Beamforming Optimization of Secrecy Rate in Cognitive Radio Networks Assisted by STAR RIS

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Abstract—The secure communication problem in spectrum-sharing underlay cognitive radio (CR) systems for secondary users (SU) is examined in the presence of multiple eavesdroppers (Eves). A novel approach employing a simultaneous transmitting and reflecting reconfigurable intelligent surface (STAR-RIS) is proposed to enhance the secrecy rate (SR) of SU. To address this, an alternating optimization (AO) algorithm based on successive convex approximation (SCA) and semi-definite relaxation (SDR) is developed. The transmit beamforming vectors at the base station (BS) and the phase shifts of the STAR-RIS are jointly optimized. The algorithm demonstrates efficient convergence to an optimal solution with a reduced number of iterations. Simulation results confirm a significant improvement in the secrecy rate of SU when compared to traditional RIS and combined RIS (CRIS) systems.

Keywords—simultaneous transmitting and reflecting reconfigurable intelligent surface, cognitive radio, beamforming.

I. INTRODUCTION

With the rapid development of Internet of Everything (IoE) technology, spectrum resources are becoming increasingly scarce. CR has been proposed as a promising solution to address this issue. By leveraging spectrum sensing and sharing technologies, CR effectively mitigates the conflict between the growing number of wireless devices and spectrum scarcity[1].However, due to the broadcast nature of radio transmissions and the openness of CR, malicious devices may exploit licensed spectrum, posing significant security risks. Physical layer security (PLS) techniques enhance CR security by "hiding" confidential information, reducing eavesdropping risks, and improving secrecy rates[2].

The existing wireless communication environment has the characteristics of uncontrollable changes, which is easy to have a negative impact on the communication system. In [4], a differential convex algorithm framework was proposed, which jointly optimizes the beamformer of the secondary transmitter and the RIS phase shift matrix to enhance transmission power in RIS-assisted cognitive networks. In [5], it had been investigated an active RIS-assisted MISO CR system, transforming primary user (PU) SR constraint into a Second Order Cone (SOC) form and using an iterative penalty function to alternately optimize the transmission and reflection beamforming. STAR-RIS was introduced in [6], it ordered to address the limitation of traditional Reconfigurable Intelligent Surfaces (RIS) that only reflect incoming signals. The role of STAR-RIS in enhancing physical-layer security for cognitive radio systems has been increasingly explored. A time-switching protocol for STAR-RIS was employed to satisfy the secrecy rate constraints of SU, interference thresholds for PU, and the amplitude and phase constraints of the STAR-RIS elements in [7]. This approach also involved optimizing the beamforming vectors for both the base station and STAR-RIS to minimize the base station's transmission power. In [8], STAR-RIS assisted MIMO CR system was proposed, demonstrating that STAR-RIS enhances signal transmission by adjusting the phase and amplitude of Reflective Elements. The system utilized methodologies such as Block Coordinate Descent, Gaussian randomization, and SCA, showing significant improvements in SU transmission performance compared to traditional RIS. The performance of STAR-RIS assisted CR-NOMA networks was studied in [9], leading to the conclusion that STAR-RIS can significantly enhance the performance of the Industrial Internet of Things (IoT) within the context of Flexible Industrial 5.0, particularly in high-SNR regions. Further performance improvements were achieved by optimizing the number of STAR-RIS elements, power allocation, and the placement of the STAR-RIS.

This paper establishes Multi-Eavesdroppers STAR-RIS-CR system. The goal is to maximize the secure communication rate for SU while minimizing interference to PU. For this purpose, STAR-RIS-assisted CR is utilized and the safe beamforming and STAR-RIS phase-shift matrices are jointly optimized. The resulting optimization problem is non-convex due to the high coupling of the optimization variables. We propose an alternating optimization algorithm based on SCA scheme and SDR method, which divides the problem into two sub-problems and alternates optimization until convergence is achieved. Simulation results show that, compared with CRIS, RIS, and STAR-RIS with random phases, the proposed scheme significantly improves the SU's secure communication rate and achieves algorithm convergence with relatively fewer iterations.

SYSTEM MODEL

The communication system of the proposed STAR-RIS-CR is illustrated in Fig.1. BS with N antennas, two CR user pairs, using a single antenna in R and T region, while there are K Eves denoted as Eves, which located in the reflecting and transmitting region around the SU, for $k = \{1, \dots, K\}$. In the system of this paper, considered the existence of direct links from the BS to other receiver nodes, and improve the secure communication rate of the SU by introducing the STAR-RIS with M passive elements. $H \in \mathbb{C}^{M \times N}$ denote the channel between the BS and the STAR-RIS. $H_l = \{h_{Bsul} \in \mathbb{C}^{N\times1}, h_{Bekl} \in \mathbb{C}^{N\times1}\}$, $h_{Bpul} \in \mathbb{C}^{N\times1}$, $g_{rpul} \in \mathbb{C}^{M\times1}$ $G_l = \{g_{rsul} \in \mathbb{C}^{M\times1}, g_{rekl} \in \mathbb{C}^{M\times1}\}$,denote the channel between BS to SU or Eves, BS to PU, STAR-RIS to SU, STAR-RIS to PU and STAR-RIS to Eves, $l \in \{r,t\}$, $k \in K$. In this paper, we aim to maximize the secrecy rates of SU. We assume complete channel state information is available at both BS and STAR-RIS. The channels are subject to quasi-static flat fading.

A. STAR-RIS Model of Energy Splitting Protocol

STAR-RIS supports three communication strategies: Energy Splitting (ES)[10], Mode Switching (MS), and Time Switching (TS). The MS strategy divides the units into two parts for transmission and reflection, limiting full-dimensional beamforming gain. The TS strategy periodically switches the operational state of all units in different time slots, requiring strict time synchronization and increasing hardware complexity. In contrast, we ultimately choose the ES strategy, which optimizes the transmission and reflection coefficients of each STAR-RIS unit, offering greater flexibility in communication system design. Specifically, the reflection and transmission amplitude and phase shifts of the mth element of STAR-RIS is respectively expressed as α_m^r, α_m^t, θ_m^r, θ_m^t, $v_l^m = \sqrt{\alpha_m^l} e^{j\theta_m^l}$ represents the reflection and transmission coefficient of the mth element of STAR-RIS, and $\alpha_m^r, \alpha_m^t \in [0,1]$, $\alpha_m^r + \alpha_m^t = 1$, $\theta_m^r, \theta_m^t \in [0, 2\pi)$, $\forall m \in M$. $l \in \{r,t\}$.

B. Broadcasting Signal Model

In the broadcasting signal model, the signals sent from BS is $x = \sum_l w_l s_l$, where $w_l \in \mathbb{C}^{N \times 1}$ and $s_l \sim \mathcal{CN}(0,1)$ denote the BS beamforming vector for users in two regions and signal carrying secrecy information from the BS to SU respectively. It is well known that the maximum transmit power budget of BS is $P_{\max}$. Maximizing the SU secrecy rate should be obtained under the condition of ensuring the transmit power, easily get $w_r^H w_r + w_t^H w_t \le P_{\max}$. Then the received signal at the CR users is the sum signal from the BS and the reflected/transmitted one by the STAR-RIS, and given by [11], $y_{sul} = \left(h_{Bsul}^H + g_{rsul}^H V_l H\right) x + n_{sul}$, $y_{pul} = \left(h_{Bpul}^H + g_{rpul}^H V_l H\right) x + n_{pul}$, $y_{evekl} = \left(h_{Bekl}^H + g_{rekl}^H V_l H\right) x + n_{evekl}$, where $n_{sul} = n_{pul} = n_{evekl} \sim \mathcal{CN}(0, \sigma_0^2)$ is the additive Gaussian white noise (AWGN) and let denote $V_l = \mathrm{diag}(v_l)$ as the reflection coefficient matrix.

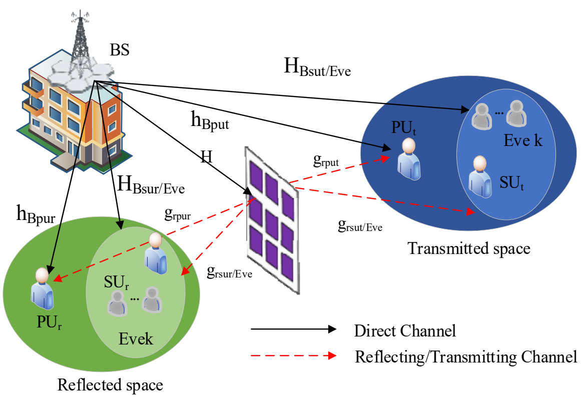

Fig 1: STAR-RIS-CR System Model

In the CR system, s_l can being transmitted through the equivalent channel as follows: $\bar{h}_{sul}^H = h_{Bsul}^H + g_{rsul}^H V_l H$, $\bar{h}_{sul}^H = h_{Bsul}^H + g_{rsul}^H V_l H$, $\bar{h}_{evekl}^H = h_{Bekl}^H + g_{rekl}^H V_l H$, At the receiver, the SU decodes signals, considering others as interference. Eavesdroppers can only eavesdrop SU signals. The Signal-to-Noise Ratio (SNR) for the SU and the kth eavesdropper is (1) ($* = \{\text{sul}, \text{evekl}\}$):

$$SNR_* = n_0 \left|\bar{h}_*^H w_l\right|^2 \Big/ \left(n_0 \left|\bar{h}_*^H w_{l'}\right|^2 + 1\right) \tag{1}$$

where $n_0 = 1/\sigma_0^2$, $l = r$, $l' = t$; and if $l = t$, otherwise.

The BS introduces interference to the PU, a phenomenon termed as the Interference Power Constraint (IPC) within CR systems. This interference can be quantified as:

$$T_{PU} = \left|\bar{h}_{pur}^H w_r\right|^2 + \left|\bar{h}_{put}^H w_t\right|^2 \le Th \tag{2}$$

The Th thresholds are closely linked to the coefficients of the STAR-RIS, is utilized by both the primary and secondary systems. Any alteration in the STAR-RIS coefficients significantly impacts the IT experienced by the PU.

II. PROBLEM DESCRIPTION AND SOLUTION

A. Problem Description

The optimization problem addressed in this work is to enhance the secrecy rate (SR) for SU by jointly optimizing the beamforming vectors w_r, w_t of the signals and the phase shift matrices v_r, v_t. Using equation (1), the achievable secrecy rate at the SU, measured in bits per second per Hertz (bps/Hz), is given by:

$$R_{SU} = \sum_l \left(\log_2(1 + SNR_{sul}) - \max \log_2(1 + SNR_{evekl})\right) \tag{3}$$

Then, the optimization problem can be formulated problem 1 as follows :

$$P1: \quad \max_{w_l, v_l} R_{SU}(w_l, v_l) \tag{4}$$

$$\text{s.t.} \quad \sum_l \mathbf{w}_l^H \mathbf{w}_l \le P_{\max} \tag{4a}$$

$$T_{PU} = \sum_l \left|\bar{h}_{pul}^H w_l\right|^2 \le Th \tag{4b}$$

$$\sum_l \left|v_l^m\right| = 1 \tag{4c}$$

$$\alpha_m^r, \alpha_m^t \in [0,1], \alpha_m^r + \alpha_m^t = 1$$
$$v_l^m \in [0, 2\pi), \forall m \in M, l = \{r,t\} \tag{4d}$$

In the ES protocol, initial coupling of transmission and reflection beamforming complicates resource allocation. The non-convexity of the objective and constraints is beyond conventional convex optimization. We propose an Alternating Optimization (AO) algorithm, utilizing SCA and SDR, to be discussed next.

B. PROPOSED SOLUTION

For Problem P1, an alternating optimization algorithm is proposed, splitting the task into Sub-problem 1 (beamforming w_r, w_t) and Sub-problem 2 (phase shift matrix v_r, v_t). Optimizing one while holding the other constant, the process repeats until convergence, then alternates to solve for P1.

a). Optimizing w_r, w_t for Given v_r, v_t

In this subsection, we focus on optimizing the beamforming vectors at the base station. Initially, we optimize w_r, w_t, assuming the phase shift matrices v_r, v_t are given. Due to the large number of parameters involved, some simplifications are necessary before we proceed with the optimization. $H_{sul} = \bar{h}_{sul}\bar{h}_{sul}^H$, $H_{evekl} = \bar{h}_{evekl}\bar{h}_{evekl}^H$, $W_l = w_l w_l^H$, and $H_{pul} = \bar{h}_{pul}\bar{h}_{pul}^H$.Thus, P1 transforms into P2:

$$P2: \max_{W_l} \sum_l \left(\log_2\left(1 + \frac{n_0 \mathrm{Tr}(H_{sul}W_l)}{n_0 \mathrm{Tr}(H_{sul}W_{l'}) + 1}\right)\right) - \max_{k\in\mathcal{K}} \left(\log_2\left(1 + \frac{n_0 \mathrm{Tr}(H_{evekl}W_l)}{n_0 \mathrm{Tr}(H_{evekl}W_{l'}) + 1}\right)\right) \quad (5)$$

$$\text{s.t.} \quad \sum_l Tr(W_l) \le P_{\max} \quad (5a)$$

$$T_{PU} = \sum_l Tr(H_{pul}W_l) \le Th \quad (5b)$$

$$W_l \ge 0, \text{(4d)} \quad (5c)$$

However, W_l need to satisfy $W_l \ge 0$ and rank (W_l) =1. Due to the rank-one constraint, the above optimization process is still a nonconvex problem. we apply SDR to relax this constraint. Thus, we have the following optimization problem. which is difficult to solve. By introducing a slack variable $\xi_l > 0$. So P2 can be translated to P3 as follows:

$$P3: \quad \max_{W_l} \sum_l (R_{sul} - \xi_l) \quad (6)$$

$$\text{s.t.} \quad \max_{k\in\mathcal{K}}(R_{\text{evek,l}}) \le \xi_l,\ k\in\mathcal{K},\ \xi_l > 0 \quad (6a)$$

(5a), (5b), (5c)

As shown above, the objective function in P3 is non-convex due to the joint relationship of variables w_r, w_t. P3 is a typical convex-concave function. We employ SCA method in conjunction with iterative SDR for solving it. Initially, the function $R_{sul}(W_l)$ can be rewritten as follows:

$$R_{sul}(W_l) = A_l(W_{l'}, W_l) - A_l(W_{l'}) \quad (7)$$

For convenience, the scenario will be shown below using $l = r$, and the same conclusion can be obtained for $l = t$. The formula above has:

$$A_r(W_r, W_t) = \log_2\left(1 + n_0 \mathrm{Tr}(H_{sur}(W_r + W_t))\right) \quad (8)$$

$$A_r(W_t) = \log_2\left(1 + n_0 \mathrm{Tr}(H_{sur}W_t)\right) \quad (9)$$

Secondly, the similar transformation is applied to the eavesdropper's eavesdropping rate represented as follows:

$$A_{rk}(W_r, W_t) = \log_2\left(1 + n_0 \mathrm{Tr}(H_{\text{evekr}}(W_r + W_t))\right) \quad (10)$$

$$A_{rk}(W_t) = \log_2\left(1 + n_0 \mathrm{Tr}(H_{\text{evekr}}(W_t))\right) \quad (11)$$

For a function *f*, which can be approximated using a Taylor expansion, the first-order derivative of $A_r(W_t)$ is expressed as follows:

$$dA_r(W_t) = \mathrm{Tr}\left(\frac{n_0 H_{sur}}{1 + n_0 \mathrm{Tr}(H_{sur}W_t)}\right) d(W_t) \quad (12)$$

Then, utilizing the beamforming vectors W_t^c, we apply a Taylor expansion at that point, as shown in equation (9), to derive equation (13)

$$A_r(W_t) \ge A_r(W_t^c) + \mathrm{Tr}(\lambda_r(W_t - W_t^c)) = \bar{A}_r(W_t) \quad (13)$$

where $\lambda_r = n_0 H_{sur}/1 + n_0 \mathrm{Tr}(H_{sur}W_t)$, W_t^c denotes the result of the c-th iteration.

Next, the first-order differentiation is also performed for (17), and the result is as follows:

$$dA_{rk}(W_r, W_t) = \mathrm{Tr}\left(\frac{n_0 H_{\text{evekr}}}{1 + n_0 \mathrm{Tr}(H_{\text{evekr}}(W_r + W_t))}\right) d(W_r) + \mathrm{Tr}\left(\frac{n_0 H_{\text{evekr}}}{1 + n_0 \mathrm{Tr}(H_{\text{evekr}}(W_r + W_t))}\right) d(W_t) \quad (14)$$

Then a Taylor expansion (10) at that point (W_r^c, W_t^c) to obtain (15):

$$A_{rk}(W_r, W_t) \ge A_{rk}(W_r^c, W_t^c) + Tr(\lambda_{evek,r}(W_t - W_t^c)) + Tr(\lambda_{evek,r}(W_r - W_r^c)) = \bar{A}_{rk}(W_r, W_t) \quad (15)$$

where $\lambda_{\text{evek},r} = n_0 H_{\text{evekr}}/1 + n_0 \mathrm{Tr}(H_{\text{evekr}}(W_r + W_t))$, (W_r^c, W_t^c) denotes the result of the c-th iteration.

Finally, we initialize to start the iterative optimization of the algorithm, and P3 can be approximated as

$$P4: \quad \max_{W_l} \sum_l \left(A_l(W_l, W_{l'}) - \bar{A}_l(W_{l'}) - \xi_l\right) \quad (16)$$

$$\text{s.t.} \quad \max_{k\in\mathcal{K}} \left(\bar{A}_{l,k}(W_l, W_{l'}) - A_{l,k}(W_{l'})\right) \le \xi_l \quad (16a)$$

(5a) (5b) (5c)

After being processed by the aforementioned methods, Problem P4 is transformed into a convex problem that can be solved using the CVX. The method disregards the constraint rank (W_l) =1 by employing SDR, we utilize Gaussian randomization for subsequent processing to obtain the solution that best result w_r, w_t.

b). Optimizing v_r, v_t for Given w_r, w_t

In this subsection, after obtaining w_r, w_t, we solve the sub-problem of optimizing the phase shift. Unlike RIS, STAR-RIS operates with the ES protocol, which separately reflects and transmits arrival signals that satisfy the condition $\alpha_m^t + \alpha_m^r = 1$. Similarly, before proceeding with optimization, we perform a simple processing of some variables. Let denote $g_{rsul}^H V_l H = v_l^H \mathrm{diag}(h_{rsul}^H) H = v_l^H H_{sul}, \bar{h}_{sul}^H = h_{sul}^H + h_{rsul}^H V_l H = \bar{v}_l^H H_{sl}$, $g_{rekl}^H V_l H = v_l^H \mathrm{diag}(h_{rekl}^H) H = v_l^H H_{rekl}, \bar{h}_{rekl}^H = h_{evekl}^H + h_{rekl}^H V_l H = \bar{v}_l^H H_{Ekl}$, $g_{rpul}^H V_l H = v_l^H \mathrm{diag}(h_{rpul}^H) H = v_l^H H_{pul}, \bar{h}_{rekl}^H = h_{evekl}^H + h_{rekl}^H V_l H = \bar{v}_l^H H_{Ekl}$, $\tilde{H}_{Sl} = H_{Sl} W_l H_{Sl}^H$, $\breve{H}_{Sl} = H_{Sl} W_{l'} H_{Sl}^H$, $\tilde{H}_{Ekl} = H_{Ekl} W_l H_{Ekl}^H$, $\breve{H}_{Ekl} = H_{Ekl} W_{l'} H_{Ekl}^H$, $\tilde{H}_{Pl} = H_{Pl} W_l H_{Pl}^H$, $\breve{H}_{Pl} = H_{Pl} W_{l'} H_{Pl}^H$, $v_l^H = \left[\sqrt{\alpha_1^l} e^{j\theta_1^l}, \ldots, \sqrt{\alpha_M^l} e^{j\theta_M^l}\right]$, $\bar{v}_l^H = \left[v_l^H, 1\right]$, $\bar{V}_l = \bar{v}_l^H \bar{v}_l$, $H_{Sl} = \left[H_{sul}, h_{sul}^H\right]^H$, $H_{Ekl} = \left[H_{evekl}, h_{evekl}^H\right]^H$, $H_{pul} = \left[H_{pul}, h_{pul}^H\right]^H$.

Accordingly, P1 can be translated as follows:

$$\text{P5:} \quad \max_{\mathrm{V}_l} \sum_l \left(\log_2\left(1 + \frac{n_0 \mathrm{Tr}\left(\tilde{H}_{Sl}\bar{V}_l\right)}{n_0 \mathrm{Tr}\left(\breve{H}_{Sl}\bar{V}_l\right) + 1}\right)\right) - \max_{k\in\mathcal{K}} \left(\log_2\left(1 + \frac{n_0 \mathrm{Tr}\left(\tilde{H}_{Ekl}\bar{V}_l\right)}{n_0 \mathrm{Tr}\left(\breve{H}_{Ekl}\bar{V}_l\right) + 1}\right)\right) \quad (17)$$

$$T_{PU} = \sum_l Tr\left(\tilde{H}_{Pl}\bar{V}_l + \breve{H}_{Pl}\bar{V}_l\right) \le Th \quad (17a)$$

$$\bar{V}_l \ge 0 \quad (17b)$$

$$\sum_l \bar{V}_l(m, m) = 1, \quad \forall m \in M + 1 \quad (17c)$$

Here, the processing is identical to the steps of BS optimized beamforming. At first, the function $R_{sul}(\bar{V}_l)$ can be reformulated into a DC-type form as follows:

$$R_{sul}(\bar{V}_l) = B_l(\bar{V}_l) - B_{l\_}(\bar{V}_l) \tag{18}$$

Similarly, (24) can be rewritten as

$$B_l(\bar{V}_l) = \log_2\left(1 + n_0 \mathrm{Tr}(\tilde{H}_{Sl} + \breve{H}_{Sl})\bar{V}_l\right) \tag{19}$$

$$B_{l\_}(\bar{V}_l) = \log_2\left(1 + n_0 \mathrm{Tr}(\breve{H}_{Sl}\bar{V}_l)\right) \tag{20}$$

Then $R_{evekl}\left(\bar{V}_l\right)$ can also be rewritten as

$$R_{evek,l}(\bar{V}_l) = B_{lk}(\bar{V}_l) - B_{lk\_}(\bar{V}_l) \tag{21}$$

Similarly, (28) can be rewritten as

$$B_{lk}(\bar{V}_l) = \log_2\left(1 + n_0 \mathrm{Tr}(\tilde{H}_{Ekl} + \breve{H}_{Ekl})\bar{V}_l\right) \tag{22}$$

$$B_{lk\_}(\bar{V}_l) = \log_2\left(1 + n_0 \mathrm{Tr}(\breve{H}_{Ekl}\bar{V}_l)\right) \tag{23}$$

The first-order derivative of $B_{l\_}(\bar{V}_l)$ can be expressed as

$$dB_{l\_}(\bar{V}_l) = \mathrm{Tr}\left(\frac{n_0 \breve{H}_{Sl}}{1 + n_0 \mathrm{Tr}(\breve{H}_{Sl}\bar{V}_l)}\right) d(\bar{V}_l) \tag{24}$$

Then, using the beamforming vectors $\bar{V}_l^c$, a Taylor expansion (20) at that point to obtain (25):

$$B_{l\_}(\bar{V}_l) \geq B_{l\_}(\bar{V}_l^c) + \mathrm{Tr}(\eta_l(\bar{V}_l - \bar{V}_l^c)) = \bar{B}_{l\_}(\bar{V}_l^c) \tag{25}$$

where $\eta_l = n_0 \breve{H}_{Sl} / 1 + n_0 \mathrm{Tr}(\breve{H}_{Sl}\bar{V}_l)$. $\bar{V}_l^c$ denotes the result of the cth iteration.

Similarly, we can obtain result for $B_{lk}(\bar{V}_l)$:

$$dB_{lk}(\bar{V}_l) = \mathrm{Tr}\left(\frac{n_0(\tilde{H}_{Ekl} + \breve{H}_{Ekl})}{1 + n_0 \mathrm{Tr}((\tilde{H}_{Ekl} + \breve{H}_{Ekl})\bar{V}_l)}\right) d(\bar{V}_l) \tag{26}$$

$$B_{lk}(\bar{V}_l) \geq B_{lk}(\bar{V}_l) + \mathrm{Tr}(\eta_{evekl}(\bar{V}_l - \bar{V}_l^c)) = \bar{B}_{lk}(\bar{V}_l^c) \tag{27}$$

where $\eta_{evekl} = n_0(\tilde{H}_{Ekl} + \breve{H}_{Ekl}) / 1 + n_0 \mathrm{Tr}((\tilde{H}_{Ekl} + \breve{H}_{Ekl})\bar{V}_l)$ .P5 can be approximated as follows:

$$P6: \quad \max_{\bar{V}_l} \sum_l B_l(\bar{V}_l) - \bar{B}_{l\_}(\bar{V}_l^c) - \zeta_l \tag{28}$$

$$\text{s.t.} \quad \bar{B}_{lk}(\bar{V}_l^c) - B_{lk\_}(\bar{V}_l) \leq \zeta_l, k \in K, \zeta_l > 0 \tag{28a}$$

(20a) (20b) (20c)

The problem is convex and can be solved using convex optimization tools. We can obtain $\bar{V}_l$ which is subjected to Eigenvalue Decomposition (EVD) under the satisfaction of the energy conservation law, and then recover them using Gaussian randomization. Algorithm 1 outlines the overall optimization process.

III. Simulation and Numerical Results

For realism, we adopt a 3D coordinate system (in meters), based on the STAR-RIS-CR system model. In this paper, the proposed scheme is compared with the CRIS, RIS, and STAR-RIS random phase shift matrices. The parameters are given in Table I.

Fig.2 shows the relationship between the total transmit power of the BS $P_{\max}$ and the secrecy rate of the SU. At this time, the interference power constraint $T_{PU} = -60dBm$. As shown in Figure 2, with increasing base station transmission power $P_{\max}$, the secrecy rate of the SU in proposed scheme rises steadily. The STAR-RIS scheme outperforms others, as depicted, offering higher secrecy rates. It excels under the ES protocol, surpassing a simple combination of RIS, indicating a more than double amount. Thus, STAR-RIS notably boosts SU secrecy rates in multi-eavesdropper environments.

Algorithm 1 Proposed algorithm for solving P1

Input: $P_{\max}, \sigma_0^2, \varepsilon, C_{\max}, Th$

Initialize: BS beamforming vectors w_r, w_t ,STAR-RIS Phase Shift v_r, v_t , c = 1

1: Repeat

2: W_l^c , $\bar{V}_l^c$ c = 1 , calculated $\lambda_l, \lambda_{evekl}, \eta_l, \eta_{evekl}$.

3: With the params W_l^c ,solve P4 to obtained W_l^{c+1} , w_l^{c+1} .With the results w_l^{c+1} ,solve P6 and find $\bar{V}_l^{c+1}$, v_l^{c+1} .

4: Update c = c+1 .

5: Until if the optimization objective value satisfies $\left(R_{SU}^{c+1} - R_{SU}^c\right) / R_{SU}^c \leq \varepsilon$ or the maximum number of iterations $c > C_{\max}$.

Output: $w_r^*, w_t^*, v_r^*, v_t^*$

TABLE I. Simulation Parameters.

Parameter	***Value***
SU coordinates	(60,40,1.5), (-60,40,1.5)
PU coordinates	(60,60,1.5), (-60,60,1.5)
BS,STAR-RIS coordinates	(0,0,5), (0,50,10)
Path Loss Per Unit Distance	$L_0 = 30dB$
Noise Variance	$\sigma_0^2 = -105\text{dBm}$
Convergence Error	$\varepsilon = 10^{-3}$
Maximum number of iterations	$C_{\max} = 30$
Path Loss Factor	$C_{BSTARS} = 2.5$, $C_{Bsul} = C_{Bpul} = C_{Bevekl} = 4$ $C_{rsul} = C_{rpul} = C_{revekl} = 2$

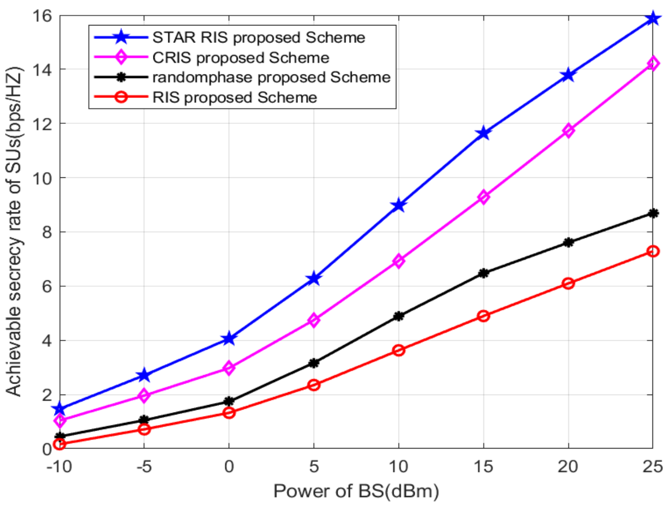

Fig.2 Secrecy rate of SU versus $P_{\max}(dBm)$

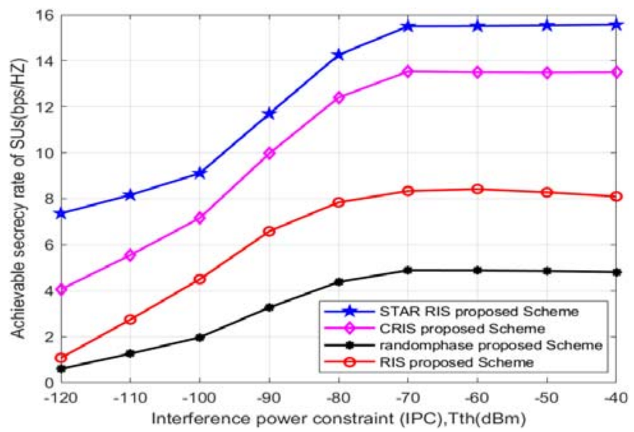

Fig.3 Secrecy rate of the SU versus IPC (Th)

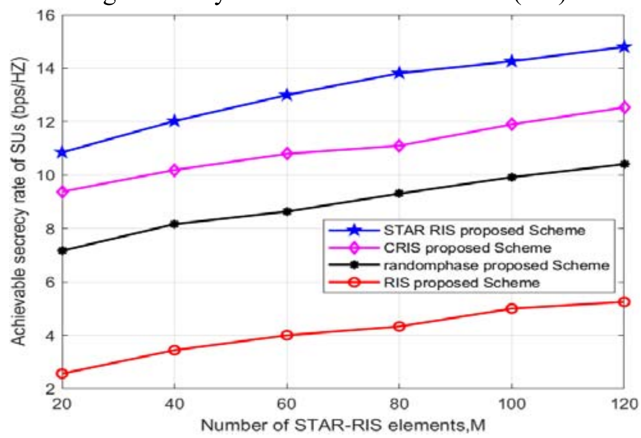

Fig.4 Secrecy rate of SU versus STAR-RIS elements M

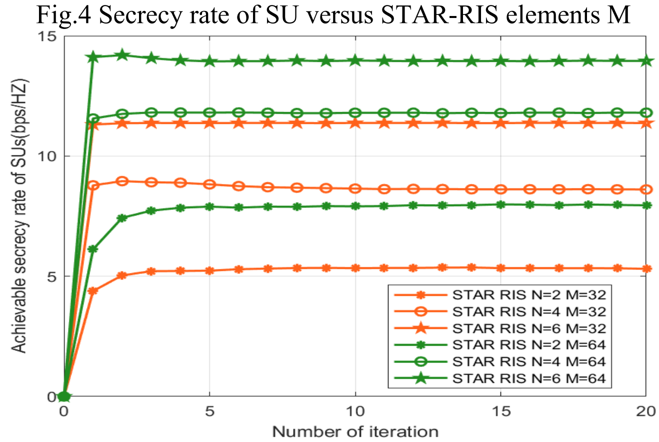

Fig. 5 Iteration curve

This paper investigates the relationship between IPC for PU and the secure rate for SU, as illustrated in Fig.3. With parameters set at N=4, M=64, and $P_{\max} = 20dBm$, and considering K=3 eavesdroppers, the study reveals that secrecy rates increase with IPC. This is because PU can tolerate more interference, benefiting SU. However, the rate plateaus at $Th = -70dBm$, indicating that Th is not the primary factor influencing SU secrecy rates.

Fig.4 shows how the number of STAR-RIS elements M affects the SU secure rate. With N=4, $P_{\max} = 15dBm$, K=3, and $Th = -60dBm$, simulations reveal a gradual increase in secure rates as M grows. This growth is attributed to the enhanced beamforming gain from additional STAR-RIS elements, which improves the BS-STAR-RIS-SU link. More elements also mean more signal paths to boost SU signal quality and reduce eavesdropper interference.

To showcase the algorithm's convergence in our scheme, we analyze how antenna count at the BS, STAR-RIS elements, and iteration numbers interact. Fig.5 compares the secrecy rate convergence for (N=2, M=32), (N=2, M=64), (N=4, M=32), (N=4, M=64), (N=6, M=32), and (N=6, M=64).The results show that the rate stabilizes after less than five iterations. Moreover, the secrecy rate of SU rises with M, confirming STAR-RIS ability to enhance communication quality, with more elements leading to better performance.

IV. Conclusion

This paper examines a cognitive radio (CR) system in a multi-eavesdropper environment, enhanced by STAR-RIS for secure communication. We propose a novel algorithm that optimizes base station beamforming and STAR-RIS phase shifts, using SCA and SDR to tackle the non-convex optimization problem. Simulations demonstrate the algorithm's rapid convergence and efficiency, highlighting the influence of STAR-RIS on secure communication performance.

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