Security Enhancement for Coupled Phase-Shift STAR-RIS Networks
Zheng Zhang, Member, IEEE, Zhaolin Wang, Member, IEEE, Yuanwei Liu, Senior Member, IEEE, Bingtao He, Member, IEEE, and Jian Chen, Member, IEEE

Abstract—The secure transmission of the simultaneously transmitting and reflecting reconfigurable intelligent surface (STAR-RIS) aided communication system is investigated. Considering the coupled phase shifts of STAR-RISs and the fair secrecy requirement of users, a new secure beamforming design is proposed for addressing the unique full-space mutual eavesdropping in STAR-RIS aided communications. In particular, a penalty-based secrecy beamforming algorithm is proposed to solve the resulting non-convex optimization problem, where closed-form solutions of the coupled phase-shift coefficients are obtained in each iteration. Numerical results demonstrate that 1) the proposed scheme achieves higher secrecy capacity than conventional RIS; 2) 4-bit discrete phase shifters are sufficient for secrecy guarantee.

Index Terms—Beamforming, coupled phase shifts, physical layer security, simultaneous transmission and reflection (STAR).

I. INTRODUCTION

To cope with the rapidly growing demands for various emerging applications and ubiquitous wireless communications, reconfigurable intelligent surface (RIS) has been envisioned as a promising key enabler for next-generation wireless networks [1], [2], [3]. However, the inherent limitation of half-space coverage of conventional reflecting-only RIS restricts its application flexibility and electromagnetic propagation adjustment capacity. Against this background, a new principle of simultaneous transmitting and reflecting RIS (STAR-RIS) has been proposed [4]. By splitting the incident signal into transmitted and reflected signal on both sides of the surfaces, STAR-RISs are capable of enabling a full-space smart radio environment [5], [6].

However, the unique ability of STAR-RIS to reconfigure full-space radio propagation environments inevitably results in full-space wiretapping. In other words, the eavesdroppers on any side of STAR-RIS can access the confidential information passing through STAR-RIS, which raises more stringent security challenges from the information-theory perspective. Fortunately, it has been claimed that physical layer security (PLS) techniques are expected to secure STAR-RIS aided communications by exploiting intrinsic features of wireless channels, such as fading, noise, and interference [7], [8], [9], [10].

Noteworthy, the security design proposed in the aforementioned works [7], [8], [9], [10], is based on the ideal STAR-RIS model with independent phase shifts, which requires complicated semi-passive or active STAR-RIS metasurface architectures. While for low-cost passive lossless STAR-RISs, recent works [11], [12] have pointed out that the transmission and reflection phase shifts are coupled with each other, which implies there exists a fixed phase-shift difference ($\pi$ or $\frac{\pi}{2}$) between the transmission and reflection coefficients. As such, the existing security design [7], [8], [9], [10] cannot ensure the network security as well as the phase-shift coupling constraint, which requires the redesign of the transmit beamforming and STAR-RIS coefficients. Additionally, the conventional sum secrecy capacity maximization schemes in [7], [8], where more transmit power is concentrated on the users with better channel conditions, cannot guarantee fairness among legitimate users in terms of security transmission.

Motivated by the above, this paper studies secure beamforming optimization with the aim of minimum secrecy capacity maximization for a coupled STAR-RIS network. The main contributions of this paper are summarized below.

• We propose a coupled phase-shift STAR-RIS aided secrecy communication framework, where the confidential information is transmitted to an indoor user (IU) and an outdoor user (OU) in the presence of eavesdroppers. Based on this framework, we jointly optimize the transmit beamforming of the BS and the coupled phase-shift coefficients of the STAR-RIS to maximize the minimum secrecy capacity of the IU and the OU.

• We propose a penalty-based secrecy beamforming (PSB) algorithm to solve the resulting optimization problem. In the iteration of the PSB algorithm, the optimal solution of the transmit beamforming at the BS is obtained by semi-infinite relaxation (SDR), and the optimal solution of the coupled phase-shift coefficients of the STAR-RIS is obtained in closed form. Then, we extend the PSB algorithm to the case of STAR-RIS with discrete phase-shift.

• Numerical results reveal that: 1) the coupled phase-shift STAR-RIS is superior to the conventional RIS regarding secrecy performance; and 2) 4-bit discrete phase shifts are sufficient for the coupled phase-shift STAR-RIS to achieve comparable performance as the continuous phase shifts.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. Network Description

We consider a coupled phase-shift STAR-RIS aided downlink communication network as shown in Fig. 1, in which an $M$-antenna BS exploits an $N$-element STAR-RIS to transmit the confidential signal to a single-antenna IU and a single-antenna OU in presence of two single-antenna eavesdroppers ($E_1$ and $E_2$). Without loss of generality, we assume that IU is on the transmission side of the STAR-RIS1 and

1STAR-RIS is the similar concept to intelligent omni-surface (IOS) that supports the dual-functionality of signal transmission and reflection, but mainly based on metasurface-based implementation architecture (smart glass [13] or graphene) instead of periodic positive-intrinsic-negative (PIN) diodes.

Manuscript received 22 August 2022; revised 4 December 2022; accepted 4 February 2023. This work was supported in part by the National Natural Science Foundation of China under Grants 62271368 and 62201421, in part by the Key Research and Development Program of Shaanxi under Grant 2023-YBGY-041, in part by China Postdoctoral Science Foundation under Grants BX20190264 and 2019M60258, in part by the National Science Basic Research Plan of Shaanxi Province under Grant 2021JQ-206, in part by the Guangdong Basic and Applied Basic Research Foundation under Grant 2020A1515110084, in part by the SUNRISE under Grant CHIST-ERA-20-SICT-005, in part by Engineering and Physical Sciences Research Council under Project EP/W035588/1, and in part by Royal Society under Grants RG5R1221050 and IECNSFC/201112. The review of this article was coordinated by Prof. Prabhat Kumar Upadhyay.

(Corresponding authors: Lu Lv; Jian Chen.)
Zheng Zhang, Bingtao He, Lu Lv, and Jian Chen are with the School of Telecommunications Engineering, Xidian University, Xi’an 710071, China (e-mail: zzhang_688@stu.xidian.edu.cn; bthe@xidian.edu.cn; lulv@xidian.edu.cn; jianchen@mail.xidian.edu.cn).
Zhaolin Wang and Yuanwei Liu are with the School of Electronic Engineering and Computer Science, Queen Mary University of London, London E1 4NS, U.K. (e-mail: zhaolin.wang@qmul.ac.uk; yuanwei.liu@qmul.ac.uk).
Digital Object Identifier 10.1109/TVT.2023.3243545
OU is on the reflection side. E₁ and E₂ are assumed to be situated near the IU and the OU for wiretapping signal. Due to the obstacles, there is no direct link between the BS and IU/OU/E₁/E₂. The baseband equivalent channels from STAR-RIS to BS, IU, OU, E₁, and E₂ are denoted as \( G \in \mathbb{C}^{N \times M} \), \( h_{b,1} \in \mathbb{C}^{N \times 1} \), \( h_{b,2} \in \mathbb{C}^{N \times 1} \), \( h_{b,3} \in \mathbb{C}^{N \times 1} \), and \( h_{b,5} \in \mathbb{C}^{N \times 1} \), respectively. The Rician fading model is adopted for \( G \), and the Rayleigh fading model is adopted for the remaining channels. We mainly focus on the secrecy enhancement against the internal eavesdroppers, where E₁ and E₂ are the other active users with security clearance only for their own information and untrusted by users IU and OU from the data perspective [7], [8], [9], [10]. Thus, the legitimate/eavesdropping CSI can be perfectly obtained by exploiting the parallel factor decomposition estimation methods [14], [15]. However, when the eavesdroppers are the external nodes of wiretapping network, it is still available for the BS to employ the inadvertent local oscillator power leakage of eavesdroppers’ radio frequency front-end to estimate CSI [16].

### B. Coupled Phase-Shift Model of STAR-RIS

The STAR-RIS is assumed to consist of \( N \) half-wavelength elements, all of which can operate in the three modes [4], i.e., mode switching (MS), time switching (TS) and energy splitting (ES). In the MS mode, the STAR-RIS elements are divided into two categories of transmission (T) elements and reflection (R) elements, while in the TS mode, the STAR-RIS elements cyclically switch between the T and R modes. For the ES mode, each element operate in the T&R mode, where the signal energy incident upon each element is split into two parts by the amplitude coefficients \( \beta_{n}^T \) and \( \beta_{n}^R \), while the reflection and transmission phase shifts satisfy \( \theta_{n}^T, \theta_{n}^R \in \{0, 2\pi\} \) [5]. We focus on the purely passive lossless hardware architecture of STAR-RIS, the elements are only excited by the incident signal, which produce the magnetization and electric polarization currents and radiate the corresponding transmission and reflection fields. Notably, the excited magnetic and electric currents are required to strictly abide by the law of conservation of energy and the boundary condition, which indicates that there is an inevitable coupling between transmission and reflection coefficients.

Therefore, we have

\[
\beta_{n}^T = 1 - \beta_{n}^R, \quad 1 \leq n \leq N,
\]

\[
|\theta_{n}^T - \theta_{n}^R| = \frac{\pi}{2} \text{ or } \frac{3\pi}{2}, \quad 1 \leq n \leq N.
\]

As such, for an \( N \)-element STAR-RIS, the transmission/reflection coefficient matrix is given by

\[
\Theta_{TR} = \text{diag}\left( \sqrt{\beta_{1}^T e^{j\theta_{1}^T}}, \ldots, \sqrt{\beta_{N}^T e^{j\theta_{N}^T}} \right).
\]

### C. Signal Model

The BS exploits the multiple beamforming vectors \( w_{1}, w_{0} \in \mathbb{C}^{M \times 1} \) to send the confidential signal \( s_{1} \) and \( s_{0} \) (\( \mathbb{E}\{|s_{1}|^2\} = \mathbb{E}\{|s_{0}|^2\} = 1 \)) to IU and OU, respectively. However, due to the unique ES mechanism of STAR-RIS, each incident signal is fully divided into the reflection signal and the transmission signal, which implies that the eavesdroppers can also receive multi-user signal. Thus, the received signal at IU and E₁ are given by

\[
y_{c} = h_{b,3}^H \Theta_{TR}^H G \left( \sum_{\phi \in \{1,0\}} w_{\phi} s_{\phi} \right) + n_{c}, \quad c \in \{I, E_{1}\},
\]

where \( n_{1}, n_{E_{1}} \sim \mathcal{CN}(0, \sigma^2) \) represent the additive white Gaussian noise (AWGN) at the IU and E₁. Similarly, the received signal at OU and E₂ are given by

\[
y_{c} = h_{b,3}^H \Theta_{TR}^H G \left( \sum_{\phi \in \{1,0\}} w_{\phi} s_{\phi} \right) + n_{c}, \quad c \in \{O, E_{2}\}.
\]

On receiving superimposed signal, each legitimate user only decodes its own signal while treating the other’s signal as interference. Without loss of generality, we assume that E₁ and E₂ can decode any interested signal from the reflected or transmitted signal observations, i.e., the inter-user interference is considered at each eavesdropper. Hence, the achievable rates for legitimate users and eavesdroppers² to decode signal they are interested in are given by

\[
R_{q} = \log_{2} \left( 1 + \frac{|h_{b,3}^H \Theta_{IR} G w_{q}|^2}{|h_{b,3}^H \Theta_{IR} G w_{q}|^2 + \sigma^2} \right),
\]

\[
R_{k,q} = \log_{2} \left( 1 + \frac{|h_{b,3}^H \Theta_{IR} G w_{q}|^2}{|h_{b,3}^H \Theta_{IR} G w_{q}|^2 + \sigma^2} \right),
\]

where \( k \in \{1, 2\}, \quad q \in \{1, O\}, \quad \beta \in \{1, O, \beta \neq g\} \).

Accordingly, by adopting the wiretap code scheme, the secrecy capacity of IU or OU is given by

\[
R_{k,q} = [R_{q} - \max \{R_{k,q}, R_{k,q}\}]^+, \quad q \in \{1, O\},
\]

where \([x]^+ = \max\{x, 0\}\).

### D. Problem Formulation

In this paper, we target for maximizing the minimum secrecy capacity of legitimate users by jointly optimizing transmit beamforming at the BS and coupled transmission and reflection coefficients at the STAR-RIS, subject to the transmit power budget and amplitude/phase-shift coupling constraints. The problem is formulated as follows.

\[
\max_{w_{1}, w_{0}, \Theta_{TR}} \min_{\phi \in \{1,0\}} R_{k,q},
\]

s.t. \( \sum_{\phi \in \{1,0\}} |w_{\phi}|^2 \leq P_{\text{max}}, \)

\[
|\theta_{n}^T - \theta_{n}^R| = \frac{\pi}{2} \text{ or } \frac{3\pi}{2}, \quad 1 \leq n \leq N,
\]

\[
\beta_{n}^T + \beta_{n}^R = 1, \quad \forall n,
\]

\[
|\theta_{n}^T - \theta_{n}^R| = \frac{\pi}{2} \text{ or } \frac{3\pi}{2}, \quad 1 \leq n \leq N.
\]

where \( P_{\text{max}} \) represents the transmit power budget at the BS. Note that (9b) denotes the total power consumption constraint at the BS, while (9c) and (9d) denote the amplitude and phase-shift coupling constraints of the passive and lossless STAR-RIS considered in this paper.

²Although this paper considers the non-scheduled eavesdroppers, the proposed scheme can be properly modified for supporting more sophisticated scenarios. For example, when eavesdroppers are colluding nodes, through the equivalent transformation [17, eq. (6)], we can derive the eavesdropping rate expression similar to (7), which can be handled by the proposed algorithm.
III. PROPOSED SOLUTION

In this section, we devise a PSB algorithm to tackle the non-convex problem (9). Precisely, we first construct an augmented lagrangian (AL) problem with the relaxed phase-shift constraints in the outer loop, and then, the transmit beamforming, the transmission/reflection coefficients and the optimal coupled coefficients are alternately optimized by employing SDR technique and first-order optimality condition in the inner loop. Finally, an appropriate modification of the proposed algorithm is designed for the extension to the discrete coupled phase shifts.

A. Outer Layer Problem Reformulation

Here, we denote $u_i = [\sqrt{\rho}e^{j\theta_1}, \ldots, \sqrt{\rho}e^{j\theta_N}]^T$, $u_i = [\sqrt{\rho}e^{j\theta_1}, \ldots, \sqrt{\rho}e^{j\theta_N}]^T$, $V_{\rho} = G_{U} \text{diag}(h_{k,s})$ and $V_{Bk} = G_{\nu} \text{diag}(h_{k,s})$, where $\rho \in \{1, 0\}$ and $k \in \{1, 2\}$. Thus, the secrecy capacity can be equivalently expressed as

$$R_{\rho} = \log_2 \left(1 + \frac{\text{Tr}(W_{\rho} V_{\rho} U_{\rho}^H V_{\rho}^H)}{\text{Tr}(W_{\rho} V_{\rho} U_{\rho}^H V_{\rho}^H) + \sigma^2} + \eta_{\rho} \right)$$

(10)

where the semi-positive matrices satisfy $W_{\rho} = w_{\rho} w_{\rho}^H$ and $U_{\rho} = u_{\rho} u_{\rho}^H$. To tackle the non-convexity of (10), we construct a linear lower bound expression $R_{\rho}$ for the first term in (10). Precisely, let

$$2^{\eta_{\rho}} \leq \text{Tr} \left(W_{\rho} V_{\rho} U_{\rho}^H V_{\rho}^H \right) + \text{Tr} \left(W_{\rho} V_{\rho} U_{\rho}^H V_{\rho}^H \right) + \sigma^2,$$

(11)

$$\eta_{\rho} \geq \mu_{\rho},$$

(12)

where $\{l_{\rho}, \eta_{\rho}, \mu_{\rho}\}$ are the auxiliary variables. Then, we can express $R_{\rho}$ as a linear form, i.e., $R_{\rho} = \eta_{\rho} - \eta_{\rho}$. Similarly, we introduce auxiliary variables $\{l_{E, k,s}, \eta_{E, k,s}, \mu_{E, k,s}\}$, and we can construct a linear upper bound expression $R_{E, k,s} = c_{E, k,s} - c_{E, k,s}$ for the second term of (10), which satisfies

$$2^{\eta_{E, k,s}} \leq \text{Tr} \left(W_{E, k,s} V_{E, k,s} U_{E, k,s}^H V_{E, k,s}^H \right) + \sigma^2,$$

(14)

$$\eta_{E, k,s} \geq \mu_{E, k,s},$$

(15)

where $\{l_{E, k,s}, \eta_{E, k,s}, \mu_{E, k,s}\}$ are the auxiliary variables initialized as 1 and updated by $y_{\rho} = \mu_{\rho}$ and $\nu_{k,s} = \nu_{k,s}$ at each iteration. As a result, we can rewrite the problem (9) as

$$\max_{w_{\rho}, \nu_{k,s}, l_{E, k,s}, l_{\rho}, \eta_{\rho}, \mu_{\rho}} \min_{\rho \in \{1, 0\}} R_{\rho} - R_{E, k,s},$$

(18a)

s.t.

$$\sum_{\rho \in \{1, 0\}} \text{Tr}(W_{\rho}) \leq P_{\max},$$

(18b)

$$U_{\rho}(n, n) + U_{\rho}(n, n) = 1, \forall n,$$

(18c)

To handle the non-convex constraints (9d) in problem (18), we consider exploiting the penalty based approach to relax the phase coupling by introducing the auxiliary variables $\tilde{u}_{\rho} = \left[\sqrt{\rho}e^{j\theta_1}, \ldots, \sqrt{\rho}e^{j\theta_N}\right]^T$. Specifically, by enabling the equality constraint $u_{\rho} = u_{\rho}$ as the penalty term in the objective function (18a), we can reformulate the original problem (9) as the following AL problem

$$\min_{\rho \in \{1, 0\}} \tilde{g}_{\rho},$$

(19a)

s.t.

$$\tilde{u}_{\rho}(n) = \pm j\tilde{u}_{\rho}(n), \sum_{\ell \in \{\ell\}} |\tilde{u}_{\rho}(n)|^2 = 1,$$

(19b)

$$\max_{\rho \in \{1, 0\}} R_{\rho} - R_{E, k,s} - \frac{1}{\rho} \sum_{\ell \in \{\ell\}} \|\tilde{u}_{\rho} - \tilde{U}_{\rho}\|^2$$

(19c)

where $\tilde{g}_{\rho} = R_{\rho} - R_{E, k,s} - \frac{1}{\rho} \sum_{\ell \in \{\ell\}} \|\tilde{u}_{\rho} - \tilde{U}_{\rho}\|^2$ with $\rho > 0$ denoting the penalty scaling factor.

B. Inner Layer Problem Optimization

1) Transmit Beamforming Optimization: For any given $\{U_{\rho}, \tilde{u}_{\rho}\}$, the active beamforming $\{W_{\rho}, W_{O}\}$ can be optimized via solving following problem

$$\max_{\rho \in \{1, 0\}} \min_{l_{E, k,s} \leq \nu_{E, k,s}, \mu_{E, k,s}} \max_{l_{\rho} \leq \eta_{\rho}, \mu_{\rho}} \min_{l_{E, k,s} \leq \nu_{E, k,s}, \mu_{E, k,s}} \max_{l_{\rho} \leq \eta_{\rho}, \mu_{\rho}} R_{\rho} - R_{E, k,s},$$

(20a)

s.t.

$$\{1, (13) - (15), (18b), (18d), (18e)\}$$

(20b)

Problem (20) can be efficiently solved by iteratively updating $y_{\rho} = \mu_{\rho}$ and $y_{k,s} = \nu_{k,s}$. Note that the rank-one constraints can be reasonably dropped because the rank of $W_{\rho}$ only relies on that of $U_{\rho}$, i.e., rank($W_{\rho}$) \leq rank($U_{\rho}$) = 1, which is proved in [9, Remark 1].

2) Relaxed Transmission/Reflection Coefficient Optimization: With the fixed $\{W_{\rho}, W_{O}\}$, the transmission and reflection coefficients $\{U_{\rho}\}$ can be optimized through solving following problem

$$\max_{\rho \in \{1, 0\}} \min_{l_{E, k,s} \leq \nu_{E, k,s}, \mu_{E, k,s}} \max_{l_{\rho} \leq \eta_{\rho}, \mu_{\rho}} \min_{l_{E, k,s} \leq \nu_{E, k,s}, \mu_{E, k,s}} \max_{l_{\rho} \leq \eta_{\rho}, \mu_{\rho}} \tilde{g}_{\rho},$$

(21a)

s.t.

$$\{1, (13) - (15), (18c), (18f)\}$$

(21b)

Here, we adopt the penalty based difference-of-convex (DC) method for extracting the $u_{\rho}$ and $u_{\rho}$. Precisely, by equivalently converting rank($U_{\rho}$) = 1 to Tr($U_{\rho}$) = $\|U_{\rho}\|_2$, the objective function can be replaced by following DC form with dropping the rank-one constraints [10].

$$\tilde{g}_{\rho} = \tilde{g}_{\rho} - \tau \left(\sum_{\ell \in \{\ell\}} \Re \left(\text{Tr}(U_{\rho}^H (I - u_{\rho} u_{\rho}^H))\right)\right),$$

(22)

where $\Re(\cdot)$ denotes the real part of the complex number, and $\tau > 0$ denotes the scaling coefficient of rank-one penalty terms. Note that when $\tau$ approaches $+\infty$, the rank-one $U_{\rho}$ can be obtained [18].
Algorithm 1: PSB Algorithm.

1: Initialize the iteration parameters with \( l = 1 \);
2: Outer layer repeat
3: Inner layer repeat
4: Optimize \( \{ \mathbf{W}_l, \mathbf{W}_l^d \} \) by solving problem (20);
5: Optimize \( \{ \mathbf{U}_l, \mathbf{U}_l^d \} \) by solving problem (21);
6: Update \( \{ \hat{\mathbf{u}}_l, \tilde{\mathbf{u}}_l \} \) by (24) and (25);
7: Until converge with the accuracy \( \varepsilon_{in,in} \);
8: \( \rho^l = c_5 \rho^{l-1} \) with \( c_5 < 1 \);
9: Set \( l = l + 1 \);
10: Until converge with the accuracy \( \varepsilon_{in,out} \).

3) Coupled Transmission/Reflection Coefficient Optimization: With the fixed rank-one matrices \( \{ \mathbf{W}_l, \mathbf{W}_l^d \} \), the objective function (19a) can be reduced to \( \| \mathbf{u}_c^H - \mathbf{u}_c^J \|_2^2 \), which can be further rewritten as

\[
\min_{\mathbf{u}_c} \sum_{c \in \{s, t \}} \| \mathbf{u}_c - \mathbf{u}_c^J \|_2^2, \tag{23a}
\]

s.t. (19b). \( \tag{23b} \)

Since optimization variables \( \{ \mathbf{u}_c(n), \mathbf{u}_c(m) \} (n \neq m) \) are absolutely separable in the objective function, the problem (23) can be optimized by solving \( N \) independent subproblems with respect to \( \{ \mathbf{u}_c(n), \mathbf{u}_c(m) \} \).

With the algebraic manipulations in Appendix A, the optimal coupled phase shifts and amplitudes are given by

\[
\begin{align*}
\tilde{\theta}_n^{\text{opt}} &= \begin{cases}
-\sqrt{\mathbf{v}_n^H(n) + j \mathbf{v}_n^H(n)} & \text{if } \mathbf{p}_n \mathbf{q}_n \geq 0; \\
-\sqrt{\mathbf{v}_n^H(n) - j \mathbf{v}_n^H(n)} & \text{if } \mathbf{p}_n \mathbf{q}_n < 0; \\
\end{cases} \\
\tilde{\theta}_n^{\text{opt}} &= \sqrt{\mathbf{v}_n^H(n) + j \mathbf{v}_n^H(n)} \\
\frac{\sqrt{\mathbf{v}_n^H(n)}}{\sqrt{\mathbf{v}_n^H(n) + \mathbf{v}_n^H(n)}} &= \frac{\mathbf{q}_n}{\sqrt{\mathbf{p}_n^2 + \mathbf{q}_n^2}} \\
\frac{\sqrt{\mathbf{v}_n^H(n)}}{\sqrt{\mathbf{v}_n^H(n) - \mathbf{v}_n^H(n)}} &= \frac{\mathbf{p}_n}{\sqrt{\mathbf{p}_n^2 + \mathbf{q}_n^2}} \\
\frac{\sqrt{\mathbf{v}_n^H(n)}}{\sqrt{\mathbf{v}_n^H(n) + \mathbf{v}_n^H(n)}} &= \frac{\mathbf{q}_n}{\sqrt{\mathbf{p}_n^2 + \mathbf{q}_n^2}}
\end{align*}
\] \( \tag{24} \)

Note that we can substitute two solutions of \( \tilde{\theta}_n^{\text{opt}} \) into the objective (A1a) of subproblem (A-1), and the better-performance solution can be determined as the final coupled phase-shift solution of this iteration.

C. Overall Algorithm

The overall algorithm is summarized in Algorithm-1, where \( \varepsilon_{in,in} \) and \( \varepsilon_{in,out} \) respectively denote the convergence accuracy of the inner loop and the outer loop. The overall computational complexity of Algorithm-1 is mainly determined by solving the SDP with respect to \( \{ \mathbf{W}_l, \mathbf{W}_l^d \} \) and \( \{ \mathbf{U}_l, \mathbf{U}_l^d \} \) in the inner loop. By exploiting the interior point method, the overall complexity is given by \( O \left( \log \left( \frac{1}{\varepsilon_{in,in}} \right) (l_2 M^{1.5} + l_2 N^{3.5}) \right) \), where \( O \) denotes the big-O notation, and \( l_2 \) and \( l_2 \) denote the iteration numbers for solving problem (20) and (21).

Remark 1: The proposed algorithm can be easily extended to the multi-IU/OU and multi-eavesdropper scenario. Consider that the BS communicates with \( K_I \geq 2 \) indoor users (IUs) and \( K_O \geq 2 \) outdoor users (OUs) in the presence of multiple eavesdroppers. In this case, the optimization problem can be reformulated by rewriting the interference in (6) and (7) as \( \sum_{j \neq i} K_i - 1 \| \mathbf{h}^{H} \Theta_j^{H} \mathbf{G}_j \|^2 \) and \( \sum_{j \neq i} K_i - 1 \| \mathbf{h}^{H} \Theta_j^{H} \mathbf{G}_j \|^2 \) for \( \{ i, 2 \} \), where \( E_i \) and \( E_2 \) are the best wiretap-performance eavesdroppers in the transmission and reflection region, respectively. Note that the new introduced non-convex interference terms can be handled by operations of (11)–(17) in the same way.

D. Extension to Discrete Coupled Phase Shifts

Generally, discrete phase-shift adjustment is practical and realistic for STAR-RIS, which yields a uniform quantized phase-shift feasible region, i.e.,

\[
\theta_n^{d, \text{opt}} \in \Omega \left( 0, \frac{2 \pi}{2^q}, \ldots, \frac{2 \pi (2^q - 1)}{2^q} \right), \ \forall n, \tag{25}
\]

where \( q \) denotes the number of quantization bits. Note that the optimization problem in discrete phase-shift case possesses the same structure as the continuous phase-shift case except for discrete phase-shift constraint. Thus, we can first perform the PSB algorithm to obtain the solution \( \theta_n^{d, \text{opt}} \) with continuous phase shifters. Then, the discrete phase shifts can be obtained by \( \theta_n^{d, \text{opt}} = \arg \min_{\theta_n^{d, \text{opt}}} \{ \theta_n^{d, \text{opt}} - \theta_n^{d, \text{opt}} \} \).

IV. NUMERICAL RESULTS

In this section, numerical results are provided to validate the performance of the proposed algorithm. As shown in Fig. 2, we consider a three-dimensional coordinate system setup, where the BS is located at \( (0, 0, 0) \) meter (m), STAR-RIS is deployed at \( (50, 0, 0) \) m, IU and OU are located at \( (50, 5, 0) \) m and \( (50, -5, 0) \) m, respectively, while \( E_1 \) and \( E_2 \) are situated at \( (50, 10, 0) \) m and \( (50, -10, 0) \) m. Both the large-scale path loss and small-scale fading are considered, so the channel is given by \( h = \sqrt{L_0 d^{-\alpha}} \left( \sqrt{\frac{1}{\alpha}} + \sqrt{\frac{1}{\alpha}} \right) \). Hereto, \( h \) and \( b \) denote the LoS and non-LoS components of \( h \), \( L_0 \) represents the path loss at the unit reference distance, \( \alpha \) and \( d \) are the corresponding path loss exponent and the transmit distance, and \( \kappa \) is the Rician factor. The main simulation parameters are set as \( L_0 = 30 \) dB, \( \alpha_L = 2.3, \alpha_S = 2.2, \alpha_S = 2.5, \sigma_1 = -105 \) dBm, \( \varepsilon_{in,in} = \varepsilon_{in,out} = 10^{-3}, c_1 = 0.99 \) and \( c_2 = 0.95 \). Note that \( \kappa = 5 \) for Rician channels and \( \kappa = 0 \) for Rayleigh channels. Moreover, each result is averaged over 100 independent Monte-Carlo trials.

Fig. 3 depicts the convergence performance of the proposed algorithm with different \( M \) and \( N \). We observe that the minimum secrecy capacity monotonically increases with the number of iterations and converges to stable solutions within the finite iterations. We also observe that increasing both \( M \) and \( N \) is conducive to improving the minimum capacity.
Fig. 3. Convergence of Algorithm-1 with $P_{\text{max}} = -5 \text{ dBm}$.

Fig. 4. The minimum secrecy capacity versus the number of quantification bits with $M = 8$ and $N = 20$.

STAR-RIS in the low transmit power region. But with the increasing transmit power, the time resource utilization efficiency of ES STAR-RIS becomes the dominant factor, thus achieving higher secrecy capacity in the high transmit power region.

Fig. 5 plots minimum secrecy capacity versus the number of the phase-shift quantization bits. We observe from Fig. 5 that regardless of whether the phase shifts are coupled or not, at least 4-bit quantization is required to realize nearly the same performance as continuous phase shifts. It is because different from the conventional reflecting/transmitting-only RIS, STAR-RIS needs to simultaneously strengthen the legitimate links and reduce the confidential information leakage to the eavesdroppers in an omnidirectional space, so a more exact phase-shift control is required. It is also shown that due to the existence of “double path loss” for SATR-RIS aided cascaded links, deploying STAR-RIS at the user end can achieve higher secrecy performance. Moreover, since the difference between the transmission phase shift and the reflection phase shift is fixed to $\frac{\pi}{2}$, so the coupled STAR-RIS is invalidated in the case of 1-bit quantification.

V. CONCLUSION

A novel secrecy beamforming scheme was proposed for coupled phase-shift STAR-RIS aided downlink communications. A PSB algorithm was developed to maximize the minimum secrecy capacity among legitimate users via jointly optimizing transmit beamforming and transmission/reflection coefficients with coupled phase shifts. Simulation results were provided to demonstrate the secrecy advantage of the proposed secrecy beamforming scheme compared to the benchmark schemes. It is also revealed that at least 4-bit quantification should be guaranteed for the coupled phase-shift STAR-RIS to achieve the comparable secrecy performance of the continuous phase-shift case.

APPENDIX A

OPTIMAL SOLUTION DERIVATION

With the equivalent algebraic manipulations, the problem (23) can be rewritten as

$$\max_{\hat{u}, \hat{v}} \Re \left[ \langle u^H \rangle \hat{u}(n) \right] + \Re \left[ \langle v \rangle \hat{v}(n) \right],$$

s.t. (19b).

Then, with any fixed $\hat{u}$, the objective function (A1a) can be rewritten as

$$\Re \left[ \langle u^H \rangle \hat{u}(n) \right] = \Re \left[ \langle v \rangle \hat{v}(n) \right] = e^{j\beta} \Re \left[ \langle u^H \rangle \hat{u}(n) \right],$$

where $v^H = u^H \text{diag} \left( \left[ \sqrt{\beta_1}, \ldots, \sqrt{\beta_N} \right] \right)$. 

Authorized licensed use limited to the terms of the applicable license agreement with IEEE. Restrictions apply.
It reaches maximum only when \( \angle \left( \psi^H \right) = \angle \tilde{H} \), objective function (24) is equivalent to
\[
R \left( \psi^H (n) \sqrt{\beta_n} + \psi^H (n) \sqrt{\beta_n} \right),
\]
where \( \psi^H = u^H \text{diag} \left( e^{j \theta_n}, ..., e^{j \theta_N} \right) \).

Let \( p_n = |\psi^H (n)| \cos (\angle \tilde{H} (n)) \) and \( q_n = |\psi^H (n)| \cos (\angle \tilde{H} (n)) \),
the objective function can be further expressed as \( p_n \sqrt{\beta_n} + q_n \sqrt{\beta_n} \).
Then, by checking the first-order optimality condition, the optimal amplitude coefficients are derived as (25). This completes the derivation.

REFERENCES

[1] M. Di Renzo et al., “Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and road ahead,” IEEE J. Sel. Areas Commun., vol. 38, no. 11, pp. 2450–2525, Nov. 2020.

[2] Y. Liu et al., “Reconfigurable intelligent surfaces: Principles and opportunities,” IEEE Commun. Surveys Tuts., vol. 23, no. 3, pp. 1546–1577, Jul.–Sep. 2021.

[3] Z. Ding et al., “A state-of-the-art survey on reconfigurable intelligent surface-assisted non-orthogonal multiple access networks,” Proc. IEEE., vol. 110, no. 9, pp. 1358–1379, Sep. 2020.

[4] Y. Liu et al., “STAR: Simultaneous transmission and reflection for 360° coverage by intelligent surfaces,” IEEE Wireless Commun., vol. 28, no. 6, pp. 102–109, Dec. 2021.

[5] J. Xu, Y. Liu, X. Mu, and O. A. Dobre, “STAR-RISs: Simultaneous transmitting and reflecting reconfigurable intelligent surfaces,” IEEE Commun. Lett., vol. 25, no. 9, pp. 3134–3138, Sep. 2021.

[6] X. Mu, Y. Liu, L. Guo, J. Lin, and R. Schober, “Simultaneously transmitting and reflecting (STAR) RIS aided wireless communications,” IEEE Trans. Wireless Commun., vol. 21, no. 5, pp. 3083–3098, May 2022.

[7] H. Niu, Z. Chu, F. Zhou, and Z. Zhu, “Simultaneous transmission and reflection reconfigurable intelligent surface assisted secrecy MISO networks,” IEEE Commun. Lett., vol. 25, no. 11, pp. 3498–3502, Nov. 2021.

[8] W. Wang, W. Ni, H. Tian, Z. Yang, C. Huang, and K.-K. Wong, “Safe-guarding NOMA networks via reconfigurable dual-functional surface under imperfect CSI,” IEEE J. Sel. Topics Signal Process., vol. 16, no. 5, pp. 950–966, Aug. 2022.

[9] Y. Han, N. Li, Y. Liu, T. Zhang, and X. Tao, “Artificial noise aided secure NOMA communications in STAR-RIS networks,” IEEE Wireless Commun. Lett., vol. 11, no. 6, pp. 1191–1195, Jun. 2022.

[10] 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 Trans. Wireless Commun., vol. 21, no. 12, pp. 11207–11221, Dec. 2022.

[11] Y. Liu, X. Mu, R. Schober, and H. V. Poor, “Simultaneously transmitting and reflecting (STAR)-RISs: A coupled phase-shift model,” in Proc. IEEE Int. Conf. Commun., 2022, pp. 2840–2845.

[12] J. Xu et al., “Simultaneously transmitting and reflecting (STAR) intelligent omni-surfaces, their modeling and implementation,” IEEE Veh. Technol. Mag., vol. 17, no. 2, pp. 46–54, Jun. 2022.

[13] NTT DOCOMO, “DOCOMO conducts world’s first successful trial of transparent dynamic metasurface,” Jan. 2020. [Online]. Available: https://www.nttdocomo.co.jp/english/info/mediacenter/pr/2020/011700.html

[14] L. Wei et al., “Joint channel estimation and signal recovery for RIS-empowered multi-user communications,” IEEE Trans. Commun., vol. 70, no. 7, pp. 4640–4655, Jul. 2022.

[15] L. Wei, C. Huang, G. C. Alexandropoulos, C. Yuen, Z. Zhang, and M. Debbarh, “Channel estimation for RIS-empowered multi-user MISO wireless communications,” IEEE Trans. Commun., vol. 69, no. 6, pp. 4144–4157, Jun. 2021.

[16] A. Mukherjee and A. L. Swindlehurst, “Detecting passive eavesdroppers in the MIMO wiretap channel,” in Proc. IEEE Int. Conf. Acoust., 2012, pp. 2809–2812.

[17] Q. Shi, W. Xu, J. Wu, E. Song, and Y. Wang, “Secure beamforming for MIMO broadcasting with wireless information and power transfer,” IEEE Trans. Wireless Commun., vol. 14, no. 5, pp. 2841–2853, May 2015.

[18] T. Jiang and Y. Shi, “Over-the-air computation via intelligent reflecting surfaces,” in Proc. IEEE Glob. Commun. Conf., 2019, pp. 1–6.

[19] Kyocera, “KYOCERA develops transmissive metasurface technology that redirects wireless signals for improved 5G and 6G performance,” Apr. 2022. [Online]. https://global.kyocera.com/newsroom/news/2022/000526.html