.zip, Sep. 2021.

[12] "Etsi launches a new group on reconfigurable intelligent surfaces," https://www.etsi.org/newsroom/press-releases/1979-etsi-launches-a-new-group-on-reconfigurable-intelligent-surfaces, Oct. 2021.

[13] "Meeting detail of tc5 wg6 meeting 55," https://www.ccsa.org.cn/, Sep. 2020.

[14] Y. Liu, X. Mu, J. Xu, R. Schober, Y. Hao, H. V. Poor, and L. Hanzo, "Star: Simultaneous transmission and reflection for 360° coverage by intelligent surfaces," *IEEE Wireless Communications*, vol. 28, no. 6, pp. 102–109, Dec, 2021.

[15] Y.-C. Liang, R. Long, Q. Zhang, J. Chen, H. V. Cheng, and H. Guo, "Large intelligent surface/antennas (lisa): Making reflective radios smart," *Journal of Communications and Information Networks*, vol. 4, no. 2, pp. 40–50, Jun, 2019.

[16] M. D. Renzo, M. Debbah, D.-T. Phan-Huy, A. Zappone, M.-S. Alouini, C. Yuen, V. Sciancalepore, G. C. Alexandropoulos, J. Hoydis, H. Gacanin *et al.*, "Smart radio environments empowered by reconfigurable ai meta-surfaces: An idea whose time has come," *EURASIP Journal on Wireless Communications and Networking*, vol. 2019, no. 1, pp. 1–20, May, 2019.

[17] S. Gong, X. Lu, D. T. Hoang, D. Niyato, L. Shu, D. I. Kim, and Y.-C. Liang, "Toward smart wireless communications via intelligent reflecting surfaces: A contemporary survey," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 4, pp. 2283–2314, Jun, 2020.

[18] S. Kisseleff, W. A. Martins, H. Al-Hraishawi, S. Chatzinotas, and B. Ottersten, "Reconfigurable intelligent surfaces for smart cities: Research challenges and opportunities," *IEEE Open Journal of the Communications Society*, vol. 1, pp. 1781–1797, Nov, 2020.

[19] M. A. ElMossallamy, H. Zhang, L. Song, K. G. Seddik, Z. Han, and G. Y. Li, "Reconfigurable intelligent surfaces for wireless communications: Principles, challenges, and opportunities," *IEEE Transactions on Cognitive Communications and Networking*, vol. 6, no. 3, pp. 990–1002, May, 2020.

[20] Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface-aided wireless communications: A tutorial," *IEEE Transactions on Communications*, vol. 69, no. 5, pp. 3313–3351, Jan, 2021.

[21] W. Long, R. Chen, M. Moretti, W. Zhang, and J. Li, "A promising technology for 6g wireless networks: Intelligent reflecting surface," *Journal of Communications and Information Networks*, vol. 6, no. 1, pp. 1–16, Mar, 2021.

[22] S. Kisseleff, S. Chatzinotas, and B. Ottersten, "Reconfigurable intelligent surfaces in challenging environments: Underwater, underground, industrial and disaster," *IEEE Access*, vol. 9, pp. 150 214–150 233, 2021.

[23] X. Yuan, Y.-J. A. Zhang, Y. Shi, W. Yan, and H. Liu, "Reconfigurable-intelligent-surface empowered wireless communications: Challenges and opportunities," *IEEE wireless communications*, vol. 28, no. 2, pp. 136–143, Feb, 2021.

[24] Y. Liu, X. Liu, X. Mu, T. Hou, J. Xu, M. Di Renzo, and N. Al-Dhahir, "Reconfigurable intelligent surfaces: Principles and opportunities," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 3, pp. 1546–1577, May, 2021.

[25] H. Zhang, B. Di, K. Bian, Z. Han, H. V. Poor, and L. Song, "Toward ubiquitous sensing and localization with reconfigurable intelligent surfaces," *Proceedings of the IEEE*, vol. 110, no. 9, pp. 1401–1422, May, 2022.

[26] E. Björnson, H. Wymeersch, B. Matthiesen, P. Popovski, L. Sanguinetti, and E. de Carvalho, "Reconfigurable intelligent surfaces: A signal processing perspective with wireless applications," *IEEE Signal Processing Magazine*, vol. 39, no. 2, pp. 135–158, Feb, 2022.

[27] B. Zheng, C. You, W. Mei, and R. Zhang, "A survey on channel estimation and practical passive beamforming design for intelligent reflecting surface aided wireless communications," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 2, pp. 1035–1071, Feb, 2022.

[28] S. Aboagye, A. R. Ndjiongue, T. M. N. Ngatched, O. A. Dobre, and H. V. Poor, "Ris-assisted visible light communication systems: A tutorial," *IEEE Communications Surveys Tutorials*, pp. 1–1, Dec, 2022.

[29] H. Zhang, S. Zeng, B. Di, Y. Tan, M. D. Renzo, M. Debbah, Z. Han, H. V. Poor, and L. Song, "Intelligent omni-surfaces for full-dimensional wireless communications: Principles, technology, and implementation," *IEEE Communications Magazine*, vol. 60, pp. 39–45, Feb, 2022.

[30] H. Zhang and B. Di, "Intelligent omni-surfaces: Simultaneous refraction and reflection for full-dimensional wireless communications," *IEEE Communications Surveys Tutorials*, vol. 24, no. 4, pp. 1997–2028, Aug, 2022.

[31] Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," *IEEE Communications Magazine*, vol. 58, no. 1, pp. 106–112, Nov, 2019.

[32] Y. Cheng, K. H. Li, Y. Liu, K. C. Teh, and H. V. Poor, "Downlink and uplink intelligent reflecting surface aided networks: Noma and oma," *IEEE Transactions on Wireless Communications*, vol. 20, no. 6, pp. 3988–4000, Feb, 2021.

[33] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M.-S. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE access*, vol. 7, pp. 116 753–116 773, Aug, 2019.

[34] M. Najafi, V. Jamali, R. Schober, and H. V. Poor, "Physics-based modeling and scalable optimization of large intelligent reflecting surfaces," *IEEE Transactions on Communications*, vol. 69, no. 4, pp. 2673–2691, Dec, 2020.

[35] Z. Zhang, L. Dai, X. Chen, C. Liu, F. Yang, R. Schober, and H. V. Poor, "Active ris vs. passive ris: Which will prevail in 6g?" *arXiv preprint arXiv:2103.15154*, 2021.

[36] C. You and R. Zhang, "Wireless communication aided by intelligent reflecting surface: Active or passive?" *IEEE Wireless Communications Letters*, vol. 10, no. 12, pp. 2659–2663, Sep, 2021.

[37] R. Long, Y.-C. Liang, Y. Pei, and E. G. Larsson, "Active reconfigurable intelligent surface-aided wireless communications," *IEEE Transactions on Wireless Communications*, vol. 20, no. 8, pp. 4962–4975, Mar, 2021.

[38] J. Lončar and Z. Šipuš, "Challenges in design of power-amplifying active metasurfaces," in *2020 International Symposium ELMAR*, Zadar, Croatia, Oct, 2020, pp. 9–12.

[39] K. Zhi, C. Pan, H. Ren, K. K. Chai, and M. Elkashlan, "Active ris versus passive ris: Which is superior with the same power budget?" *IEEE Communications Letters*, vol. 26, no. 5, pp. 1150–1154, Mar, 2022.

[40] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Transactions on Wireless Communications*, vol. 18, no. 11, pp. 5394–5409, Aug, 2019.

[41] B. Zheng, Q. Wu, and R. Zhang, "Intelligent reflecting surface-assisted multiple access with user pairing: Noma or oma?" *IEEE Communications Letters*, vol. 24, no. 4, pp. 753–757, Jan, 2020.

[42] X. Mu, Y. Liu, L. Guo, J. Lin, and N. Al-Dhahir, "Exploiting intelligent reflecting surfaces in noma networks: Joint beamform-

ing optimization," *IEEE Transactions on Wireless Communications*, vol. 19, no. 10, pp. 6884–6898, Jul, 2020.

[43] S. Zhang, H. Zhang, B. Di, Y. Tan, Z. Han, and L. Song, "Beyond intelligent reflecting surfaces: Reflective-transmissive metasurface aided communications for full-dimensional coverage extension," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 11, pp. 13 905–13 909, Sep, 2020.

[44] A. Papazafeiropoulos, Z. Abdullah, P. Kourtessis, S. Kisseleff, and I. Krikidis, "Coverage probability of star-ris-assisted massive mimo systems with correlation and phase errors," *IEEE Wireless Communications Letters*, vol. 11, no. 8, pp. 1738–1742, Jun, 2022.

[45] C. Zhang, W. Yi, K. Han, Y. Liu, Z. Ding, and M. Di Renzo, "Simultaneously transmitting and reflecting ris aided noma with randomly deployed users," in *2021 IEEE Global Communications Conference (GLOBECOM)*, Madrid, Spain, Dec, 2021, pp. 1–6.

[46] Z. Xie, W. Yi, X. Wu, Y. Liu, and A. Nallanathan, "Star-ris aided noma in multicell networks: A general analytical framework with gamma distributed channel modeling," *IEEE Transactions on Communications*, vol. 70, no. 8, pp. 5629–5644, Jun, 2022.

[47] C. Wu, Y. Liu, X. Mu, X. Gu, and O. A. Dobre, "Coverage characterization of STAR-RIS networks: NOMA and OMA," *IEEE Communications Letters*, vol. 25, no. 9, pp. 3036–3040, Jun, 2021.

[48] M. Bloch and J. Barros, *Physical-layer security: from information theory to security engineering*. Cambridge University Press, 2011.

[49] M. Wijewardena, T. Samarasinghe, K. T. Hemachandra, S. Atapattu, and J. S. Evans, "Physical layer security for intelligent reflecting surface assisted two–way communications," *IEEE Communications Letters*, vol. 25, pp. 2156–2160, Mar, 2021.

[50] A. Mukherjee, S. A. A. Fakoorian, J. Huang, and A. L. Swindlehurst, "Principles of physical layer security in multiuser wireless networks: A survey," *IEEE Communications Surveys & Tutorials*, vol. 16, pp. 1550–1573, Feb, 2014.

[51] A. Almohamad, A. M. Tahir, A. Al-Kababji, H. M. Furqan, T. M. S. Khattab, M. O. Hasna, and H. Arslan, "Smart and secure wireless communications via reflecting intelligent surfaces: A short survey," *IEEE Open Journal of the Communications Society*, vol. 1, pp. 1442–1456, Sep, 2020.

[52] J. David Vega-Sánchez, G. Kaddoum, and F. J. López-Martínez, "Physical layer security of ris-assisted communications under electromagnetic interference," *IEEE Communications Letters*, vol. 26, no. 12, pp. 2870–2874, Sep, 2022.

[53] Y. Han, N. Li, Y. Liu, T. Zhang, and X. Tao, "Artificial noise aided secure noma communications in star-ris networks," *IEEE Wireless Communications Letters*, vol. 11, no. 6, pp. 1191–1195, Mar, 2022.

[54] Z. Zhang, J. Chen, Y. Liu, Q. Wu, B. He, and L. Yang, "On the secrecy design of star-ris assisted uplink noma networks," *IEEE Transactions on Wireless Communications*, vol. 21, no. 12, pp. 11 207–11 221, Jul, 2022.

[55] S. Fang, G. Chen, Z. Abdullah, and Y. Li, "Intelligent omni surface-assisted secure mimo communication networks with artificial noise," *IEEE Communications Letters*, vol. 26, no. 6, pp. 1231–1235, Mar, 2022.

[56] S. pin Xu, C. Liu, H. Wang, M. Qian, and J. Li, "On secrecy performance analysis of multi-antenna star-ris-assisted downlink noma systems," *EURASIP Journal on Advances in Signal Processing*, vol. 2022, pp. 1–31, Dec, 2022.

[57] H. Niu, Z. Chu, F. Zhou, and Z. Zhu, "Simultaneous transmission and reflection reconfigurable intelligent surface assisted secrecy miso networks," *IEEE Communications Letters*, vol. 25, no. 11, pp. 3498–3502, Aug, 2021.

[58] W. Wang, W. Ni, H. Tian, Z. Yang, C. Huang, and K.-K. Wong, "Robust design for star-ris secured internet of medical things," in *2022 IEEE International Conference on Communications Workshops (ICC Workshops)*. Seoul, Republic of Korea: IEEE, Jul, 2022, pp. 574–579.

[59] W. Wang, W. Ni, H. Tian, and L. Song, "Intelligent omni-surface enhanced aerial secure offloading," *IEEE Transactions on Vehicular Technology*, vol. 71, no. 5, pp. 5007–5022, Feb, 2022.

[60] M. S. Ali, H. Tabassum, and E. Hossain, "Dynamic user clustering and power allocation for uplink and downlink non-orthogonal multiple access (noma) systems," *IEEE Access*, vol. 4, pp. 6325–6343, Aug, 2016.

[61] S. M. R. Islam, N. Avazov, O. A. Dobre, and K.-s. Kwak, "Power-domain non-orthogonal multiple access (noma) in 5g systems: Potentials and challenges," *IEEE Communications Surveys Tutorials*, vol. 19, no. 2, pp. 721–742, Oct, 2017.

[62] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-orthogonal multiple access (noma) for cellular future radio access," in *2013 IEEE 77th Vehicular Technology Conference (VTC Spring)*, Dresden, Germany, Jun, 2013, pp. 1–5.

[63] Z. Ding and H. Vincent Poor, "A simple design of irs-noma transmission," *IEEE Communications Letters*, vol. 24, no. 5, pp. 1119–1123, Feb, 2020.

[64] Q. Wu, T. Lin, M. Liu, and Y. Zhu, "Bios: An omni ris for independent reflection and refraction beamforming," *IEEE Wireless Communications Letters*, vol. 11, no. 5, pp. 1062–1066, Mar, 2022.

[65] H. Niu and X. Liang, "Weighted sum-rate maximization for star-riss-aided networks with coupled phase-shifters," *IEEE Systems Journal*, pp. 1–10, Apr, 2022.

[66] A. Mohamed, N. S. Perović, and M. Di Renzo, "Intelligent omni-surfaces (ioss) for the mimo broadcast channel," in *2022 IEEE 23rd International Workshop on Signal Processing Advances in Wireless Communication (SPAWC)*. Oulu, Finland: IEEE, July 2022, pp. 1–5.

[67] Y. Liu, B. Duo, Q. Wu, X. Yuan, and Y. Li, "Full-dimensional rate enhancement for uav-enabled communications via intelligent omni-surface," *IEEE Wireless Communications Letters*, vol. 11, no. 9, pp. 1955–1959, Jul, 2022.

[68] S. Zhang, H. Zhang, B. Di, Y. Tan, M. Di Renzo, Z. Han, H. V. Poor, and L. Song, "Intelligent omni-surfaces: Ubiquitous wireless transmission by reflective-refractive metasurfaces," *IEEE Transactions on Wireless Communications*, vol. 21, no. 1, pp. 219–233, Jul, 2021.

[69] Y. Zhang, B. Di, H. Zhang, M. Dong, L. Yang, and L. Song, "Codebook design and beam training for intelligent omni-surface aided communications," in *2022 IEEE Wireless Communications and Networking Conference (WCNC)*, Austin, TX, USA, May, 2022, pp. 500–505.

[70] W. Cai, M. Li, Y. Liu, Q. Wu, and Q. Liu, "Joint beamforming design for intelligent omni surface assisted wireless communication systems," *IEEE Transactions on Wireless Communications*, Feb, 2022.

[71] H. Niu, Z. Chu, F. Zhou, P. Xiao, and N. Al-Dhahir, "Weighted sum rate optimization for star-ris-assisted mimo system," *IEEE Transactions on Vehicular Technology*, vol. 71, no. 2, pp. 2122–2127, Nov, 2022.

[72] P. P. Perera, V. G. Warnasooriya, D. Kudathanthirige, and H. A. Suraweera, "Sum rate maximization in star-ris assisted full-duplex communication systems," *ICC 2022 - IEEE International Conference on Communications*, pp. 3281–3286, Mar, 2022.

[73] J. Zuo, Y. Liu, Z. Ding, and L. Song, "Simultaneously transmitting and reflecting (star) ris assisted noma systems," in *2021 IEEE Global Communications Conference (GLOBECOM)*. Madrid, Spain: IEEE, Dec, 2021, pp. 1–6.

[74] H. Liu, G. Li, X. Li, Y. Liu, G. Huang, and Z. Ding, "Effective capacity analysis of star-ris-assisted noma networks," *IEEE Wireless Communications Letters*, vol. 11, no. 9, pp. 1930–1934, Jul, 2022.

[75] B. Zhao, C. Zhang, W. Yi, and Y. Liu, "Ergodic rate analysis of star-ris aided noma systems," *IEEE Communications Letters*, vol. 26, no. 10, pp. 2297–2301, Jul, 2022.

[76] N. Zhang, Y. Liu, X. Mu, and W. Wang, "Queue-aware star-ris assisted noma communication systems," *ArXiv*, vol. abs/2202.12333, Feb, 2022.

[77] C. Wu, C. You, Y. Liu, S. Shi, and M. D. Renzo, "Two-timescale design for star-ris aided noma systems," *ArXiv*, vol. abs/2207.00792, July, 2022.

[78] M. F. U. Abrar, M. Talha, R. I. Ansari, S. A. Hassan, and H. Jung, "Star-ris-assisted hybrid noma mmwave communication: Optimization and performance analysis," *ArXiv*, vol. abs/2205.06695, May, 2022.

[79] Y. Guo, F. Fang, D. Cai, and Z. Ding, "Energy-efficient design for a noma assisted star-ris network with deep reinforcement learning," *IEEE Transactions on Vehicular Technology*, pp. 1–5, Nov, 2022.

[80] J. Zuo, Y. Liu, Z. Ding, and X. Wang, "Uplink noma for star-ris networks," *ArXiv*, vol. abs/2110.05686, Oct, 2021.

[81] X. Mu, Y. Liu, J. Xu, L. Guo, and J. Lin, "Joint beamforming optimization for simultaneously transmitting and reflecting (star) ris aided communications : (invited paper)," in *2021 55th Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, USA, Oct, 2021, pp. 709–714.

[82] X. Mu, Y. Liu, L. Guo, J. Lin, and R. Schober, "Simultaneously transmitting and reflecting (star) ris aided wireless communications," *IEEE Transactions on Wireless Communications*, vol. 21, no. 5, pp. 3083–3098, Oct, 2021.

[83] R. Zhong, Y. Liu, X. Mu, Y. Chen, X. Wang, and L. Hanzo, "Hybrid reinforcement learning for star-riss: A coupled phase-shift model based beamformer," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 9, pp. 2556–2569, May, 2022.

[84] Y. Wang, P. Guan, H. Yu, and Y. Zhao, "Transmit power optimization of simultaneous transmission and reflection ris assisted full-duplex communications," *IEEE Access*, vol. 10, pp. 61 192–61 200, May, 2022.

[85] T. Hou, J. Wang, Y. Liu, X. Sun, A. Li, and B. Ai, "A joint design for star-ris enhanced noma-comp networks: A simultaneous-signal-enhancement-and-cancellation-based (ssecb) design," *IEEE Transactions on Vehicular Technology*, vol. 71, no. 1, pp. 1043–1048, Nov, 2021.

[86] Y. Zhang, B. Di, H. Zhang, Z. Han, H. V. Poor, and L. Song, "Meta-wall: Intelligent omni-surfaces aided multi-cell mimo communications," *IEEE Transactions on Wireless Communications*, vol. 21, no. 9, pp. 7026–7039, Mar. 2022.

[87] S. Fang, G. Chen, P. Xiao, K. Wong, and R. Tafazolli, "Intelligent omni surface-assisted self-interference cancellation for full-duplex miso system," *ArXiv*, vol. abs/2208.06457, Aug, 2022.

[88] Y. Chen, Y. Wang, Z. Wang, and P. Zhang, "Robust beamforming for active reconfigurable intelligent omni-surface in vehicular communications," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 10, pp. 3086–3103, Aug, 2022.

[89] S. Yang, J. Zhang, W. Xia, H. Gao, and H. Zhu, "Joint power and discrete amplitude allocation for star-ris-aided noma system," *IEEE Transactions on Vehicular Technology*, pp. 1–6, Aug, 2022.

[90] W. Ni, Y. Liu, Y. C. Eldar, Z. Yang, and H. Tian, "Enabling ubiquitous non-orthogonal multiple access and pervasive federated learning via star-ris," in *2021 IEEE Global Communications Conference (GLOBECOM)*, Madrid, Spain, Dec, 2021, pp. 1–6.

[91] C. Wu, X. Mu, Y. Liu, X. Gu, and X. Wang, "Resource allocation in star-ris-aided networks: Oma and noma," *IEEE Transactions on Wireless Communications*, vol. 21, no. 9, pp. 7653–7667, Mar, 2022.

[92] J. Xu, Y. Liu, X. Mu, and O. A. Dobre, "Star-riss: Simultaneous transmitting and reflecting reconfigurable intelligent surfaces," *IEEE Communications Letters*, vol. 25, no. 9, pp. 3134–3138, May, 2021.

[93] C. Wu, C. You, Y. Liu, X. Gu, and Y. Cai, "Channel estimation for star-ris-aided wireless communication," *IEEE Communications Letters*, vol. 26, no. 3, pp. 652–656, Dec, 2021.

[94] T. Wang, M.-A. Badiu, G. Chen, and J. P. Coon, "Outage probability analysis of star-ris assisted noma network with correlated channels," *IEEE Communications Letters*, vol. 26, no. 8, pp. 1774–1778, May, 2022.

[95] X. Yue, J. Xie, Y. Liu, Z. Han, R. Liu, and Z. Ding, "Simultaneously transmitting and reflecting reconfigurable intelligent surface assisted noma networks," *IEEE Transactions on Wireless Communications*, pp. 1–1, Aug, 2022.

[96] C. Zhang, W. Yi, Y. Liu, Z. Ding, and L. Song, "Star-ios aided noma networks: Channel model approximation and performance analysis," *IEEE Transactions on Wireless Communications*, vol. 21, no. 9, pp. 6861–6876, Feb 2022.

[97] M. Aldababsa, A. Khaleel, and E. Basar, "Star-ris-noma networks: An error performance perspective," *IEEE Communications Letters*, vol. 26, no. 8, pp. 1784–1788, Jun, 2022.

[98] B. Sheng, "On element selection in star-ris for noma transmission," *Mobile Information Systems*, Mar, 2022.

[99] J. Xu, Y. Liu, and X. Mu, "Performance analysis for the coupled phase-shift star-riss," in *2022 IEEE Wireless Communications and Networking Conference (WCNC)*, Austin, TX, USA, Apr, 2022, pp. 489–493.

[100] J. Xu, Y. Liu, X. Mu, R. Schober, and H. V. Poor, "Star-riss: A correlated tr phase-shift model and practical phase-shift configuration strategies," *IEEE Journal of Selected Topics in Signal Processing*, vol. 16, no. 5, pp. 1097–1111, May, 2022.

[101] G. C. Alexandropoulos, N. Shlezinger, and P. del Hougne, "Reconfigurable intelligent surfaces for rich scattering wireless communications: Recent experiments, challenges, and opportunities," *IEEE Communications Magazine*, vol. 59, pp. 28–34, Jun, 2021.

[102] X. Yang, C.-K. Wen, and S. Jin, "Mimo detection for reconfigurable intelligent surface-assisted millimeter wave systems," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 8, pp. 1777–1792, Jun, 2020.

[103] S. Basharat, S. A. Hassan, H. B. Pervaiz, A. Mahmood, Z. Ding, and M. Gidlund, "Reconfigurable intelligent surfaces: Potentials, applications, and challenges for 6g wireless networks," *IEEE Wireless Communications*, vol. 28, pp. 184–191, Sep, 2021.

[104] K. Keykhosravi, M. F. Keskin, S. Dwivedi, G. Seco-Granados, and H. Wymeersch, "Semi-passive 3d positioning of multiple ris-enabled users," *IEEE Transactions on Vehicular Technology*, vol. 70, pp. 11 073–11 077, Sep, 2021.

[105] I. Alamzadeh, G. C. Alexandropoulos, N. Shlezinger, and M. F. Imani, "A reconfigurable intelligent surface with integrated sensing capability," *Scientific Reports*, vol. 11, Oct, 2021.

[106] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng, and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems," *IEEE Communications Magazine*, vol. 52, no. 11, pp. 104–110, Nov, 2014.

[107] D. Xu, V. Jamali, X. Yu, D. W. K. Ng, and R. Schober, "Optimal resource allocation design for large irs-assisted swipt systems: A scalable optimization framework," *IEEE Transactions on Communications*, vol. 70, no. 2, pp. 1423–1441, Jan, 2022.