

Article

Weighted Secrecy Sum Rate Optimization for Simultaneously Transmitting and Reflecting Reconfigurable Intelligent Surface-Assisted Multiple-Input Single-Output Systems

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Abstract: The study investigates the effectiveness of a novel Simultaneously Transmitting and Reflecting Reconfigurable Intelligent Surface (STAR-RIS) technology in enhancing the physical layer security of Multiple-Input Single-Output (MISO) systems. To address the complexity of the security challenge, we examine two distinct phase shift strategies, namely, the coupled phase scheme and the independent phase scheme. The coupled paradigm focuses on optimizing weighted sum secrecy rate (WSSR) through a customized Block Coordinate Descent (BCD) approach integrated with path tracking, aiming to achieve a balanced security enhancement. Furthermore, for the independent phase shift paradigm, an optimization algorithm based on the Concave–Convex Procedure (CCCP) is explored to provide a flexible security solution. The numerical results validate the superior performance of STAR-RIS, confirming its potential as a robust security enhancer for MISO systems.

Keywords: coupled phase shifts; simultaneous transmitting and reflecting reconfigurable intelligent surface; weighted sum secrecy rate; physical layer security



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1. Introduction

In the era of global 5G deployment, research attention is now turning toward B5G and 6G networks. These next-generation networks necessitate enhanced spectral and energy efficiencies, ultra-low latency in the microsecond range, and extensive network coverage [1]. Furthermore, 6G networks are anticipated to facilitate superior wireless communications and simultaneous high-precision radio sensing, which are critical for emerging applications such as smart cities and the Internet of Vehicles (IoV). Consequently, integrated sensing and communication (ISAC) has emerged as a mainstream trend and a focal point of research in recent years within the context of 6G technology [2]. Nevertheless, private data are exposed to the communication environment when electromagnetic waves are transmitted over open wireless channels, making them highly susceptible to security threats such as jamming and eavesdropping [3]. However, 6G networks provide more security challenges across various communication scenarios. First, in multi-user environments characteristic of the 6G era, the proximity of communication nodes and users increases the likelihood of inter-user interference and potential eavesdroppers, significantly heightening security risks in multi-user communication scenarios. This is due to the increase in network connection density. Physical layer security (PLS) has emerged as a critical driver for the development of 6G networks. PLS enables safe communication by using wireless channel natural qualities and characteristics [4]. Unlike traditional encryption methods, PLS avoids the high complexity of encryption procedures while requiring minimal hardware resources. Ref. [5] utilized some of the power available from the transmitter to generate artificial noise (AN) to interfere with the eavesdropper's channel. This technique enhances the confidentiality of communications by diminishing the quality of the signal received by the eavesdropper. Ref. [6] investigated two different eavesdropping channel models and

proposed cooperative jamming to improve the system's secrecy rate. However, many physical security methods, such as traditional beamforming and directional modulation, are inadequate for ensuring complete communication security [7].

To address current limitations, it is crucial to develop cost-effective approaches for wireless systems. By leveraging advancements in metasurfaces and fabrication technologies, Reconfigurable Intelligent Surfaces (RISs) have emerged as promising innovations [8–10]. RISs are two-dimensional planar arrays composed of multiple sub-wavelength electromagnetic metamaterial components [11]. The electromagnetic response of these RIS units can be precisely controlled by adjusting their microstructure, which includes the amplitude, phase, polarization, and frequency of incident electromagnetic waves. With the assistance of RISs, signals from various links can be coherently combined with legitimate users (Bobs) to enhance the signal constructively and suppress information leakage to eavesdroppers (Eves). This capability positions RISs as a key technology in advancing physical layer security [12].

Nevertheless, RISs are designed solely to reflect incident signals, providing a 180-degree semi-plane reflection. Consequently, users must be located on the same side as both the RISs and the base station (BS), resulting in relatively limited coverage. For instance, consider a challenging scenario with multiple Bobs and Eves distributed on both sides of the RISs. In this situation, there will always be some Bobs and Eves in the communication dead zone that are not supported by the RISs. This leads to undesirable security threats and energy loss [13].

In response to this limitation, the concept of Simultaneously Transmitting and Reflecting Reconfigurable Intelligent Surface (STAR-RIS) has been introduced [14–16]. In contrast to conventional RISs, the wireless signal incident on the STAR-RIS is divided into transmitted and reflected signals that propagate to both sides of the surface, realizing a fully spatially reconfigurable wireless environment. STAR-RIS consists of a large number of low-cost elements whose transmission and reflection coefficients (TARCs) are adjusted in real-time within the elemental units using control circuits, typically implemented by microcontrollers or field-programmable gate arrays (FPGAs). The output of the optimization algorithm is converted into specific control commands, which are sent to the hardware control circuit to control the STAR-RIS. For passive-lossless design, the elements can possess independent TARCs or coupled TARCs, depending on the electrical and magnetic characteristics of the STAR-RIS. Existing studies on STAR-RIS assume that the phase-shift coefficients for transmission and reflection are independently tunable, presupposing that the electric and magnetic impedances, which are confined to purely imaginary values, can be arbitrarily selected. However, this may not be feasible for entirely passive STAR-RIS [17]. In the recent study referenced as [18], it was demonstrated that within low-cost passive lossless STAR-RIS, there exists an intrinsic coupling between the phase-shift coefficients of transmission and reflection. This interdependency poses novel design challenges, as it necessitates a joint consideration of both transmission and reflection characteristics during the optimization process. The coupling effect complicates the system design but also opens avenues for the development of advanced optimization algorithms and the enhancement of communication system performance. This discovery underscores the need for a holistic approach to the design and analysis of STAR-RIS to fully harness their potential in cost-effective communication networks. To solve the coupling phase shift problem, ref. [19] proposes an efficient cell alternating optimization (AO) algorithm to find high-quality suboptimal solutions. In the work presented by the authors in reference [20], they introduce the AO algorithm. This algorithm performs an exhaustive search over discrete amplitude and phase shift sets, resulting in a high computational complexity.

STAR-RIS has significant potential in ISAC technology, which is the fundamental pillar of future 6G. Ref. [21] focuses on outage-based beamforming design for dual-functional radar-communication systems in 6G networks. The beamforming techniques discussed in [22,23] are related to the beamform optimization in the STAR-RIS-assisted MISO system.

Both papers aim to enhance the security and efficiency of wireless communication systems through advanced beamforming strategies.

Motivated by the above, we investigate a downlink MISO communication system enhanced by STAR-RIS in this system, in which BS provides service to two legitimate users located around the STAR-RIS, while two illegitimate users are also present. Based on this model, we jointly design an optimization problem for active beamforming (BF) at the BS and passive BF at the STAR-RIS. Our objective is to maximize WSSR while adhering to direct link conditions and quality of service (QoS) constraints. We consider two phasing schemes: the coupled phase (CP) scheme and the independent phase (IP) scheme. In this paper, we focus on maximizing WSSR for the CP scheme. We first approximate the optimal value of WSSR using the Successive Convex Approximation (SCA) method. To address the non-convexity of the QoS constraints, we transform them into solvable convex constraints using the Second-Order Cone Programming (SOCP) method. For the multivariate optimization of the CP scheme, we employ the Block Coordinate Descent (BCD) algorithm, which divides the variables into three blocks and optimizes the beam variables, coupled phase shift variables, and auxiliary variables sequentially in an alternating manner. For optimizing the coupled phase-shift variables, we utilize the existing Penalized Dyadic Decomposition (PDD) framework to update them alternately in closed form. For the IP scheme, the non-convex phase shift constraints are approximated as tractable convex constraints using the Concave–Convex Procedure (CCCP) method. Numerical results compare the performance of the proposed algorithms, which are validated against four benchmark schemes for both coupled and independent phase-shift models. To the best of our knowledge, similar algorithms in this specific area have not been examined in this study. This research provides new ideas and methods to enhance the security of MISO PLS systems and promote their development and application.

We organize the remainder of this paper in the following order: Section 2 presents the STAR-RIS-assisted MISO system model and formulates the optimization problem for various phase shift schemes. Section 3 shows the analysis of the proposed algorithms. Section 4 presents the simulation results of the algorithms and compares the performance of different schemes. Section 5 summarizes the thesis work.

Notations: Bold letters represent vectors. $\mathbb{C}$ represents the set of complex numbers. $\mathbb{E}\{x\}$ represents the mathematical expectation about x . $\mathcal{CN}(\mu, \sigma^2)$ stands for the complex Gaussian distribution with mean μ and variance σ^2 . $\text{Diag}(\cdot)$ is for constructing a triangular matrix. $\Re\{\cdot\}$ and $\Im\{\cdot\}$ denote the real and imaginary parts of the complex variable, respectively. $\|\cdot\|$ denotes the Euclidean norm of a vector or the Frobenius of a matrix. $\text{Tr}(\mathbf{A})$ represents the trace of matrix $\mathbf{A}$.

2. System Model and Problem Formulation

2.1. System Model

As illustrated in Figure 1, we investigate a multicast downlink MISO communication system equipped with a four-node STAR-RIS. An N -antenna BS exploits an M -element STAR-RIS to transmit the confidential signals to two single-antenna receivers, which are called Bob_T and Bob_R, in presence of two single-antenna eavesdroppers, namely, Eve_T and Eve_R. We consider that the STAR-RIS concurrently serves both the transmission and reflection regions. Specifically, the receiver situated in the l -th region is designated as the l -th Bob, where $l \in \{T, R\}$. The baseband equivalent channels from STAR-RIS to BS, Bob, and Eve are represented as $\mathbf{h}_{BS} \in \mathbb{C}^{M \times N}$, $\mathbf{h}_{Sl} \in \mathbb{C}^{M \times 1}$, $\mathbf{g}_l \in \mathbb{C}^{M \times 1}$. It is assumed that the direct channel between the BS and the user, denoted by $\mathbf{h}_{Bl} \in \mathbb{C}^{N \times 1}$, $\mathbf{h}_l \in \mathbb{C}^{N \times 1}$. Assuming the availability of perfect channel state information (CSI) of these links is obtained by BS [24], the STAR-RIS is configured via a controller, typically realized through a field-programmable gate array. For CP scheme, where each transmitting and reflecting coefficients element $m \in \mathfrak{M} \triangleq \{1, 2, \dots, M\}$, its reflection and transmission coefficients are given by $\beta_m^T e^{j\phi_m^T}$ and $\beta_m^R e^{j\phi_m^R}$, respectively, where $\beta_m^T, \beta_m^R \in [0, 1]$ and $\phi_m^T, \phi_m^R \in [0, 2\pi)$ denote the amplitude and phase configurations, respectively. Due to energy conservation, passive

lossless STAR-RISs have to meet the following constraints $(\beta_m^T)^2 + (\beta_m^R)^2 = 1$. In the case of a passive and lossless STAR-RIS, the electrical and magnetic impedances manifest as purely imaginary values, i.e., $\beta_m^T \beta_m^R \cos(\phi_m^T - \phi_m^R) = 0$ which ϕ_m^T and ϕ_m^R are coupled by the condition $|\phi_m^T - \phi_m^R| = \frac{\pi}{2}, \frac{3\pi}{2}$. For the IP scheme, the transmission and reflection phases are independent of each other.

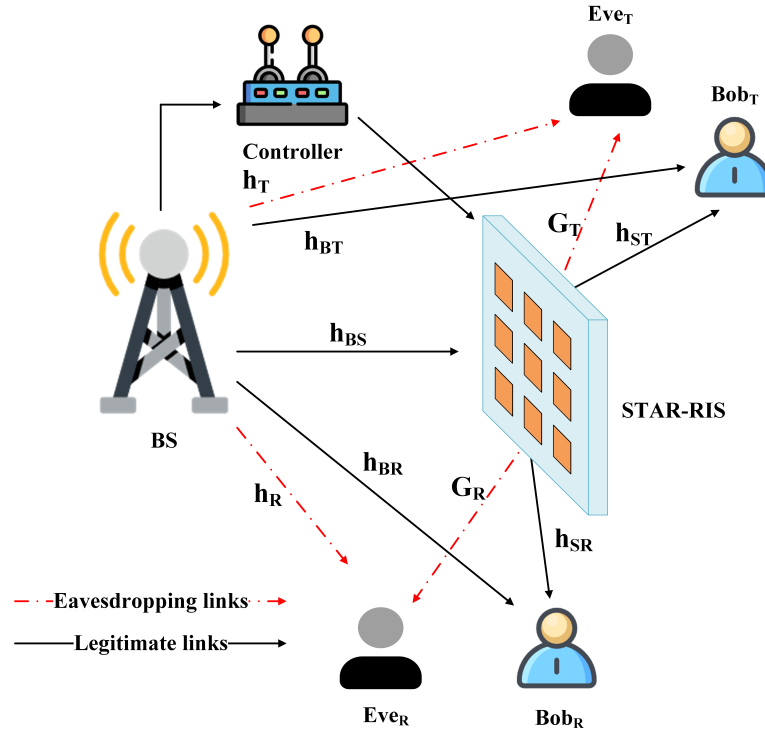


Figure 1. STAR-RIS-aided secure communication from a BS to a user in the presence of an eavesdropper.

$\Theta_l = \text{Diag}(\beta_1^l e^{j\phi_1^l}, \dots, \beta_M^l e^{j\phi_M^l}) \in \mathbb{C}^{M \times M}$ denotes the coefficient for the l -th Bob. BS exploits the multiple beamforming vectors $\mathbf{w}_T, \mathbf{w}_R \in \mathbb{C}^{N \times 1}$ to send the confidential signals x_T and x_R with $\mathbb{E}\{|s_T|^2\} = \mathbb{E}\{|s_R|^2\} = 1$ to Bob_T and Bob_R , respectively. Neglecting the signals reflected by the STAR-RIS twice or more due to severe path loss, the received signals at the user and the eavesdropper can be, respectively, expressed as

$$y_{B,l} = (\mathbf{h}_{Bl}^H + \mathbf{h}_{Sl}^H \Theta_l \mathbf{h}_{BS}) \sum_i \mathbf{w}_i x_i + n_{B,l} \quad (1)$$

$$y_{E,l} = (\mathbf{h}_l^H + \mathbf{g}_l^H \Theta_l \mathbf{h}_{BS}) \sum_i \mathbf{w}_i x_i + n_{E,l} \quad (2)$$

where $n_{B,l}, n_{E,l} \sim \mathcal{CN}(0, \sigma^2)$ represent the additive white Gaussian noise (AWGN) at both reflection and transmission, $i \in \{T, R\}$ denote reflection and transmission areas. Using $\theta^H = \text{diag}(\Theta)^T$, we have $\mathbf{h}_{Bl}^H + \mathbf{h}_{Sl}^H \Theta_l \mathbf{h}_{BS} = \mathbf{h}_{Bl}^H + \theta^H \mathbf{H}_l$ and $\mathbf{h}_l^H + \mathbf{g}_l^H \Theta_l \mathbf{h}_{BS} = \mathbf{h}_l^H + \theta^H \mathbf{G}_l$, where $\mathbf{H}_l = \text{Diag}(\mathbf{h}_{Sl}^H) \mathbf{h}_{BS}$, and $\mathbf{G}_l = \text{Diag}(\mathbf{g}_l^H) \mathbf{h}_{BS}$, respectively. It is presumed that the l -th Eve is solely intercepting the data intended for Bob, who is situated within the same vicinity. Then, for the independent or coupled phase scheme, the signal-to-interference-plus-noise ratio (SINR) at the Bob_l and Eve_l can be expressed as

$$\text{SINR}_{Bob_l} = \frac{|\mathbf{h}_{Bl}^H + \theta^H \mathbf{H}_l \mathbf{w}_l|^2}{|\mathbf{h}_{Bl}^H + \theta_l^H \mathbf{H}_l \mathbf{w}_{l'}|^2 + \sigma^2} \quad (3)$$

$$\text{SINR}_{Eve_l} = \frac{|\mathbf{h}_l^H + \theta_l^H \mathbf{G}_l \mathbf{w}_l|^2}{|\mathbf{h}_l^H + \theta_l^H \mathbf{G}_l \mathbf{w}_{l'}|^2 + \sigma^2} \quad (4)$$

respectively, where $l = r, l' = t$, and vice versa. Thus, for the independent or coupled phase scheme, the secrecy rate for the l -th Bob is represented as

$$R_l^{SEC} = [\ln(1 + \text{SINR}_{\text{Bob}_l}) - \ln(1 + \text{SINR}_{\text{Eve}_l})]^+. \quad (5)$$

where $[x]^+ \triangleq \max\{x, 0\}$.

2.2. Problem Formulation

In this paper, our objective is to enhance WSSR for the Bobs through the collective optimization of BF and TARC, i.e., $\mathbf{w}_l$ and θ_l . Specifically, the optimization problem can be formulated as follows:

$$\max_{\theta_l, \mathbf{w}_l} \sum_l \varphi_l R_l^{SEC} \quad (6a)$$

$$\text{s.t.} \quad \sum_l \|\mathbf{w}_l\|^2 \leq P_{\max}, \quad (6b)$$

$$[\theta_l]_m = \sqrt{\beta_m^l} e^{j\theta_m^l}, \sum_l \beta_l = 1, \forall m \in \mathfrak{M}, \quad (6c)$$

$$\theta_m^l \in [0, 2\pi), \beta_l^m \in [0, 1], \forall m \in \mathfrak{M}, \quad (6d)$$

$$\text{SINR}_{\text{Bob}_l} \geq \Gamma_{\min}, \quad (6e)$$

$$|\theta_m^T - \theta_m^R| = \frac{\pi}{2} \text{ or } \frac{3\pi}{2}, \forall m \in \mathfrak{M}. \quad (6f)$$

where $\varphi_l \in [0, 1]$, $\sum_l \varphi_l = 1$ represent the weighting factor for the l -th Bob. Note that (6b) denotes the total power constraint for the BS with the maximum power $P_{\max}$, (6c)–(6d) denote the phase shift and amplitude constraints for the STAR-RIS, (6e) ensures the minimum QoS requirement of each legitimate user, which $\Gamma_{\min}$ denotes the minimum rate requirement of legitimate users. Constraint (6f) is only valid when the CP scheme is employed.

3. Proposed Algorithms

3.1. The BCD Method for the CP Scheme

The transmission and reflection phase shifts of STAR-RIS's CP scheme are coupled, introducing complex nonlinear constraints. This coupling complicates the optimization problem and hinders the direct application of traditional optimization methods. The BCD framework is widely used to solve non-convex problems, which can guarantee an approximately optimal solution by solving multiple convex subproblems derived from the original non-convex problem in chunks. This is particularly important for the CP scheme. Therefore, we propose a BCD-based method to solve the CP scheme. We decompose the variables into two blocks, i.e., $\{\mathbf{w}_l\}$ and $\{\theta_T, \theta_R\}$, and perform iterative optimization in an alternating form. Specifically, the sub-problem of optimizing the reflection and transmission coefficients (i.e., $\{\theta_T, \theta_R\}$) is addressed using the PDD framework. In this framework, the solved subproblems are transformed into augmented Lagrangian (AL) problems by incorporating penalty terms. The variables and the introduced penalty factors are optimized iteratively until convergence is achieved.

To start with, we first decouple problem (6a) in tractable subproblem, and iteratively derive solutions for these subproblems.

First of all, in the vicinity of point $\{\mathbf{w}_l^*, \theta_l^*\}$, we have constants $\{d_l^1, d_l^2, d_l^3, d_l^4\}$, given by

$$d_l^1 = 1 / \left(\left| \left(\mathbf{h}_{Bl}^H + \boldsymbol{\theta}_l^{*H} \mathbf{H}_l \right) \mathbf{w}_{l'}^* \right|^2 + \sigma^2 \right), \quad (7a)$$

$$d_l^2 = \frac{d_l^1 \left| \left(\mathbf{h}_{Bl}^H + \boldsymbol{\theta}_l^{*H} \mathbf{H}_l \right) \mathbf{w}_l^* \right|^2}{\left| \left(\mathbf{h}_{Bl}^H + \boldsymbol{\theta}_l^{*H} \mathbf{H}_l \right) \mathbf{w}_l^* \right|^2 + \left| \left(\mathbf{h}_{Bl}^H + \boldsymbol{\theta}_l^{*H} \mathbf{H}_l \right) \mathbf{w}_{l'}^* \right|^2 + \sigma^2}, \quad (7b)$$

$$d_l^3 = \left| \left(\mathbf{h}_l^H + \boldsymbol{\theta}_l^{*H} \mathbf{G}_l \right) \mathbf{w}_l^* \right|^2 / \left(\left| \left(\mathbf{h}_l^H + \boldsymbol{\theta}_l^{*H} \mathbf{G}_l \right) \mathbf{w}_{l'}^* \right|^2 + \sigma^2 \right), \quad (7c)$$

$$d_l^4 = - \left| \left(\mathbf{h}_l^H + \boldsymbol{\theta}_l^{*H} \mathbf{G}_l \right) \mathbf{w}_{l'}^* \right|^2 + \sigma^2, \quad (7d)$$

Based on the given equations and neglecting the constant terms, around the specified point $\{\mathbf{w}_l^*, \boldsymbol{\theta}_l^*\}$, R_l^{SEC} can be reformulated as follows:

$$\begin{aligned} R_l^{SEC} = & d_l^1 2\Re \left\{ \mathbf{w}_l^H \left(\mathbf{h}_{Bl} + \mathbf{H}_l^H \boldsymbol{\theta}_l \right) \left(\mathbf{h}_{Bl}^H + \boldsymbol{\theta}_l^{*H} \mathbf{H}_l \right) \mathbf{w}_l^* \right\} \\ & + d_l^2 \left[\left| \left(\mathbf{h}_{Bl}^H + \boldsymbol{\theta}_l^{*H} \mathbf{H}_l \right) \mathbf{w}_{l'} \right|^2 + \left| \left(\mathbf{h}_{Bl}^H + \boldsymbol{\theta}_l^{*H} \mathbf{H}_l \right) \mathbf{w}_l \right|^2 \right] \\ & + \frac{1}{1 + d_l^3} \frac{\left| \left(\mathbf{h}_l^H + \boldsymbol{\theta}_l^{*H} \mathbf{G}_l \right) \mathbf{w}_{l'} \right|^2}{2\Re \left\{ \mathbf{w}_{l'}^H \left(\mathbf{h}_l + \mathbf{G}_l^H \boldsymbol{\theta}_l \right) \left(\mathbf{h}_l^H + \boldsymbol{\theta}_l^{*H} \mathbf{G}_l \right) \mathbf{w}_{l'}^* \right\} + d_l^4} \end{aligned} \quad (8)$$

It is obvious that (8) is convex in the interest of maintaining conciseness and clarity, refer to [25] for comprehensive details.

To address the non-convex QoS constraints, method of SOCP is employed to effectuate a further transformation of the constraint condition (6e) into:

$$\Im \left\{ \left(\mathbf{h}_{Bl}^H + \boldsymbol{\theta}_l^H \mathbf{H}_l \right) \mathbf{w}_l \right\} = 0, \quad (9)$$

$$\sqrt{1 + \frac{1}{\Gamma_{min}}} \Re \left\{ \left(\mathbf{h}_{Bl}^H + \boldsymbol{\theta}_l^H \mathbf{H}_l \right) \mathbf{w}_l \right\} \geq \left\| \left(\mathbf{h}_{Bl}^H + \boldsymbol{\theta}_l^H \mathbf{H}_l \right) \mathbf{W} \sigma^2 \right\|, \quad (10)$$

where $\mathbf{W} = [\mathbf{w}_T, \mathbf{w}_R]$. Upon holding constant any value within the set of parameters $\mathbf{w}_l$ or $\boldsymbol{\theta}_l$, the aforementioned constraint assumes the form of an elliptical constraint.

Based on the above equation, with fixed $\boldsymbol{\theta}_l$ we can reformulate (6a)–(6f) as

$$\min_{\boldsymbol{\theta}_l, \mathbf{w}_l} \sum_l \phi_l R_l^{SEC} \quad (11a)$$

$$\begin{aligned} \text{s.t.} \quad & \left| \boldsymbol{\theta}_m^T - \boldsymbol{\theta}_m^R \right| = \frac{\pi}{2} \text{ or } \frac{3\pi}{2}, \forall m \in \mathfrak{M}, \\ & (6b) \sim (6d), (9), (10). \end{aligned} \quad (11b)$$

with fixed $\boldsymbol{\theta}_l$, (11a) and (11b) as w.r.t $\mathbf{w}_l$ is convex which can be solved by the optimization toolbox CVX [26]. The primary distinction lies in the fact that, at this juncture, the phase of the STAR-RIS is in a state of coupling. According to the [27], we introduce auxiliary

variables $\tilde{\boldsymbol{\theta}}_l = \left[\sqrt{\tilde{\beta}_1^l} e^{j\tilde{\phi}_1^l}, \dots, \sqrt{\tilde{\beta}_M^l} e^{j\tilde{\phi}_M^l} \right]^T$, $\forall l \in \{T, R\}$, satisfying $\tilde{\boldsymbol{\theta}}_l = \boldsymbol{\theta}_l$. By incorporating the above equality constraint into the objective function through the introduction of a penalty term, then, following the idea of PDD, problem (11a) and (11b) can be recast as

$$\min_{\theta_l, \mathbf{w}_l} \sum_l \phi_l R_l^{SEC} + \frac{1}{2\rho} \left\| \tilde{\theta}_l - \theta_l + \rho \lambda_l \right\|^2 \quad (12a)$$

$$\text{s.t. } (\tilde{\beta}_m^T)^2 + (\tilde{\beta}_m^R)^2 = 1, \forall m \in \mathfrak{M}, \quad (12b)$$

$$\sqrt{\tilde{\beta}_m^T} \sqrt{\tilde{\beta}_m^R} \cos(\tilde{\theta}_{T,m} - \tilde{\theta}_{R,m}) = 0, \forall m \in \mathfrak{M}, \quad (12c)$$

$$(6b), (9), (10).$$

where ρ is a nonnegative penalty factor, λ_l represents the Lagrangian dual variables and $l \in \{T, R\}$. It is established that as $\lambda \rightarrow 0$ approaches zero, we set the objective function to zero to ensure the satisfaction of constraint $\tilde{\theta}_l = \theta_l$. The alternating update of $\mathbf{w}_l$, $\{\theta_T, \theta_R\}$, $\{\tilde{\theta}_T, \tilde{\theta}_R\}$, λ_l and ρ satisfy the Karush–Kuhn–Tucker (KKT) conditions. The optimal solution can be obtained On this basis. Following the ideas of BCD, problem (12a)–(12c) can be divided into two sub-problems, respectively.

3.1.1. Optimization of $\{\mathbf{w}_l, \theta_T, \theta_R\}$

Given $\{\tilde{\theta}_T, \tilde{\theta}_R\}$, λ_l , and ρ_l , $l \in \{T, R\}$, it is noteworthy that the objective function of Equations (11a) and (11b) exhibits convexity w.r.t $\mathbf{w}_l$ and $\{\theta_T, \theta_R\}$, which can be solved by CVX.

3.1.2. Optimization of $\{\tilde{\theta}_T, \tilde{\theta}_R\}$

The variables $\{\mathbf{w}_l, \theta_T, \theta_R\}$ exclusively appear in the constraints and the penalty term of the objective function, the resulting problem can be expressed as follows

$$\min_{\tilde{\theta}_l} \left\| \tilde{\theta}_l - \theta_l + \rho \lambda_l \right\|^2 \quad (13a)$$

$$\text{s.t. } (\tilde{\beta}_m^T)^2 + (\tilde{\beta}_m^R)^2 = 1, \forall m \in \mathfrak{M}, \quad (13b)$$

$$\sqrt{\tilde{\beta}_m^T} \sqrt{\tilde{\beta}_m^R} \cos(\tilde{\theta}_{T,m} - \tilde{\theta}_{R,m}) = 0, \forall m \in \mathfrak{M}. \quad (13c)$$

We decompose $\tilde{\theta}_l$ to amplitude vector $\tilde{\beta}_l = [\tilde{\beta}_1^l, \dots, \tilde{\beta}_M^l]^T$ and phase-shift vector $\tilde{\psi}_l = [e^{j\tilde{\phi}_1^l}, \dots, e^{j\tilde{\phi}_M^l}]^T$, define $\tilde{\vartheta}_l = \text{diag}(\tilde{\beta}_l^H)(-\theta_l + \rho \lambda_l)$, $\varphi_m^+ = \tilde{\vartheta}_{T,m}^* + j\tilde{\vartheta}_{R,m}^*$, $\varphi_m^- = \tilde{\vartheta}_{T,m}^* - j\tilde{\vartheta}_{R,m}^*$. Consequently, with given $\tilde{\beta}_T$ and $\tilde{\beta}_R$, we can obtain a closed-form solution for $\tilde{\psi}_T$ and $\tilde{\psi}_R$:

$$\begin{aligned} (\tilde{\psi}_{T,m}^*, \tilde{\psi}_{R,m}^*) = \arg \min_{(\tilde{\psi}_{T,m}, \tilde{\psi}_{R,m}) \in \kappa_m} \Re(\tilde{\psi}_{T,m}^*, \tilde{\psi}_{T,m}) \\ + \Re(\tilde{\psi}_{R,m}^*, \tilde{\psi}_{R,m}) \end{aligned} \quad (14)$$

where κ_m denotes a set of a pair of closed-form solutions:

$$\kappa_m = \left\{ \left(e^{j(\pi - \angle \varphi_m^+)}, e^{j(\frac{3}{2}\pi - \angle \varphi_m^+)} \right), \left(e^{j(\pi - \angle \varphi_m^-)}, e^{j(\frac{1}{2}\pi - \angle \varphi_m^-)} \right) \right\} \quad (15)$$

Nextly, we define $\tilde{\boldsymbol{\theta}}_l = \text{diag}(\tilde{\boldsymbol{\psi}}_l^H)(-\boldsymbol{\theta}_l + \rho\lambda_l)$, $a_n = |\tilde{\boldsymbol{\theta}}_T^*| \cos(\angle \tilde{\boldsymbol{\theta}}_T^*)$, $b_n = |\tilde{\boldsymbol{\theta}}_R^*| \sin(\angle \tilde{\boldsymbol{\theta}}_R^*)$, $\xi_n = \text{sgn}(b_n) \arccos\left(\frac{a_n}{\sqrt{a_n^2 + b_n^2}}\right)$, then, for any given $\tilde{\boldsymbol{\psi}}_T$ and $\tilde{\boldsymbol{\psi}}_R$, the optimal solutions for the elements of $\tilde{\boldsymbol{\beta}}_T$ and $\tilde{\boldsymbol{\beta}}_R$ are given by

$$\begin{cases} \tilde{\beta}_{T,m}^* = \sin(\omega_n), \\ \tilde{\beta}_{R,m}^* = \cos(\omega_n). \end{cases} \quad (16)$$

where

$$\omega_n = \begin{cases} -\frac{1}{2}\pi - \xi_n, & \text{if } \xi_n \in \left[-\pi, -\frac{1}{2}\pi\right), \\ 0, & \text{if } \xi_n \in \left[-\frac{1}{2}\pi, \frac{1}{4}\pi\right), \\ \frac{1}{2}\pi, & \text{otherwise.} \end{cases} \quad (17)$$

Finally, in accordance with the PDD framework, the dual variables $\{\lambda_T, \lambda_R\}$ and the penalty factor ρ are subject to iterative updating.

The overall procedure is given in Algorithm 1, where $R^{(q)}$ denotes the obtained WSSR in the q -th iteration, and η denotes the stopping threshold, $\delta = \max\left\{\|\boldsymbol{\theta}_T - \tilde{\boldsymbol{\theta}}_T\|, \|\boldsymbol{\theta}_R - \tilde{\boldsymbol{\theta}}_R\|\right\}$ denotes the constraint violation function.

Algorithm 1 Algorithm of Problem (11a) and (11b)

- 1: Set feasible variables $\{\mathbf{w}_l^{(0)}, \boldsymbol{\theta}_l^{(0)}\}$ and $q = 0$.
 - 2: **repeat**
 - 3: **repeat**
 - 4: (a) Obtain $\{\mathbf{w}_T^{(q)}, \mathbf{w}_R^{(q)}\}$ via solving (11a) and (11b) using CVX, with fixed $\{\boldsymbol{\theta}_l^{(q-1)}, \mathbf{w}_l^{(q-1)}\}$.
 - (b) Obtain $\{\boldsymbol{\theta}_T^{(q)}, \boldsymbol{\theta}_R^{(q)}\}$ via solving (12a)–(12c) using CVX, with fixed $\{\mathbf{w}_l^{(q)}, \boldsymbol{\theta}_l^{(q-1)}\}$.
 - (c) update $\tilde{\boldsymbol{\psi}}_l$ by (14).
 - (d) update $\tilde{\boldsymbol{\beta}}_l$ by (16).
 - (e) $q \leftarrow q + 1$.
 - (f) Calculate WSSR $R^{(q)}$ by (6a).
 - 5: **until** $R^{(q)} - R^{(q-1)} < \kappa$.
 - 6: **if** $\delta < \eta$ **then**
 - 7: set $\lambda_l = \lambda_l + \frac{1}{\rho}(\tilde{\boldsymbol{\theta}}_l - \boldsymbol{\theta}_l)$
 - 8: **else**
 - 9: set $\rho = c\rho$
 - 10: **end if** set $\eta = 0.9\delta$
 - 11: **until** δ below threshold.
 - 12: **return** Outputs
-

3.2. Extension to the IP Scheme

The objective function and constraints of the STAR-RIS's IP scheme may contain multiple locally optimal solutions, making it challenging for traditional optimization methods to guarantee the identification of a globally optimal solution. The CCCP method can be used as an iterative algorithm for solving non-convex optimization problems, and its basic idea is to decompose a complex non-convex problem into a series of easier-to-solve convex optimization subproblems. The CCCP method ensures the convergence of the algorithm by

constructing a discrete-time dynamical system that guarantees a monotonically decreasing value of the objective function at each iteration. This is particularly important for complex optimization problems in IP schemes, where the optimal solution can be achieved within a reasonable number of iterations. Specifically, we use the CCCP method to decompose the non-convex independent phase shift constraints into a series of convex sub-constraints to gradually approximate the global optimal solution.

With given θ_l , the optimization of $\mathbf{w}_l$ is as the same as CP scheme. The main difference is without the constraint (6f). In accordance with CCCP, the constraint (6c) and (6d) is decomposed into the subsequent expression:

$$\text{Tr}(\mathbf{D}_{1,l}) \leq 2\text{Tr}(\theta_l^{(n)} \theta_l^{(n)H}) - \text{Tr}(\theta_l^{(n)} (\theta_l^{(n)})^H), \quad (18)$$

$$\begin{bmatrix} \mathbf{D}_{1,l} & \boldsymbol{\Theta}_l & \theta_l \\ \boldsymbol{\Theta}_l^H & \mathbf{D}_{2,l} & \theta_l \\ \theta_l^H & \theta_l^H & 1 \end{bmatrix} \geq 0, \quad (19)$$

where n denotes the number of iterations, $\mathbf{D}_{1,l} \in \mathbb{H}^{M \times M}$ and $\mathbf{D}_{2,l} \in \mathbb{H}^{M \times M}$ are slack variables. With fixed $\mathbf{w}_l$, the optimization of θ_l can be solved by CVX. More details can be referred to [28]. Then, optimization of IP scheme can be formulated as follows:

$$\min_{\theta_l, \mathbf{w}_l} \sum_l \phi_l R_l^{SEC} \quad (20a)$$

$$\text{s.t.} \quad (6b), (9), (10), (18), (19). \quad (20b)$$

The overall process of the CCCP method is illustrated in Algorithm 2 below.

Algorithm 2 CCCP Method to Solve Problem (20a) and (20b)

- 1: Set feasible variables $\{\mathbf{w}_l^{(0)}, \theta_l^{(0)}\}$ and $q = 0$.
 - 2: **repeat**
 - 3: (a) Obtain $\{\mathbf{w}_T^{(q)}, \mathbf{w}_R^{(q)}\}$ via solving (6a)–(6f) using CVX, with fixed $\{\theta_l^{(q-1)}, \mathbf{w}_l^{(q-1)}\}$.
 - (b) Obtain $\{\theta_T^{(q)}, \theta_R^{(q)}\}$ via solving (20a) and (20b) using CVX, with fixed $\{\mathbf{w}_l^{(q)}, \theta_l^{(q-1)}\}$.
 - (c) $q \leftarrow q + 1$.
 - (d) Calculate WSSR $R^{(q)}$ by (6a).
 - 4: **until** $R^{(q)} - R^{(q-1)} < \kappa$.
 - 5: **return** Outputs
-

4. Numerical Results

In this section, we present numerical results to compare the performance of the proposed algorithm with four benchmark scenarios. WSSR is a crucial performance metric for PLS. Next, we discuss the impact of various variables on the performance of WSSR. The three-dimensional (3D) simulation setup is illustrated in Figure 2, where BS and STAR-RIS are positioned at (0, 0, 5) and (145, 0, 0) meters, respectively. Bob_l and Eve_l are randomly distributed along a semicircle centered on STAR-RIS with a radius of $d_T = d_R = 5$ m. The STAR-RIS is located at the center of this semicircle. In the simulations conducted, the narrow-band quasi-static fading channels extending from the BS to the STAR-RIS are characterized as Rician fading channels in the ensuing manner [29].

$$\mathbf{h}_{BS} = \sqrt{\frac{\rho_0}{d_{BS}^{\alpha_{BS}}}} \left(\sqrt{\frac{K_{BS}}{K_{BS} + 1}} \mathbf{h}_{BS}^{LOS} + \sqrt{\frac{1}{K_{BS} + 1}} \mathbf{h}_{BS}^{NLOS} \right) \quad (21)$$

where K_{BS} is the Rician factor set as 5 dB, $\alpha_{BS} = 2.2$ denotes the corresponding path loss exponents, d_{BS} denotes the distances between the BS and the STAR-RIS, $\rho_0 = 1$ represents

the path loss at a reference distance of 1 m, $\mathbf{h}_{BS}^{LOS} = \mathbf{a}\mathbf{b}^H$ is the normalized line-of-sight (LoS) component, with $\mathbf{a} = [a_1, \dots, a_N]^T$ and $\mathbf{b} = [b_1, \dots, b_M]^T$ denote the steering vectors, and $\mathbf{h}_{BS}^{NLOS}$ is the Rayleigh fading representing the non-line-of-sight (NLOS) component, the other indirect link channels are modeled similarly. It is assumed that the direct channel between the BS and Bob_I, Eve_I is Rayleigh channel with the distance-dependent path loss which all direct links set $\alpha = 3.6$. The path loss factor for direct links is higher than that for indirect links, which allows for a more accurate simulation and validation of the benefits of STAR-RIS in enhancing communication performance.

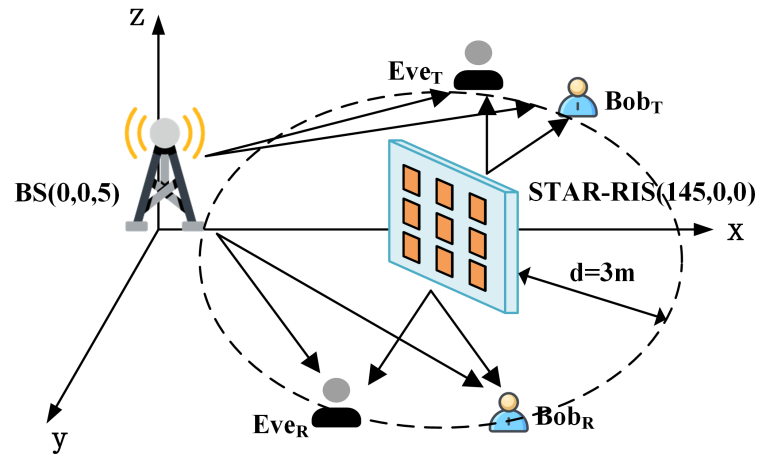


Figure 2. Simulation setup for the considered network.

The STAR-RIS is a uniform rectangular array (URA) whose size is $M = X \times Y$, where X is the element of the x-axis (vertical) and Y is the element of the y-axis (horizontal). We set $M = 30$. The BS is a large uniform linear array (ULA), which is comprised of N elements. The number of antennas is set to $N = 4$ and the noise power is set to $\sigma^2 = -80$ dBm. $P_t = 0$ dBm is the transmit power budget and the minimum rate requirement of legitimate users is set to $\Gamma_{min} = -5$ dBm. The weight parameter and the algorithm convergence factor are set to $\phi_l = 0.5, \forall l$. and $\kappa = 10^{-3}$, respectively. For the parameters of the PDD method, we set $c = 0.1, \eta = 10^{-3}$. The initial value of $\rho = 0.1$. Moreover, each result is averaged over 150 independent Monte-Carlo trials.

Figure 3 depicts the convergence performance of the proposed algorithm with different M and N . From this figure, we observe that the WSSR stabilizes within approximately 5 iterations. An intuitive explanation for this result is that the direct link offers improved initial channel conditions, allowing the optimization algorithm to identify a superior solution more quickly during the initial stage, which accelerates the overall convergence process. Additionally, the reasonable setting of channel parameters and the low computational complexity of the proposed algorithm further enhance its rapid convergence. It is discerned that the WSSR exhibits a monotonic augmentation concomitant with the iterative process and culminates in equilibrated solutions after a finite number of iterations, and the iterative process converges more quickly. In addition, larger M, N achieves a higher WSSR at the cost of slower convergence speed, since more variables need to be optimized. Due to coupling constraints, the WSSR with independent phase shift is slightly larger than the WSSR with coupled phase shift.

Next, we consider the following benchmark scenarios for performance comparison, i.e., (1) IP scheme. (2) CP scheme. (3) Mode switching (MS): in this mode, all elements of the STAR-RIS are divided into two groups which $\beta_l \in \{0, 1\}$. (4) Time switching (TS): in this mode, the STAR-RIS utilizes temporal variation to alternate element states between T and R modes across distinct orthogonal time slots. (5) Conventional wiretap channel, i.e., without using STAR-RIS (W-RIS). (6) Conventional RIS (C-RIS): the two conventional RISs are deployed adjacent to each other at the same location as the STAR-RIS. The above

benchmark scheme is a comparison of common STAR-RIS optimization algorithms in the field [29].

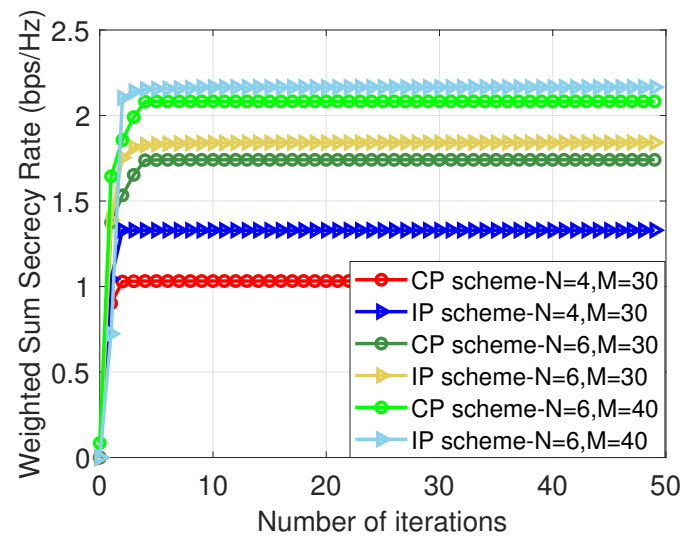


Figure 3. Convergence performance of the proposed algorithm.

Figure 4 evaluates the WSSR attained by various methodologies in relation to the allocated transmit power budget, TS surpasses IP and CP in security at low power due to its inherent wiretap avoidance and clear decoding. However, as power rises, IP and CP's efficient time use prevails, which diminishes the reception capability of eavesdroppers, leading to greater secrecy at high power levels. IP scheme exhibits higher WSSR at all transmit power levels, which shows that the IP scheme is more efficient in exploiting the transmit power to enhance the secrecy rate, specifically because its phase shifts can be adjusted independently with higher design freedom to achieve higher secrecy rates. However, in exchange for complex hardware implementations that increase the difficulty and cost of implementing the system. The CP scheme outperforms C-RIS and MS in secrecy efficacy. The WSSR of CP is slightly lower than that of IP due to the effect of coupling phase shift. The CP scheme may not perform as well as the IP scheme, especially in scenarios where elaborate beamforming and high secrecy performance are required. Calculations show that the average error in confidentiality rates for the CP and IP schemes is under 3 percent.

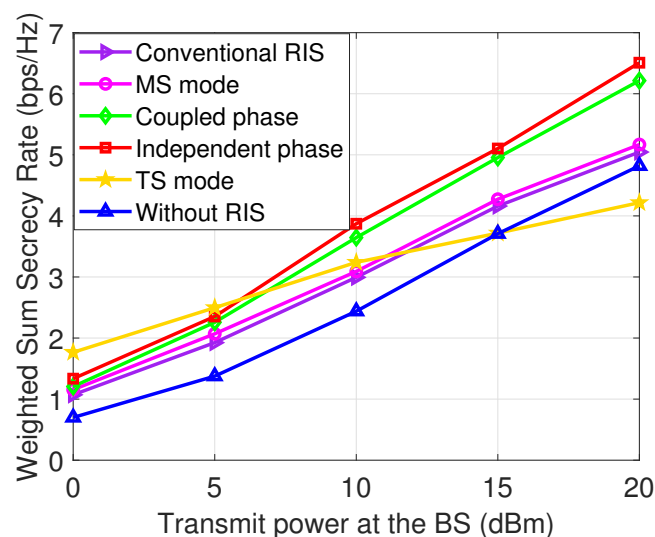


Figure 4. The WSSR versus P_t with $M = 30$.

In Figure 5, we can find that the WSSR increases with M for all these schemes. C-RIS lag due to limited degrees-of-freedom (DoFs) from their fixed transmission/reflection choice, widening the performance gap with STAR-RIS as M grows. This comparison validates STAR-RIS's utility in wireless networks. TS naturally avoids mutual eavesdropping between users through time switching, which is particularly important in multi-user scenarios. The advantage becomes much more apparent as the amount of factors increases. MS outperforms the C-RIS. This is due to the fact that in a broadcast communication scenario, MS experiences no inter-user interference and can leverage the entire available communication time to enhance WSSR. The WSSR of MS and C-RIS, while also increasing with M , is not as significant as that of the CP and IP schemes. This is because their phase shift strategies are more rigid and lack the flexibility needed to fully optimize the signal transmission path. The performance of CP is slightly lower than that of IP as the number of elements increases. This is because the phase shifts of neighboring units in the CP scheme are constrained, resulting in fewer degrees of freedom in the system. Consequently, IP can manage and reduce interference more efficiently, especially in multi-user scenarios. Due to phase-shift constraints, CP may not eliminate interference, thereby affecting the WSSR.

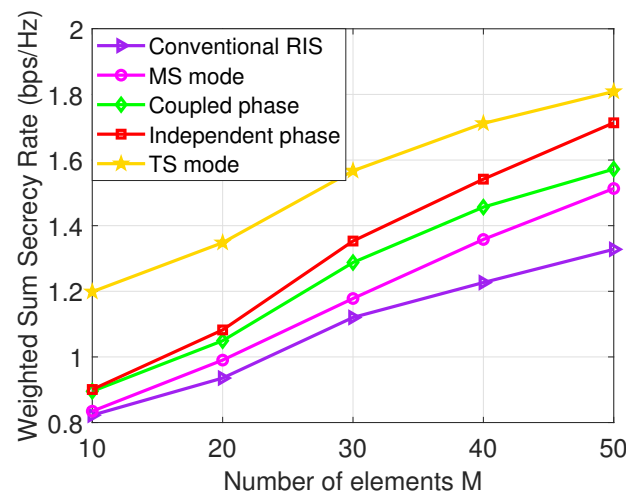


Figure 5. The WSSR versus M with $P_t = 0$ dBm.

Figure 6 illustrates the convergence behavior of the PDD procedure to update θ_l . The value of the penalty pair function δ decreases with iterations for different numbers of STAR-RIS elements. The PDD algorithm demonstrates good convergence within twenty iterations, with a threshold set at 10^{-5} . Additionally, the convergence is not sensitive to variations in M .

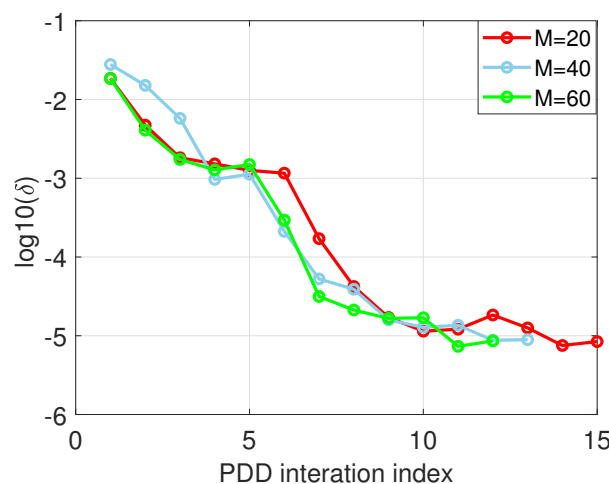


Figure 6. Convergence of the proposed PDD algorithm.

5. Conclusions

In this paper, we investigate algorithms for both independent and coupled phase shift scenarios, focusing on weight optimization and secrecy rate enhancement in STAR-RIS-aided MISO systems. We mainly discuss the coupled phase-shift scheme, employing a PDD-based optimization algorithm for BCD. This algorithm finds high-quality suboptimal solutions by performing an exhaustive search on the set of magnitude and phase offsets. By integrating the transmission and reflection characteristics with the algorithm for solving the coupled phase-shift problem, this approach offers a comprehensive method for the design and analysis of STAR-RIS systems. Our simulations demonstrate the superior WSSR of STAR-RIS and the algorithm outperforms the existing methods. STAR-RIS can effectively enhance PLS by intelligently adjusting the paths of reflected and transmitted signals. It dynamically adjusts the direction and strength of signals so that legitimate users receive stronger signals and eavesdroppers receive weaker signals, thus improving the confidentiality of communications.

In the future, the deployment of the STAR-RIS and hardware impairments will be discussed in more detail. These two aspects are important because the physical location of STAR-RIS, as well as hardware impairments, will directly affect the quality of the transmission/reflection links. Additionally, the PDD-based BCD algorithm would be enhanced by incorporating a deep learning (DL) model, which can be integrated with a PDD framework to optimize the coupled phase-shift subproblem. By alternately optimizing the coupled phase-shift coefficients, the algorithm can achieve rapid convergence. The CP scheme has the potential for practical applications, especially in scenarios where security and system performance need to be balanced. Many research directions for the CP scheme are worth pursuing, including the Internet of Medical Things (IoMT), unmanned aerial vehicle (UAV) communications, and massive MIMO systems. In addition, the IP scheme applied to STAR-RIS-enhanced robotic communications and STAR-RIS-assisted visible light communications (VLC) has potential for future research.

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