STAR-RIS-Assisted Joint Physical Layer Security and Covert Communications

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***Abstract*—This paper investigates the utilization of simultaneously transmitting and reflecting RIS (STAR-RIS) in supporting joint physical layer security (PLS) and covert communications (CCs) in a multi-antenna millimeter wave (mmWave) system. Specifically, analytical derivations are performed to obtain the closed-form expression of warden's minimum detection error probability (DEP) considering the practical assumption that BS only knows the statistical channel state information (CSI) between STAR-RIS and Willie. Subsequently, an optimization problem is formulated with the aim of maximizing the average sum of the covert rate and the secure rate while ensuring the covert requirement and quality of service (QoS) for legal users by jointly optimizing the active and passive beamformers. Due to the strong coupling among variables, an iterative algorithm based on the alternating strategy and the semi-definite relaxation (SDR) method is proposed to solve the non-convex optimization problem. Simulation results indicate that the superiority of STAR-RIS in simultaneously implementing PLS and CCs.**

***Index Terms*—Covert communications, Physical layer security, STAR-RIS, Multi-antenna, mmWave.**

I. Introduction

To safeguard users' information from eavesdropping attacks, physical layer security (PLS) has emerged as a promising technique and garnered significant attention in recent years. As a pioneering work, [1] demonstrates that a positive perfect secrecy rate can be achieved at the transceiver if the eavesdropper's channel is a diminished form of the legitimate user's channel. Following this, numerous methods have been proposed with the aim of improving the performance of PLS [2]–[4]. In particular, in [2], the utilization of artificial noise (AN) is shown to be beneficial against eavesdropping. The authors of [3], [4] both explore the uncoordinated cooperative jamming schemes to maximize the secure rate while defeating the eavesdropping by appropriately allocating the jamming power.

However, in some scenarios like secret military operations, the security level provided by PLS may not be sufficient. This is because PLS can only hide the contents of messages but not the existence of communications between authorized users, which may leave security risks that can be exploited by unauthorized users to launch attacks. Recently, covert communication (CC) as a novel security technology has drawn great attention from both military and civilian fields. CC has the ability to fundamentally conceal the presence of communications between users, providing a higher level of security than PLS. Toward this end, Bash *et al.* first demonstrate that $\mathcal{O}(\sqrt{n})$ bits of information can be reliably transmitted with a low probability of detection over additive white Gaussian noise (AWGN) channels [5]. Since then, lots of efforts have been made to improve the covert performance, e.g., the noise uncertainty [6], full-duplex receivers transmitting jamming signals [7].

Although the strategies mentioned above have demonstrated their effectiveness in enhancing the performance of PLS and CCs, it is necessary to acknowledge that their potentials may be highly constrained by the stochastic nature of the wireless propagation environment. In order to break through this constraint, reconfigurable intelligent surfaces (RISs) emerged as a promising solution which can modify the electromagnetic characteristics of the incident signals and reconfigure desirable propagation environments. These attractive features of RIS make it popular in both academia and industry, which have been widely investigated in the performance enhancement of wireless applications including PLS and CCs [8], [9].

It is noteworthy that the traditional RIS in the literature above only reflects incident signals, which requires both transmitters and receivers to situate on the same side of RIS. To overcome this limitation, a novel RIS called STAR-RIS has been proposed and developed in [10]. It separates incident signals into a reflected part and a transmitted part, and provides coefficients to adjust the signals, which allows for the construction of a full-space smart radio environment with 360° coverage. Hence, the STAR-RIS has enormous potential in wireless communications, which has sparked significant interest from both academia and industry [10]. However, the research on incorporating STAR-RISs into wireless communication systems is still in its early stages. In terms of the secure/covert communications, only a small number of works investigate the secure/covert performance gain facilitated by STAR-RIS [11], [12].

In practical scenarios, it is highly possible that users have varying security requirements for communications, e.g., some users may require secure information transmissions and some users may need a higher level of covert communications. In this case, [13] first considers a scenario with both PLS and CCs users and analyzes the average sum rate between the secure rate and covert rate. However, the inherent randomness of the wireless channels results in a limited average rate. To address this problem, we establish a novel system model enabled by the STAR-RIS for joint implementation of PLS and CCs in this paper. Specifically, we analytically derive the close-form expression of minimum DEP and formulate the optimization problem aiming at maximizing the average sum of the covert rate and the secure rate while ensuring the covert requirement and quality of service (QoS). An iterative algorithm based on SDR is designed to slove the optimization problem with coupled variabales.

II. System Model

We consider a STAR-RIS-aided system model for joint PLS and CCs, which comprises a base station (BS) with $N_{\rm t}$ antennas, a covert user (Bob), a security user (Carol), two eavesdropping/warden users (Willie and Eve), and a STAR-RIS with M elements. All users are equipped with a single antenna and operate in half-duplex mode at the mmWave band. A practical scenario is investigated where the direct links between Alice and all users are blocked by obstacles such as buildings. To enhance the communication performance between Alice and legitimate users while impairing the detections by warden users Willie and Eve, an assistant STAR-RIS is deployed near the users. Without loss of generality, we assume that the covert user Bob and security users are located on the opposite sides of the STAR-RIS, allowing them to be simultaneously served by reflected (R) and transmitted (T) signals, respectively.

In this paper, Saleh-Valenzuela channel model [14] is adopted for the mmWave communications. In addition, we assume that the uniform linear array (ULA) of antennas is employed at the BS while the STAR-RIS adopts the uniform planar array (UPA). Hence, the channels between BS and STAR-RIS, and between STAR-RIS and users of {Bob, Willie, Eve, Carol} can be modeled as

$$\mathbf{H}_{\rm BR}=\sqrt{\frac{N_{\rm t}M\rho_{\rm BR}}{L}}\sum_{l=1}^{L}\varphi_l^{\rm BR}\mathbf{a}_{\rm R}\left(\phi_l^{\rm BR},\theta_l^{\rm BR}\right)\mathbf{a}_{\rm B}^H\left(\gamma_l^{\rm BR}\right), \quad (1)$$

$$\mathbf{h}_{\varsigma}=\sqrt{\frac{M\rho_{\varsigma}}{P}}\sum_{p=1}^{P}g_p^{\varsigma}\mathbf{a}_{\rm R}\left(\phi_p^{\varsigma},\theta_p^{\varsigma}\right)\ \text{ for } \varsigma\in\{\rm rb, rw, re, rc\}, \quad (2)$$

where $\mathbf{H}_{\rm BR}\in\mathbb{C}$ and $\mathbf{h}_{\varsigma}\in\mathbb{C}$ with $\rho_{\rm BR}$ and ρ_{ς} being the path loss values related to BS-RIS link and RIS-users links, respectively. L, P denote the total number of paths in $\mathbf{H}_{\rm BR}$ and $\mathbf{h}_{\varsigma}$, and $\varphi_l^{\rm BR}$, $g_p^{\varsigma}\sim\mathcal{CN}(0,1)$ are the complex gain of the l-th path in $\mathbf{H}_{\rm BR}$ and p-th path in $\mathbf{h}_{\varsigma}$, respectively. Also, ϕ and θ represent the azimuth and elevation angle associated with BS and STAR-RIS; γ indicates the azimuth angle of departure (AoD) associated with BS; In addition, $\mathbf{a}_{\rm R}(\phi,\theta)$ and $\mathbf{a}_{\rm B}(\gamma)$ are respectively the beam steering vectors of the ULA and UPA at the BS and STAR-RIS. For their expression, please refer [15].

We assume that the BS has the knowledge of the instantaneous CSI between STAR-RIS and legal users, i.e., $\mathbf{H}_{\rm BR}$, $\mathbf{h}_{\rm rb}$, $\mathbf{h}_{\rm rc}$ and $\mathbf{h}_{\rm re}$, while only the statistical CSI between STAR-RIS and Willie, i.e., $\mathbf{h}_{\rm rw}$ is available at BS. In contrast, Willie knows the instantaneous CSI of $\mathbf{h}_{\rm rb}$ and $\mathbf{h}_{\rm rc}$, but only the statistical CSI of $\mathbf{H}_{\rm BR}$ is accessible by Willie, which introduces uncertainty that is beneficial to cover the communications between BS and Bob.

III. Analysis on the STAR-RIS-Assisted Joint PLS and CCs System

A. Theoretical Analysis on CCs

In this section, we focus on the theoretical analysis of the CCs of the system. Specifically, Willie determines the existence of communications between BS and Bob through the received signal sequences in a time slot, denoted as $\{y_{\rm w}[t]\}_{t=1}^{T}$. It has to face a binary hypothesis for the judgement of CCs, which includes a null hypothesis $\mathcal{H}_0$, denoting that BS only communicates with the security users without CCs to Bob; and an alternative hypothesis $\mathcal{H}_1$, indicating that there exists CCs between BS and Bob. Under these two hypotheses, the received signals at Bob, Willie and Carol can be respectively expressed as

$$y_{\rm b}[t]=\begin{cases}\mathbf{h}_{\rm rb}^H\mathbf{\Theta}_{\rm r}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}s_{\rm c}[t]+n_{\rm b}[t], & \mathcal{H}_0,\\ \mathbf{h}_{\rm rb}^H\mathbf{\Theta}_{\rm r}\mathbf{H}_{\rm BR}\left(\mathbf{w}_{\rm b}s_{\rm b}[t]+\mathbf{w}_{\rm c}s_{\rm c}[t]\right)+n_{\rm b}[t], & \mathcal{H}_1,\end{cases} \quad (3)$$

$$y_{\rm w}[t]=\begin{cases}\mathbf{h}_{\rm rw}^H\mathbf{\Theta}_{\rm r}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}s_{\rm c}[t]+n_{\rm w}[t], & \mathcal{H}_0,\\ \mathbf{h}_{\rm rw}^H\mathbf{\Theta}_{\rm r}\mathbf{H}_{\rm BR}\left(\mathbf{w}_{\rm b}s_{\rm b}[t]+\mathbf{w}_{\rm c}s_{\rm c}[t]\right)+n_{\rm w}[t], & \mathcal{H}_1,\end{cases} \quad (4)$$

$$y_{\rm c}[t]=\begin{cases}\mathbf{h}_{\rm rc}^H\mathbf{\Theta}_{\rm t}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}s_{\rm c}[t]+n_{\rm c}[t], & \mathcal{H}_0,\\ \mathbf{h}_{\rm rc}^H\mathbf{\Theta}_{\rm t}\mathbf{H}_{\rm BR}\left(\mathbf{w}_{\rm b}s_{\rm b}[t]+\mathbf{w}_{\rm c}s_{\rm c}[t]\right)+n_{\rm c}[t], & \mathcal{H}_1,\end{cases} \quad (5)$$

where $t\in\mathcal{T}\triangleq\{1,\cdots,T\}$ is the index of each communication channel use with the maximum number of T in a time slot. $\mathbf{\Theta}_{\xi}=\mathrm{Diag}\left\{\sqrt{\beta_{\xi}^1}e^{\mathrm{j}\phi_{\xi}^1},\ldots,\sqrt{\beta_{\xi}^M}e^{\mathrm{j}\phi_{\xi}^M}\right\}$ indicates the reflected or transmitted coefficient matrix of STAR-RIS with $\xi\in\{\rm r,t\}$, where $\beta_{\xi}^m\in[0,1]$, $\phi_{\xi}^m\in[0,2\pi)$ and $\beta_{\rm r}^m+\beta_{\rm t}^m=1$, for $\forall m\in\mathcal{M}\triangleq\{1,2,\ldots,M\}$. Also, $s_{\rm b}$, $s_{\rm c}\sim\mathcal{CN}(0,1)$ respectively represent the signals transmitted by BS to Bob and Carol, while $\mathbf{w}_{\rm b}$, $\mathbf{w}_{\rm c}\in\mathbb{C}^{N_{\rm t}\times 1}$ are the beamforming vectors correspondingly. In addition, $n_{\rm b}\sim\mathcal{CN}(0,\sigma_{\rm b}^2)$, $n_{\rm w}\sim\mathcal{CN}(0,\sigma_{\rm w}^2)$ and $n_{\rm b}\sim\mathcal{CN}(0,\sigma_{\rm c}^2)$ denote the AWGN noise at Bob, Willie and Carol.

We assume that Willie leverages the average power of the received signals, i.e., $\overline{P}_{\rm w}=\frac{1}{T}\sum_{t=1}^{T}|y_{\rm w}[t]|^2$, to do the statistical test. In line with existing works (e.g., [12]), it is assumed that Willie utilizes an infinite number of signal samples, i.e., $T\to\infty$, to judge the binary hypotheses. Hence, the received average power can be derived as

$$\overline{P}_{\rm w}=\begin{cases}\left|\mathbf{h}_{\rm rw}^H\mathbf{\Theta}_{\rm r}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}\right|^2+\sigma_{\rm w}^2, & \mathcal{H}_0,\\ \left\|\mathbf{h}_{\rm rw}^H\mathbf{\Theta}_{\rm r}\mathbf{H}_{\rm BR}\left\{\mathbf{w}_{\rm b},\mathbf{w}_{\rm c}\right\}\right\|_2^2+\sigma_{\rm w}^2, & \mathcal{H}_1.\end{cases} \quad (6)$$

To determine the existence of CCs between BS and Bob, Willie needs to analyze $\overline{P}_{\rm w}$ under the hypotheses of $\mathcal{H}_0$ and $\mathcal{H}_1$ by leveraging the decision rule $\overline{P}_{\rm w}\underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\gtrless}}\tau_{\rm dt}$, where $\mathcal{D}_0$ (or $\mathcal{D}_1$) represents the decision that Willie favors $\mathcal{H}_0$ (or $\mathcal{H}_1$) and $\tau_{\rm dt}$ is the corresponding detection threshold. In this paper, we adopt DEP to characterize Willie's detection ability for CCs between BS and Bob, considering the worst-case scenario where Willie can optimize $\tau_{\rm dt}$ to obtain the optimal detection threshold and the minimum DEP. Next, we will analytically derive the minimum DEP based on the false alarm (FA) probability $P_{\rm FA}=\Pr(\mathcal{D}_1|\mathcal{H}_0)$ and the miss detection (MD) probability $P_{\rm MD} = \Pr(\mathcal{D}_0|\mathcal{H}_1)$ from Willie's perspective. Specifically, on the basis of the distribution of $\overline{P}_{\rm w}$, $P_{\rm FA}$ and $P_{\rm MD}$ are given by.

$$P_{\rm FA} = \begin{cases} 1, & \tau_{\rm dt} \le \sigma_{\rm w}^2, \\ e^{-\frac{\tau_{\rm dt}-\sigma_{\rm w}^2}{\lambda_0}}, & \text{otherwise}, \end{cases} \tag{7}$$

$$P_{\rm MD} = \begin{cases} 0, & \tau_{\rm dt} \le \sigma_{\rm w}^2, \\ 1-e^{-\frac{\tau_{\rm dt}-\sigma_{\rm w}^2}{\lambda_1}}, & \text{otherwise}, \end{cases} \tag{8}$$

where

- $\lambda_0 = \frac{N_{\rm t} M \rho_{\rm BR}}{L} \left\|\mathbf{\Phi}\,\mathrm{vec}\left((\mathbf{w}_{\rm c}\mathbf{h}_{\rm rw}^H\mathbf{\Theta}_{\rm r})^T\right)\right\|_2^2$,
- $\lambda_1 = \frac{N_{\rm t} M \rho_{\rm BR}}{L} \left\|\mathbf{\Phi}\,\mathrm{vec}\left((\mathbf{w}_{\rm b}\mathbf{h}_{\rm rw}^H\mathbf{\Theta}_{\rm r})^T\right)\right\|_2^2 + \lambda_0$,
- $\mathbf{\Phi} = [\mathrm{vec}(\mathbf{A}_1), \cdots, \mathrm{vec}(\mathbf{A}_L)]^H$,
- $\mathbf{A}_l = \mathbf{a}_{\rm R}\left(\phi_l^{\rm BR}, \theta_l^{\rm BR}\right)\mathbf{a}_{\rm B}^H\left(\gamma_l^{\rm BR}\right)$.

Based on the analytical expression of $P_{\rm FA}$ and $P_{\rm MD}$ in (7) and (8), Willie's DEP can be derived as

$$P_{\rm e} = \begin{cases} 1, & \tau_{\rm dt} \le \sigma_{\rm w}^2, \\ 1-e^{-\frac{\tau_{\rm dt}-\sigma_{\rm w}^2}{\lambda_1}} + e^{-\frac{\tau_{\rm dt}-\sigma_{\rm w}^2}{\lambda_0}}, & \text{otherwise}. \end{cases} \tag{9}$$

In this paper, we focus on the uncertain scenario with detection threshold $\tau_{\rm dt} > \sigma_{\rm w}^2$. Next, we will analyze and derive the optimal detection threshold, denoted as $\tau_{\rm dt}^*$, and the minimum DEP $P_{\rm e}^*$ by analyzing the first-order partial derivative of $P_{\rm e}$ with respect to (w.r.t.) $\tau_{\rm dt}$ and we have $\tau_{\rm dt}^* = \frac{\lambda_1\lambda_0 \ln\frac{\lambda_1}{\lambda_0}}{\lambda_1-\lambda_0} + \sigma_{\rm w}^2$ and $P_{\rm e}^* = 1 - e^{-\frac{\lambda_0 \ln\frac{\lambda_1}{\lambda_0}}{\lambda_1-\lambda_0}} + e^{-\frac{\lambda_1 \ln\frac{\lambda_1}{\lambda_0}}{\lambda_1-\lambda_0}}$.

In order to guarantee the covertness of communications between BS and Bob, $P_{\rm e}^* \ge 1-\epsilon$ is required where $\epsilon \in (0,1)$ is a quite small value required by the system performance indicators. Considering that only the statistical CSI of $\mathbf{h}_{\rm rw}$ is available at BS, the average minimum DEP over $\mathbf{h}_{\rm rw}$, i.e., $\overline{P}_{\rm e}^* = \mathbb{E}_{\mathbf{h}_{\rm rw}}(P_{\rm e}^*)$, is utilized to evaluate the covert performance. However, λ_0 and λ_1 in $P_{\rm e}^*$ are both random functions of $\mathbf{h}_{\rm rw}$ and are coupled with each other, which makes it challenging to directly calculate $\overline{P}_{\rm e}^*$. To tackle this problem, the large system analytic technique is leveraged to handle the coupling between λ_0 and λ_1, the asymptotic analytic results of λ_0 and λ_1 can be derived as

$$\widehat{\lambda}_0 = \frac{N_{\rm t} M^2 \rho_{\rm BR}\rho_{\rm rw}}{LP} \sum_{l=1}^{L} \left(\mathbf{w}_{\rm c}^H \mathbf{\Psi}_{\rm BR}^l \mathbf{w}_{\rm c}\right) \left(\boldsymbol{\vartheta}_{\rm r}^T \mathbf{\Xi}^T \left(\left(\widehat{\mathbf{\Psi}}_{\rm BR}^l\right)^T \otimes \left(\mathbf{\Omega}_{\rm rw}^H \mathbf{\Omega}_{\rm rw}\right)\right) \mathbf{\Xi}\boldsymbol{\vartheta}_{\rm r}^*\right), \tag{10}$$

$$\widehat{\lambda}_1 = \widehat{\lambda}_0 + \frac{N_{\rm t} M^2 \rho_{\rm BR}\rho_{\rm rw}}{LP} \sum_{l=1}^{L} \left(\mathbf{w}_{\rm b}^H \mathbf{\Psi}_{\rm BR}^l \mathbf{w}_{\rm b}\right) \left(\boldsymbol{\vartheta}_{\rm r}^T \mathbf{\Xi}^T \left(\left(\widehat{\mathbf{\Psi}}_{\rm BR}^l\right)^T \otimes \left(\mathbf{\Omega}_{\rm rw}^H \mathbf{\Omega}_{\rm rw}\right)\right) \mathbf{\Xi}\boldsymbol{\vartheta}_{\rm r}^*\right), \tag{11}$$

where

- $\boldsymbol{\vartheta}_{\rm r} = \mathrm{diag}(\mathbf{\Theta}_{\rm r})$, $\mathbf{\Psi}_{\rm BR}^l = \mathbf{a}_{\rm B}\left(\gamma_l^{\rm BR}\right)\mathbf{a}_{\rm B}^H\left(\gamma_l^{\rm BR}\right)$,
- $\widehat{\mathbf{\Psi}}_{\rm BR}^l = \mathbf{a}_{\rm R}\left(\phi_l^{\rm BR}, \theta_l^{\rm BR}\right)\mathbf{a}_{\rm R}^H\left(\phi_l^{\rm BR}, \theta_l^{\rm BR}\right)$,
- $\mathbf{\Omega}_{\rm rw} = \left[\mathbf{a}_{\rm R}\left(\phi_1^{\rm rw}, \theta_1^{\rm rw}\right), \cdots, \mathbf{a}_{\rm R}\left(\phi_P^{\rm rw}, \theta_P^{\rm rw}\right)\right]^H$,
- $\mathbf{\Xi} = \Big[[\mathbf{e}_1, \mathbf{0}_{M\times(M-1)}];\ [\mathbf{0}_{M\times 1}, \mathbf{e}_2, \mathbf{0}_{M\times(M-2)}];\ \cdots;\ [\mathbf{0}_{M\times(M-1)}, \mathbf{e}_M]\Big]$.

Thus, we can further obtain the asymptotic analytic result of the minimum DEP by substituting (10) and (11) into $P_{\rm e}^*$ and adopting some algebraic manipulations, which is expressed as

$$P_{\rm ea}^* = 1 - e^{-\frac{\beta \ln\frac{\alpha+\beta}{\beta}}{\alpha}} \left(1 - \frac{\beta}{\alpha+\beta}\right), \tag{12}$$

where

- $\alpha = \frac{N_{\rm t} M^2 \rho_{\rm BR}\rho_{\rm rw}}{LP} \sum_{l=1}^{L} \left(\mathbf{w}_{\rm b}^H \mathbf{\Psi}_{\rm BR}^l \mathbf{w}_{\rm b}\right) \left(\boldsymbol{\vartheta}_{\rm r}^T \mathbf{\Xi}^T \left(\left(\widehat{\mathbf{\Psi}}_{\rm BR}^l\right)^T \otimes \left(\mathbf{\Omega}_{\rm rw}^H \mathbf{\Omega}_{\rm rw}\right)\right) \mathbf{\Xi}\boldsymbol{\vartheta}_{\rm r}^*\right)$,
- $\beta = \frac{N_{\rm t} M^2 \rho_{\rm BR}\rho_{\rm rw}}{LP} \sum_{l=1}^{L} \left(\mathbf{w}_{\rm c}^H \mathbf{\Psi}_{\rm BR}^l \mathbf{w}_{\rm c}\right) \left(\boldsymbol{\vartheta}_{\rm r}^T \mathbf{\Xi}^T \left(\left(\widehat{\mathbf{\Psi}}_{\rm BR}^l\right)^T \otimes \left(\mathbf{\Omega}_{\rm rw}^H \mathbf{\Omega}_{\rm rw}\right)\right) \mathbf{\Xi}\boldsymbol{\vartheta}_{\rm r}^*\right)$.

In the following sections, the convert constraint $P_{\rm ea}^* \ge 1-\epsilon$ will be utilized to characterize and guarantee the covert performance of the system.

Note that, when hypothesis $\mathcal{H}_1$ is true, the available covert rate at Bob can be expressed as

$$R_{\rm b}^{\rm c} = \log_2\left(1 + \frac{\left|\mathbf{h}_{\rm rb}^H \mathbf{\Theta}_{\rm r}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm b}\right|^2}{\left|\mathbf{h}_{\rm rb}^H \mathbf{\Theta}_{\rm r}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}\right|^2 + \sigma_{\rm b}^2}\right). \tag{13}$$

B. Theoretical Analysis on PLS

In this section, the theoretical analysis on the PLS of the system is addressed. Specifically, the signals received by Carol are given by equation (5), while the signals received by Eve can be expressed as.

$$y_{\rm e}[t] = \begin{cases} \mathbf{h}_{\rm re}^H \mathbf{\Theta}_{\rm t}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c} s_{\rm c}[t] + n_{\rm e}[t], & \mathcal{H}_0, \\ \mathbf{h}_{\rm re}^H \mathbf{\Theta}_{\rm t}\mathbf{H}_{\rm BR}\left(\mathbf{w}_{\rm b} s_{\rm b}[t] + \mathbf{w}_{\rm c} s_{\rm c}[t]\right) + n_{\rm e}[t], & \mathcal{H}_1. \end{cases} \tag{14}$$

Therefore, the secure rates of Carol under two hypotheses are given by

$$R_{\rm c}^{\rm s0} = \left[\log_2\left(1+\gamma_{\rm c0}\right) - \log_2\left(1+\gamma_{\rm e0}\right)\right]^+, \tag{15}$$

$$R_{\rm c}^{\rm s1} = \left[\log_2\left(1+\gamma_{\rm c1}\right) - \log_2\left(1+\gamma_{\rm e1}\right)\right]^+, \tag{16}$$

where $\gamma_{\rm c1} = \frac{\left|\mathbf{h}_{\rm rc}^H \mathbf{\Theta}_{\rm t}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}\right|^2}{\left|\mathbf{h}_{\rm rc}^H \mathbf{\Theta}_{\rm t}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm b}\right|^2 + \sigma_{\rm c}^2}$, $\gamma_{\rm c0} = \frac{\left|\mathbf{h}_{\rm rc}^H \mathbf{\Theta}_{\rm t}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}\right|^2}{\sigma_{\rm c}^2}$, $\gamma_{e1} = \frac{\left|\mathbf{h}_{\rm re}^H \mathbf{\Theta}_{\rm t}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}\right|^2}{\left|\mathbf{h}_{\rm re}^H \mathbf{\Theta}_{\rm t}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm b}\right|^2 + \sigma_{\rm e}^2}$ and $\gamma_{e0} = \frac{\left|\mathbf{h}_{\rm re}^H \mathbf{\Theta}_{\rm t}\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}\right|^2}{\sigma_{\rm e}^2}$.

IV. Problem Formulation and Algorithm Design

A. Optimization Problem Formulation

In this section, we will establish the optimization problem based on the theoretical analysis in Section III. Due to the fact that the existence of the CCs between BS and Bob is under a binary hypothesis, we define a Bernoulli variable b where $b=0$ with the probability of P_0 means that BS only transmits the secure information, while $b=1$ with the probability of $P_1 = 1-P_0$ represents that BS transmits both the covert and secure messages. In this paper, we maximize the average sum rate between the covert rate and the secure rate over b in a time slot while ensuring the covert constraint and the QoS constraints at Bob and Carol by optimizing $\mathbf{w}_{\rm b}$, $\mathbf{w}_{\rm c}$, and $\mathbf{\Theta}_{\rm r}$, $\mathbf{\Theta}_{\rm t}$. Specifically, the optimization objective of the average sum rate over the Bernoulli variable b can be expressed as

$$\begin{aligned}\overline{R}\big(\mathbf{w}_{\rm b}, \mathbf{w}_{\rm c}, \mathbf{\Theta}_{\rm r}, \mathbf{\Theta}_{\rm t}\big) =& \mathbb{E}_b\Big(bR_{\rm b}^{\rm c} + L(b)R_{\rm c}^{\rm s0} + bR_{\rm c}^{\rm s1}\Big)\\ =& P_1R_{\rm b}^{\rm c} + P_0R_{\rm c}^{\rm s0} + P_1R_{\rm c}^{\rm s1}, \end{aligned} \tag{17}$$

where $L(\cdot)$ is the logical operator with $L(0) = 1$, $L(1) = 0$.

Based on the above analysis, the optimization problem is formulated as

$$\begin{aligned}&\max_{\mathbf{w}_{\rm b}, \mathbf{w}_{\rm c}, \mathbf{\Theta}_{\rm r}, \mathbf{\Theta}_{\rm t}} \overline{R}\big(\mathbf{w}_{\rm b}, \mathbf{w}_{\rm c}, \mathbf{\Theta}_{\rm r}, \mathbf{\Theta}_{\rm t}\big),\\
&\quad \text{s.t. } \|\mathbf{w}_{\rm b}\|_2^2 + \|\mathbf{w}_{\rm c}\|_2^2 \le P_{\rm tmax}, && (18a)\\
&\qquad e^{-\frac{\beta \ln \frac{\alpha+\beta}{\beta}}{\alpha}}\left(1 - \frac{\beta}{\alpha+\beta}\right) \le \epsilon, && (18b)\\
&\qquad R_{\rm b}^{\rm c} \ge R_{\rm b}^*, R_{\rm c}^{\rm s0} \ge R_{\rm s0}^*, R_{\rm c}^{\rm s1} \ge R_{\rm s1}^* && (18c)\\
&\qquad \beta_{\rm r}^m + \beta_{\rm t}^m = 1, \phi_{\rm r}^m,\ \phi_{\rm t}^m \in [0, 2\pi),\ m \in \mathcal{M}, && (18d)\end{aligned}$$

where (18a) is the transmit power constraint of the BS with $P_{\rm tmax}$ being the maximum power budget; (18b) denotes the covertness constraint, which is equivalent to $P_{\rm ea}^* \ge 1-\epsilon$; (18c) represent the QoS constraints for covert rate and secure rate with the minimum required covert rate $R_{\rm b}^*$ and secure rate $R_{\rm s0}^*$ and $R_{\rm s1}^*$; (18d) is the amplitude and phase shift constraints for STAR-RIS. In fact, solving this optimization problem is quite challenging due to the strong coupling among variables, i.e., $\mathbf{w}_{\rm b}$, $\mathbf{w}_{\rm c}$, $\mathbf{\Theta}_{\rm r}$ and $\mathbf{\Theta}_{\rm t}$. To address this challenge, we propose an iterative algorithm that leverages an alternative strategy to effectively solve this optimization problem, which is presented in the next section.

B. Algorithm Design

In this section, we detail the proposed iterative algorithm for solving the original formulated problem (18). Specifically, this problem is divided into two subproblems which are solved to the design active and passive beamformers, respectively.

1) Joint Active beamforming design for $\mathbf{w}_{\rm b}$ and $\mathbf{w}_{\rm c}$: We first design the active beamforming variables $\mathbf{w}_{\rm b}$ and $\mathbf{w}_{\rm c}$ with given the passive beamforming variables, i.e., $\mathbf{\Theta}_{\rm r}$ and $\mathbf{\Theta}_{\rm t}$. In this circumstance, the original optimization problem can be simplified as

$$\begin{aligned}&\max_{\mathbf{w}_{\rm b}, \mathbf{w}_{\rm c}} \overline{R}\big(\mathbf{w}_{\rm b}, \mathbf{w}_{\rm c}\big),\\ &\quad \text{s.t.} \quad (18a) - (18d). \end{aligned} \tag{19a}$$

Problem (19) is a non-convex optimization problem due to the non-convexity of the objective function, the covert constraint and the QoS constraints. To tackle this problem, we first introduce three auxiliary variable ι, κ and ϖ to replace $R_{\rm b}^{\rm c}$, $R_{\rm c}^{\rm s0}$ and $R_{\rm c}^{\rm s1}$ in the objective function. In addition, it is easy to verify that the left-side of (18b) is a monotonically decreasing function of $\frac{\beta}{\alpha}$, and thus the covert constraint (18b) can be equivalently transformed as $\frac{\beta}{\alpha} \ge \varphi(\epsilon)$, where $\varphi(\epsilon)$ can be obtained by using the numerical methods such bisection search method.

In fact, (19) is still a non-convex optimization problem because of the non-convexity of the constraints (18c). To effectively address this problem, we resort to the SDR method [16]. Specifically, we first let $\mathbf{W} = \{\mathbf{w}_{\rm b}, \mathbf{w}_{\rm c}\}$ and $\mathbf{W}_{\rm cs} = \text{vec}\,(\mathbf{W})\,\text{vec}\,(\mathbf{W})^H$, then the optimization problem (19) can be equivalently transformed as

$$\begin{aligned}&\max_{\widehat{\mathbf{V}}} P_1\iota + P_1\kappa + P_0\varpi,\\
&\text{s.t. } \text{Tr}(\mathbf{W}_{\rm cs}) \le P_{\rm tmax}, \mathbf{W}_{\rm cs} \succeq 0, \text{rank}(\mathbf{W}_{\rm cs}) = 1, && (20a)\\
&\quad \text{Tr}(\mathbf{W}_{\rm cs}\widehat{\mathbf{D}}) \ge \text{Tr}(\mathbf{W}_{\rm cs}\mathbf{D}_1)\varphi(\epsilon), && (20b)\\
&\quad \iota \ge R_{\rm b}^*, \kappa \ge R_{\rm s1}^*, \varpi \ge R_{\rm s0}^*, && (20c)\\
&\quad \log_2\Big(\text{Tr}(\mathbf{W}_{\rm cs}\widehat{\mathbf{A}}) + \sigma_{\rm b}^2\Big) - \log_2\Big(\text{Tr}(\mathbf{W}_{\rm cs}\tilde{\mathbf{A}}) + \sigma_{\rm b}^2\Big) \ge \iota, && (20d)\\
&\quad \log_2\big(\text{Tr}(\mathbf{W}_{\rm cs}\check{\mathbf{B}}) + \sigma_{\rm c}^2\big) - \log_2\big(\text{Tr}(\mathbf{W}_{\rm cs}\check{\mathbf{C}}) + \sigma_{\rm e}^2\big)\\
&\quad + \log_2\big(\sigma_{\rm e}^2\big) - \log_2\big(\sigma_{\rm c}^2\big) \ge \varpi, && (20e)\\
&\quad \log_2\Big(\text{Tr}(\mathbf{W}_{\rm cs}\tilde{\mathbf{B}}) + \sigma_{\rm c}^2\Big) + \log_2\Big(\text{Tr}(\mathbf{W}_{\rm cs}\check{\mathbf{C}} + \sigma_{\rm e}^2)\Big) -\\
&\quad \log_2\Big(\text{Tr}(\mathbf{W}_{\rm cs}\breve{\mathbf{B}}) + \sigma_{\rm c}^2\Big) - \log_2\Big(\text{Tr}(\mathbf{W}_{\rm cs}\tilde{\mathbf{C}} + \sigma_{\rm c}^2)\Big) \ge \kappa, && (20f)\end{aligned}$$

where

- $\widehat{\mathbf{V}} = \{\mathbf{W}_{\rm cs}, \iota, \kappa, \varpi\}$is the defined optimization variable,
- $\widehat{\mathbf{D}} = \big(\mathbf{e}_2\mathbf{e}_2^T\big) \otimes \mathbf{D},\ \mathbf{D}_1 = \big(\mathbf{e}_1\mathbf{e}_1^T\big) \otimes \mathbf{D},$
- $\widehat{\mathbf{A}} = \mathbf{I}_2 \otimes \mathbf{A},\ \tilde{\mathbf{A}} = \big(\mathbf{e}_2\mathbf{e}_2^T\big) \otimes \mathbf{A}, \mathbf{C} = \big\|\mathbf{h}_{\rm re}^H\mathbf{\Theta}_{\rm t}\mathbf{H}_{\rm BR}\big\|_2^2,$
- $\check{\mathbf{B}} = \big(\mathbf{e}_2\mathbf{e}_2^T\big) \otimes \mathbf{B},\ \tilde{\mathbf{B}} = \mathbf{I}_2 \otimes \mathbf{B}, \breve{\mathbf{B}} = \big(\mathbf{e}_1\mathbf{e}_1^T\big) \otimes \mathbf{B},$
- $\check{\mathbf{C}} = \big(\mathbf{e}_2\mathbf{e}_2^T\big) \otimes \mathbf{C},\ \tilde{\mathbf{C}} = \mathbf{I}_2 \otimes \mathbf{C}, \breve{\mathbf{C}} = \big(\mathbf{e}_1\mathbf{e}_1^T\big) \otimes \mathbf{C},$
- $\mathbf{A} = \big\|\mathbf{h}_{\rm rb}^H\mathbf{\Theta}_{\rm r}\mathbf{H}_{\rm BR}\big\|_2^2, \mathbf{B} = \big\|\mathbf{h}_{\rm rc}^H\mathbf{\Theta}_{\rm rt}\mathbf{H}_{\rm BR}\big\|_2^2,$
- $\mathbf{D} = \sum_{l=1}^{L} \mathbf{\Psi}_{\rm BR}^l \boldsymbol{\vartheta}_{\rm r}^T \mathbf{\Xi}^T \Big(\big(\widehat{\mathbf{\Psi}}_{\rm BR}^l\big)^T \otimes \big(\mathbf{\Omega}_{\rm rw}^H\mathbf{\Omega}_{\rm rw}\big)\Big)\mathbf{\Xi}\boldsymbol{\vartheta}_{\rm r}^*.$

Note that problem (20) is still a non-convex optimization problem due to the non-convex QoS constraints and the rank-one constraint. To transform (20) into a solvable convex problem, we first handle the constraints (20d), (20e) and (20f). In particular, we can find that the left-sides of (20d), (20e) and (20f), respectively denoting as $f(\mathbf{W}_{\rm cs})$, $f_2(\mathbf{W}_{\rm cs})$ and $f_3(\mathbf{W}_{\rm cs})$, are all difference of concave (DC) functions, and thus the first-order Taylor expansion can be leveraged on them to obtain their concave lower bounds in the i-th innerloop iteration of the proposed iterative algorithm, denoting as $\widehat{f}_1\big(\mathbf{W}_{\rm cs}, \mathbf{W}_{\rm cs}^{(i)}\big)$, $\widehat{f}_2\big(\mathbf{W}_{\rm cs}, \mathbf{W}_{\rm cs}^{(i)}\big)$ and $\widehat{f}_3\big(\mathbf{W}_{\rm cs}, \mathbf{W}_{\rm cs}^{(i)}\big)$. These concave lower bounds will be adopted to replace the original expressions in the optimization problem (20).

For the rank-one constraint in (**??**), we adopt the method in [12] to transform it and add the transformed form to the objective function as the penalty term. For the detailed process please refer [12]. According to the above analysis, the optimization problem (20) can be further transformed as

$$\begin{aligned}&\max_{\mathbf{W}_{\rm cs}, \iota, \kappa, \varpi} P_1\iota + P_1\kappa + P_0\varpi - \varrho_{\rm cs}\widehat{\eta}_{\rm cs}(\mathbf{W}_{\rm cs}),\\
&\quad \text{s.t. } (20a), (20b), (20c), && (21a)\\
&\qquad \widehat{f}_1\big(\mathbf{W}_{\rm cs}, \mathbf{W}_{\rm cs}^{(i)}\big) \ge \iota, \widehat{f}_2\big(\mathbf{W}_{\rm cs}, \mathbf{W}_{\rm cs}^{(i)}\big) \ge \varpi, && (21b)\\
&\qquad \widehat{f}_3\big(\mathbf{W}_{\rm cs}, \mathbf{W}_{\rm cs}^{(i)}\big) \ge \kappa, \mathbf{W}_{\rm cs} \succeq 0, && (21c)\end{aligned}$$

where $\varrho_{\rm cs}$ is the penalty coefficient, $\widehat{\eta}_{\rm cs}(\mathbf{W}_{\rm cs}) \triangleq {\rm Tr}(\mathbf{W}_{\rm cs}) - \Big(\|\mathbf{W}_{\rm cs}^{(i)}\|_2 + {\rm Tr}\left(\mathbf{w}_{\rm cs}^{(i)}\left(\mathbf{w}_{\rm cs}^{(i)}\right)^H\left(\mathbf{W}_{\rm cs} - \mathbf{W}_{\rm cs}^{(i)}\right)\right)\Big)$, $\mathbf{w}_{\rm cs}^{(i)}$ represents the eigenvectors corresponding to the largest eigenvalues of $\mathbf{W}_{\rm cs}^{(i)}$ in i-th inner loop iteration. The optimization problem (21) is a standard convex semidefinite programming (SDP) problem which is able to be effectively solved by the existing convex optimization tools such as CVX [17].

2) Joint Passive beamforming design for $\mathbf{\Theta}_{\rm r}$ *and* $\mathbf{\Theta}_{\rm t}$*:* After obtaining the active beamformers, we then design the passive beamforming variables $\mathbf{\Theta}_{\rm r}$ and $\mathbf{\Theta}_{\rm t}$ with given the obtained $\mathbf{w}_{\rm b}$ and $\mathbf{w}_{\rm c}$. The optimization problem for joint designing the passive beamforming variables $\mathbf{\Theta}_{\rm r}$ and $\mathbf{\Theta}_{\rm t}$ can be expressed as

$$\max_{\mathbf{\Theta}_{\rm r},\mathbf{\Theta}_{\rm t}} \quad \overline{R}(\mathbf{\Theta}_{\rm r},\mathbf{\Theta}_{\rm t}),$$

$$\text{s.t.} \quad (18\text{b}) - (18\text{d}). \tag{22a}$$

Note that problem (22) is a non-convex optimization problem w.r.t. $\mathbf{\Theta}_{\rm r}$ and $\mathbf{\Theta}_{\rm t}$. Similarly, we will adopt the SDR techniques to deal with this optimization problem. The covert constraint $\frac{\beta}{\alpha} \geq \varphi(\epsilon)$ is still utilized to guarantee the covert performance. Let $\mathbf{Q}_{\rm r} = \boldsymbol{\vartheta}_{\rm r}^*\boldsymbol{\vartheta}_{\rm r}^T$, $\mathbf{Q}_{\rm t} = \boldsymbol{\vartheta}_{\rm t}^*\boldsymbol{\vartheta}_{\rm t}^T$ where $\boldsymbol{\vartheta}_{\rm r} = {\rm diag}(\mathbf{\Theta}_{\rm r})$, $\boldsymbol{\vartheta}_{\rm t} = {\rm diag}(\mathbf{\Theta}_{\rm t})$, and then the optimization problem (22) can be equivalently reformulated as

$$\max_{\mathbf{V}} \quad P_1\iota + P_1\kappa + P_0\varpi,$$

$$\text{s.t.} \quad {\rm Tr}(\mathbf{Q}_{\rm r}\mathbf{F}) \geq {\rm Tr}(\mathbf{Q}_{\rm r}\mathbf{E})\varphi(\epsilon), \tag{23a}$$

$$(20\text{c}), \tag{23b}$$

$$\log_2\left({\rm Tr}(\mathbf{Q}_{\rm r}\mathbf{G}) + {\rm Tr}(\mathbf{Q}_{\rm r}\mathbf{O}) + \sigma_{\rm b}\right) - \log_2\left({\rm Tr}(\mathbf{Q}_{\rm r}\mathbf{O}) + \sigma_{\rm b}\right) \geq \iota, \tag{23c}$$

$$\log_2\left({\rm Tr}(\mathbf{Q}_{\rm t}\mathbf{P}) + \sigma_{\rm c}^2\right) - \log_2\left(\sigma_{\rm c}^2\right) - \log_2\left({\rm Tr}(\mathbf{Q}_{\rm t}\mathbf{X}) + \sigma_{\rm e}^2\right) + \log_2\left(\sigma_{\rm e}^2\right) \geq \varpi, \tag{23d}$$

$$\log_2\left({\rm Tr}(\mathbf{Q}_{\rm t}\mathbf{S}_{\rm c}) + \sigma_{\rm c}^2\right) - \log_2\left({\rm Tr}(\mathbf{Q}_{\rm t}\mathbf{S}_{\rm e}) + \sigma_{\rm e}^2\right) - \log_2\left({\rm Tr}(\mathbf{Q}_{\rm t}\mathbf{T}) + \sigma_{\rm c}^2\right) + \log_2\left({\rm Tr}(\mathbf{Q}_{\rm t}\mathbf{U}) + \sigma_{\rm e}^2\right) \geq \kappa, \tag{23e}$$

$${\rm diag}(\mathbf{Q}_{\rm r}) + {\rm diag}(\mathbf{Q}_{\rm t}) = \mathbf{I}_{M\times 1}, \tag{23f}$$

$$\mathbf{Q}_{\rm r} \succeq 0, \mathbf{Q}_{\rm t} \succeq 0, \tag{23g}$$

$${\rm rank}(\mathbf{Q}_{\rm r}) = 1, {\rm rank}(\mathbf{Q}_{\rm t}) = 1, \tag{23h}$$

where

- $\mathbf{V} = \{\mathbf{Q}_{\rm r}, \mathbf{Q}_{\rm t}, \iota, \kappa, \varpi\}$is the defined optimization variable set,
- $\mathbf{E} = \sum_{l=1}^{L}\left(\mathbf{w}_{\rm b}^H\mathbf{\Psi}_{\rm BR}^l\mathbf{w}_{\rm b}\right)\mathbf{\Delta}^l$,
- $\mathbf{F} = \sum_{l=1}^{L}\left(\mathbf{w}_{\rm c}^H\mathbf{\Psi}_{\rm BR}^l\mathbf{w}_{\rm c}\right)\mathbf{\Delta}^l$,
- $\mathbf{\Delta}^l = \mathbf{\Xi}^T\Big(\left(\widehat{\mathbf{\Psi}}_{\rm BR}^l\right)^T \otimes \left(\mathbf{\Omega}_{\rm rw}^H\mathbf{\Omega}_{\rm rw}\right)\Big)\mathbf{\Xi}$,
- $\mathbf{G} = \|\mathbf{H}_{\rm rb}^*\mathbf{H}_{\rm BR}\mathbf{w}_{\rm b}\|_2^2, \mathbf{O} = \|\mathbf{H}_{\rm rb}^*\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}\|_2^2$,
- $\mathbf{P} = \|\mathbf{H}_{\rm rc}^*\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}\|_2^2, \mathbf{T} = \|\mathbf{H}_{\rm rc}^*\mathbf{H}_{\rm BR}\mathbf{w}_{\rm b}\|_2^2$,
- $\mathbf{U} = \|\mathbf{H}_{\rm re}^*\mathbf{H}_{\rm BR}\mathbf{w}_{\rm b}\|_2^2, \mathbf{X} = \|\mathbf{H}_{\rm re}^*\mathbf{H}_{\rm BR}\mathbf{w}_{\rm c}\|_2^2$,
- $\mathbf{S}_{\rm c} = \mathbf{P} + \mathbf{T}, \mathbf{S}_{\rm e} = \mathbf{U} + \mathbf{X}$,
- $\mathbf{H}_{\rm rb} = {\rm Diag}(\mathbf{h}_{\rm rb}), \mathbf{H}_{\rm rc} = {\rm Diag}(\mathbf{h}_{\rm rc}), \mathbf{H}_{\rm re} = {\rm Diag}(\mathbf{h}_{\rm re})$.

To transform (23) into a convex optimization problem, we first need to deal with the non-convex constraints (23c), (23d), (23e) and rank-one constraints (23h). Similarly, the first-order Taylor expansion is adopted to acquire the concave lower bounds of left-sides of constraints (23c), (23d), (23e) in q-th inner loop iteration, denoted as $h_1\left(\mathbf{Q}_{\rm r}, \mathbf{Q}_{\rm r}^{(q)}\right)$, $h_2\left(\mathbf{Q}_{\rm t}, \mathbf{Q}_{\rm t}^{(q)}\right)$ and $h_3\left(\mathbf{Q}_{\rm t}, \mathbf{Q}_{\rm t}^{(q)}\right)$. For rank-one constraints, we ultilize the similar method to rewrite them. As a result, the rank-one can be equivalently transformed as $\widehat{\eta}_{\xi}\left(\mathbf{Q}_{\xi}\right) \triangleq {\rm Tr}(\mathbf{Q}_{\xi}) - \|\mathbf{Q}_{\xi}^{(q)}\|_2 - {\rm Tr}\left(\mathbf{q}_{\xi}^{(q)}\left(\mathbf{q}_{\xi}^{(q)}\right)^H\left(\mathbf{Q}_{\xi} - \mathbf{Q}_{\xi}^{(q)}\right)\right)$, $\xi \in \{{\rm r}, {\rm t}\}$, where $\mathbf{q}_{\rm r}^{(q)}$ and $\mathbf{q}_{\rm t}^{(q)}$ are the eigenvectors corresponding to the largest eigenvalues of $\mathbf{Q}_{\rm r}^{(q)}$ and $\mathbf{Q}_{\rm t}^{(q)}$ in q-th inner loop iteration. Thus, optimization problem (23) can be re-expressed as

$$\max_{\mathbf{V}} \quad P_1\iota + P_1\kappa + P_0\varpi - \varrho_{\rm r}\widehat{\eta}_{\rm r}(\mathbf{Q}_{\rm r}) - \varrho_{\rm t}\widehat{\eta}_{\rm t}(\mathbf{Q}_{\rm t}),$$

$$\text{s.t.} \quad (23\text{a}), (23\text{b}), (23\text{f}) - (23\text{g}), \tag{24a}$$

$$h_1\left(\mathbf{Q}_{\rm r}, \mathbf{Q}_{\rm r}^{(q)}\right) \geq \iota, h_2\left(\mathbf{Q}_{\rm r}, \mathbf{Q}_{\rm r}^{(q)}\right) \geq \varpi, \tag{24b}$$

$$h_3\left(\mathbf{Q}_{\rm r}, \mathbf{Q}_{\rm r}^{(q)}\right) \geq \kappa, \tag{24c}$$

where $\varrho_{\rm r}$ and $\varrho_{\rm t}$ denote the penalty coefficients. Thus, SDP optimization problem (24) can be efficiently solved by CVX.

V. Simulation Results

In this section, the simulation results are presented to validate the effectiveness of the proposed STAR-RIS-aided joint PLS and CCs scheme. In particular, we assume that the mmWave communication system assisted by STAR-RIS operates at 28 GHz with bandwidth 251.1886 MHz. Hence, the noise power can be calculated as $\sigma_{\rm b}^2 = \sigma_{\rm c}^2 = -90$ dBm. In addition, we set the QoS minimum rates as $R_{\rm b}^* = 1$, $R_{\rm s0}^* = 1$ and $R_{\rm s1}^* = 0.5$. For the large-scale path loss values in (1) and (2), the theoretical free-space distance-dependent path-loss model [18] is leveraged, which is given by $l_{\varpi} = -30 - 22\log d_{\varpi}$ dB, $\varpi \in \{{\rm BR}, {\rm rb}, {\rm rc}, {\rm re}\}$. The distances are set as $d_{\rm BR} = 60$ m, $d_{\rm rb} = d_{\rm rc} = 10$ m and $d_{\rm re} = 15$ m. To highlight the potential of STAR-RIS in jointly implementing the PLS and CCs, a baseline scheme is proposed where two adjacent conventional RISs with $\frac{M}{2}$ elements are adopted to replace the STAR-RIS.

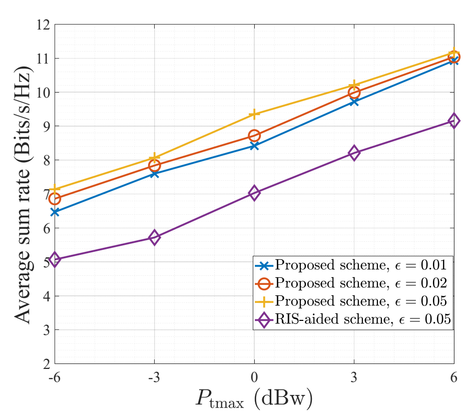

Fig. 1. Average sum rate versus the maximum transmit power $P_{\rm tmax}$ at BS with $M = 36$, $N_{\rm t} = 5$, $P_1 = 0.5$, and different covert requirements ϵ.

Fig. 1 presents the variation curves of the average sum rates versus the maximal transmit power $P_{\rm tmax}$ with different covert requirements ϵ, in comparison with the baseline utilizing the traditional RIS. It can be observed that the average sum rates gradually increase w.r.t. P_{tmax} in all cases, indicating that there exists a positive correlation between the average sum rates and P_{tmax}. Additionally, a relaxed covert requirement contributes to breaking through the performance bottleneck constrained by other system indicators. It is obvious that the proposed scheme exhibits significant performance benefits in jointly implementing the PLS and CCs in comparison to the baseline scheme. The proposed scheme can achieve better performance even if it is operated at a tighter covert requirement (i.e., $\epsilon = 0.01$).

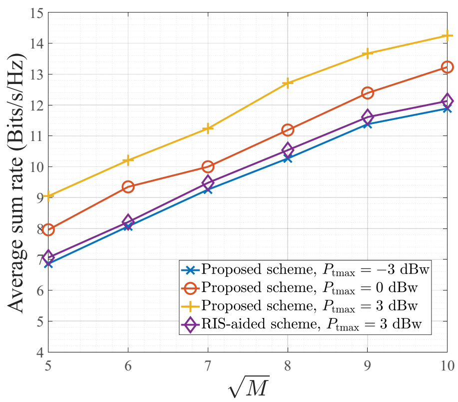

Fig. 2. Average sum rate versus the number of elements equipped at STAR-RIS with $N_{\text{t}} = 5$, $P_1 = 0.5$, $\epsilon = 0.05$ and different maximum transmit power P_{tmax}.

In Fig. 2, the performance trends of the average sum rate w.r.t. the number of elements at STAR-RIS (M) are presented, taking into account of various P_{tmax}. In particular, it is discernible that the average sum rates exhibit ascending trends with the increased M, which is due to the fact that more elements can provide a higher degree of freedom to augment performance gains. Besides, the most relaxed condition (i.e., $P_{\text{tmax}} = 3$ dBw) is adopted to implement the baseline scheme, however, the acquired performance is still worse than the proposed scheme under a stricter condition (i.e., $P_{\text{tmax}} = 0$ dBw).

VI. Conclusion

In this paper, we initially investigate the STAR-RIS enhanced joint PLS and CCs for mmWave systems. In particular, the analytical derivations of the minimum DEP is obtained by considering the practical assumptions, where only the statistical CSI between STAR-RIS and Willie is accessible at the BS. An optimization problem is constructed that focuses on maximizing the average sum rate between the covert rate and the secure rate, while also ensuring the covert constraint and QoS constraints. In order to effectively solve this non-convex optimization problem with strong coupling variables, an alternative algorithm based on the SDR method is proposed. Numerical results demonstrate the performance gains of the proposed STAR-RIS-assisted scheme in comparison with the benchmark scheme adopting the traditional RIS, which further indicates that the STAR-RIS exhibits more benefits in the implementation of the joint PLS and CCs.

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