

Fluid Reconfigurable Intelligent Surface Assisted Covert Communication

Ryotaro Ishihara[†] and Shun Kojima

Graduate School of Engineering, Chiba University, Chiba, Japan

Email:ccpa2672@chiba-u.jp[†]

Abstract—In this paper, we propose a covert communication scheme that employs a fluid reconfigurable intelligent surface (FRIS) and integrates active control with element-position reconfigurability. We formulate a covert rate maximization problem that jointly optimizes the transmit power, FRIS position selection, and the amplitudes and phases of the activated elements, subject to the FRIS power constraint and the covertness constraint at the warden. Furthermore, we develop an alternating optimization (AO) algorithm that combines transmit power control, cross-entropy optimization (CEO)-based position selection, and semidefinite relaxation (SDR)-based reflection coefficient design, termed AO-CEO-SDR algorithm. Simulation results demonstrate that applying the proposed optimization to FRIS-assisted covert communication achieves a higher covert rate than conventional schemes.

Index Terms—Covert communications, fluid reconfigurable intelligent surface, joint optimization.

I. INTRODUCTION

Wireless communication systems have evolved rapidly, making security and privacy protection increasingly important. Conventional wireless security has mainly focused on preventing unintended third parties from decoding confidential information. In recent years, however, covert communication has attracted increasing attention as a technique for hiding the existence of communication, partly due to concerns regarding the potential vulnerability of cryptographic techniques. In covert communication, a transmitter aims to send confidential information to an intended receiver, while preventing a warden from detecting the transmission [1]. Therefore, covert communication requires not only enhancing communication quality but also limiting the warden's detection capability.

Reconfigurable intelligent surface (RIS) is a promising technology that can reconfigure wireless propagation environments by controlling the phases of numerous reflecting elements, thereby improving communication quality and enhancing physical-layer security (PLS) [2], [3]. Since RISs can strengthen the received signal while suppressing signal leakage toward the warden, RIS-assisted covert communication has been actively studied [4]. However, conventional passive RISs suffer from severe attenuation of the reflected signal due to multiplicative fading over the cascaded transmitter-RIS-receiver channel [5]. To overcome this limitation, active RISs capable of amplifying reflected signals have been investigated [6]. Although active RISs can compensate for the cascaded path loss, they also amplify the internal noise, which may increase the detection probability. Therefore, in

active RIS-assisted covert communication, a method for jointly optimizing transmit power and the reflection coefficients of the active RIS has been proposed [7]. However, both conventional passive and active RISs employ reflecting elements at fixed positions. Consequently, although their phases and amplitudes can be adjusted, the reflection points themselves cannot be reconfigured according to the channel conditions.

To address this limitation, fluid RIS (FRIS) has recently emerged as a promising technology for introducing additional spatial degrees of freedom into RIS. In FRIS, the permissible region on the RIS surface is divided into multiple subareas, and each FRIS element reconfigures its reflection position within the corresponding subarea [8], [9]. As a result, FRIS can select favorable reflection positions based on channel conditions and control the corresponding reflection coefficients, rather than controlling only the phases at fixed reflection points as in conventional RIS. This position reconfigurability provides additional spatial diversity without increasing the number of elements, enabling reflection paths that benefit the receiver while degrading the channel toward the warden. Prior studies have considered the joint design of FRIS element selection and beamforming [10], and demonstrated the effectiveness of FRIS in improving communication and PLS [11], [12].

FRIS is also expected to be effective for covert communication because it can select elements from among numerous candidates that enhance the effective channel while suppressing signal leakage to the warden. Recent research on FRIS-assisted covert communication has analyzed performance metrics, including covertness outage probability and success probability, demonstrating that FRIS can enhance covert communication performance compared with fixed-position RIS [13]. However, this study primarily focuses on performance analysis under specific FRIS configurations, and a framework for optimizing FRIS while accounting for the warden's impact has not been sufficiently investigated.

Motivated by the above considerations, this paper investigates the joint optimization of an FRIS-assisted covert communication system. To maximize the average covert rate while satisfying the covertness requirement, we propose an alternating optimization-cross entropy optimization-semidefinite relaxation (AO-CEO-SDR) algorithm, which jointly optimizes the transmit power, active element selection, reflection amplitudes, and phase shifts of the FRIS. By exploiting the position-selection degrees of freedom offered by the FRIS, the proposed algorithm enhances the effective channel gain of

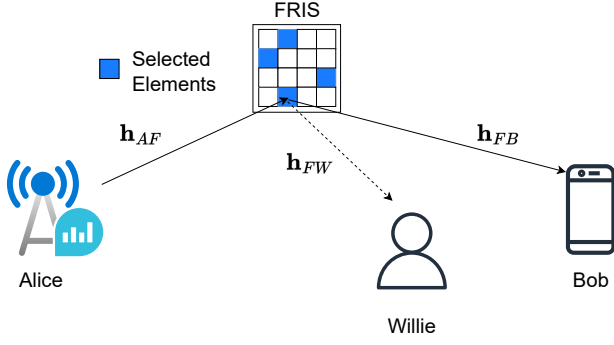


Fig. 1. System model of covert communications with FRIS.

the legitimate link while suppressing signal leakage toward the warden. Numerical results show that the proposed algorithm achieves a higher average covert rate than both an FRIS with random position selection and a conventional RIS.

II. SYSTEM MODEL

A. System and Channel Model

As shown in Fig. 1, we consider an FRIS-assisted covert communication system consisting of Alice, Bob, Willie, and an FRIS. Alice, Bob, and Willie are each equipped with a single antenna. Alice intends to transmit confidential information to Bob, while Willie monitors the wireless environment and attempts to detect Alice's transmission. The FRIS is deployed between Alice and Bob to assist the covert transmission by reflecting Alice's signal toward Bob.

The FRIS consists of $M = M_x M_z$ candidate reflecting ports arranged on a planar aperture, among which only M_o ports are activated. The FRIS position candidates are represented by $\mathbf{s} = [s_1, \dots, s_M]^T$, where $s_m \in \{0, 1\}$ and $\sum_{m=1}^M s_m = M_o$. Let β_m and θ_m denote the amplitude and phase of the m -th element, respectively. Then, the effective reflection coefficient is given by

$$v_m = s_m \beta_m e^{j\theta_m}. \quad (1)$$

Accordingly, the reflection vector of the FRIS is expressed as

$$\mathbf{v} = \mathbf{s} \odot \boldsymbol{\beta} \odot e^{j\boldsymbol{\theta}}, \quad (2)$$

and the corresponding reflection matrix is given by $\boldsymbol{\Theta} = \text{diag}(\mathbf{v})$, where $\odot$ denotes the Hadamard product.

Since the FRIS candidate ports are densely arranged, we account for the spatial correlation among candidate positions. Denote by $d_{i,j}$ the distance between the i -th and j -th candidate positions. According to the Jakes' model [8], the spatial correlation coefficient is modeled as

$$[\mathbf{J}]_{i,j} = J_0\left(\frac{2\pi d_{i,j}}{\lambda}\right), \quad (3)$$

where $J_0(\cdot)$ denotes the zeroth-order Bessel function of the first kind, and λ is the wavelength. Let $\mathbf{h}_{AF}$, $\mathbf{h}_{FB}$, and $\mathbf{h}_{FW}$ be the small-scale fading vectors before spatial correlation is applied. Accordingly, the spatially correlated channels are

expressed as $\mathbf{J}^{1/2}\mathbf{h}_{AF}$, $\mathbf{h}_{FB}^H\mathbf{J}^{1/2}$, and $\mathbf{h}_{FW}^H\mathbf{J}^{1/2}$, respectively. The equivalent channels from Alice to Bob and Willie are defined as

$$H_B(\mathbf{v}) = h_{ab} + \sqrt{L_{AF}L_{FB}}\mathbf{h}_{FB}^H\mathbf{J}^{1/2}\boldsymbol{\Theta}\mathbf{J}^{1/2}\mathbf{h}_{AF}, \quad (4)$$

$$H_W(\mathbf{v}) = h_{aw} + \sqrt{L_{AF}L_{FW}}\mathbf{h}_{FW}^H\mathbf{J}^{1/2}\boldsymbol{\Theta}\mathbf{J}^{1/2}\mathbf{h}_{AF}. \quad (5)$$

Alice transmits a covert information symbol x with transmit power P_A , where $\mathbb{E}[|x|^2] = 1$. Then, the received signal at Bob can be expressed as

$$y_B = \sqrt{P_A}H_B(\mathbf{v})x + \sqrt{L_{FB}}\mathbf{h}_{FB}^H\mathbf{J}^{1/2}\boldsymbol{\Theta}\mathbf{n}_F + n_B. \quad (6)$$

Therefore, the covert rate at Bob is written as

$$R_B = \log_2 \left(1 + \frac{P_A |H_B(\mathbf{v})|^2}{\sigma_F^2 L_{FB} |\mathbf{h}_{FB}^H\mathbf{J}^{1/2}\boldsymbol{\Theta}|^2 + \sigma_B^2} \right). \quad (7)$$

B. Covertness and Power Constraints

Since the FRIS amplifies both the signal from Alice and the internal thermal noise, the power constraint is computed as

$$P_A L_{AF} |\boldsymbol{\Theta}\mathbf{J}^{1/2}\mathbf{h}_{AF}|^2 + \sigma_F^2 |\boldsymbol{\Theta}|_F^2 \leq P_F^{\max}. \quad (8)$$

The FRIS operates in synchronization with Alice's transmission, and Willie performs a binary hypothesis test to determine whether Alice is transmitting. The received signal at Willie is given by

$$y_W = \begin{cases} n_W, & \mathcal{H}_0, \\ \sqrt{P_A}H_W(\mathbf{v})x + \sqrt{L_{FW}}\mathbf{h}_{FW}^H\mathbf{J}^{1/2}\boldsymbol{\Theta}\mathbf{n}_F + n_W, & \mathcal{H}_1, \end{cases} \quad (9)$$

where $\mathcal{H}_0$ and $\mathcal{H}_1$ denote the hypotheses that Alice is silent, and Alice transmits, respectively. Let p_0 and p_1 denote the received distributions at Willie under $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively. The covertness constraint based on the Kullback-Leibler (KL) divergence [14] is imposed as

$$D(p_0|p_1) \leq 2\epsilon^2, \quad (10)$$

where ϵ is a parameter that characterizes the strictness of the covertness constraint. Since $p_0 = \mathcal{CN}(0, \sigma_W^2)$ and $p_1 = \mathcal{CN}(0, \sigma_{W,1}^2)$, the KL divergence is given by

$$D(p_0|p_1) = \ln \left(\frac{\sigma_{W,1}^2}{\sigma_W^2} \right) + \frac{\sigma_W^2}{\sigma_{W,1}^2} - 1. \quad (11)$$

By introducing $\kappa \geq 1$ satisfying $\ln \kappa + 1/\kappa - 1 = 2\epsilon^2$, the covertness constraint can be rewritten as

$$P_A |H_W(\mathbf{v})|^2 + \sigma_F^2 L_{FW} |\mathbf{h}_{FW}^H\mathbf{J}^{1/2}\boldsymbol{\Theta}|^2 \leq (\kappa - 1)\sigma_W^2. \quad (12)$$

III. PROPOSED JOINT OPTIMIZATION FRAMEWORK

A. Problem Formulation

In this paper, we jointly design Alice's transmit power P_A , the optimal FRIS position selection vector $\mathbf{s}$, and the amplitude and phase coefficients of the activated elements, $\boldsymbol{\beta}$ and $\boldsymbol{\theta}$, to maximize the covert rate at Bob. Accordingly, the optimization

problem to be solved by the proposed scheme is formulated as

$$(P0): \max_{P_A, \mathbf{s}, \boldsymbol{\beta}, \boldsymbol{\theta}} R_B = \log_2 \left(1 + \frac{P_A |H_B(\mathbf{v})|^2}{\sigma_F^2 L_{FB} |\mathbf{h}_{FB}^H \mathbf{J}^{1/2} \boldsymbol{\Theta}|^2 + \sigma_B^2} \right) \quad (13a)$$

$$\text{s.t. } 0 \leq P_A \leq P_A^{\max}, \quad (13b)$$

$$P_A L_{AF} |\boldsymbol{\Theta} \mathbf{J}^{1/2} \mathbf{h}_{AF}|^2 + \sigma_F^2 |\boldsymbol{\Theta}|_F^2 \leq P_F^{\max}, \quad (13c)$$

$$P_A |H_W(\mathbf{v})|^2 + \sigma_F^2 L_{FW} |\mathbf{h}_{FW}^H \mathbf{J}^{1/2} \boldsymbol{\Theta}|^2 \leq (\kappa - 1) \sigma_W^2, \quad (13d)$$

$$0 \leq \beta_m \leq \beta_{\max}, \quad m = 1, \dots, M, \quad (13e)$$

$$\theta_m \in [0, 2\pi), \quad m = 1, \dots, M. \quad (13f)$$

Here, $P_A^{\max}$ denotes the maximum transmit power of Alice, and $P_F^{\max}$ denotes the maximum power budget of the FRIS.

Problem (P0) is a mixed-integer non-convex problem in which the binary FRIS element selection vector $\mathbf{s}$ is coupled with the continuous variables, namely the transmit power P_A , amplitudes $\boldsymbol{\beta}$, and phases $\boldsymbol{\theta}$. In particular, since the FRIS power constraint and the covertness constraint depend on both P_A and $\mathbf{v}$, it is difficult to solve (P0) directly. Therefore, this paper adopts an alternating optimization-cross entropy optimization-semidefinite relaxation (AO-CEO-SDR) algorithm, in which P_A , $\mathbf{s}$, and $\mathbf{v}$ are alternately updated.

B. Transmit Power Optimization

We first consider the transmit power optimization for a fixed FRIS reflection vector $\mathbf{v}$. In this case, the equivalent channels at Bob and Willie are fixed, and the covert rate R_B monotonically increases with P_A . Hence, the optimal transmit power of Alice is obtained as the largest value satisfying Alice's maximum transmit power constraint, the FRIS power constraint, and the covertness constraint at Willie.

For algorithm design, $H_B(\mathbf{v})$ and $H_W(\mathbf{v})$ are rewritten as

$$H_B(\mathbf{v}) = h_{ab} + \sqrt{L_{AF} L_{FB}} \mathbf{c}_B^H \mathbf{v}, \quad (14)$$

$$H_W(\mathbf{v}) = h_{aw} + \sqrt{L_{AF} L_{FW}} \mathbf{c}_W^H \mathbf{v}, \quad (15)$$

where $\mathbf{c}_B$ and $\mathbf{c}_W$ denote the equivalent cascaded channel vectors composed of the Alice-FRIS channel and the FRIS-Bob/Willie channels, respectively. Furthermore, we define the diagonal matrices representing the FRIS input signal power and the FRIS noise leakage as $\mathbf{D}_A = L_{AF} \text{diag}(|[\mathbf{u}_A]_1|^2, \dots, |[\mathbf{u}_A]_M|^2)$ and $\mathbf{D}_W = L_{FW} \text{diag}(|[\mathbf{r}_W]_1|^2, \dots, |[\mathbf{r}_W]_M|^2)$, respectively. Then, from the FRIS power constraint, we obtain

$$P_A \leq \frac{P_F^{\max} - \sigma_F^2 \mathbf{v}^H \mathbf{v}}{\mathbf{v}^H \mathbf{D}_A \mathbf{v}} \triangleq P_F(\mathbf{v}). \quad (16)$$

Similarly, from the covertness constraint, we obtain

$$P_A \leq \frac{(\kappa - 1) \sigma_W^2 - \sigma_F^2 \mathbf{v}^H \mathbf{D}_W \mathbf{v}}{|H_W(\mathbf{v})|^2} \triangleq P_C(\mathbf{v}). \quad (17)$$

Therefore, the optimal transmit power of Alice for a fixed $\mathbf{v}$ is given by

$$P_A^*(\mathbf{v}) = [\min\{P_A^{\max}, P_F(\mathbf{v}), P_C(\mathbf{v})\}]^+, \quad (18)$$

where $[x]^+ = \max\{x, 0\}$. If either $P_F(\mathbf{v})$ or $P_C(\mathbf{v})$ is negative, the corresponding FRIS configuration is infeasible.

Next, for fixed Alice transmit power P_A and FRIS element selection $\mathbf{s}$, we optimize the reflection vector $\mathbf{v}$ of the activated elements. By defining the diagonal matrix representing the FRIS noise term toward Bob as $\mathbf{D}_B = L_{FB} \text{diag}(|[\mathbf{r}_B]_1|^2, \dots, |[\mathbf{r}_B]_M|^2)$, the reflection coefficient optimization problem for a fixed $\mathbf{s}$ is formulated as

$$(P1): \max_{\mathbf{v}} \frac{P_A |H_B(\mathbf{v})|^2}{\sigma_F^2 \mathbf{v}^H \mathbf{D}_B \mathbf{v} + \sigma_B^2} \quad (19a)$$

$$\text{s.t. } P_A \mathbf{v}^H \mathbf{D}_A \mathbf{v} + \sigma_F^2 \mathbf{v}^H \mathbf{v} \leq P_F^{\max}, \quad (19b)$$

$$P_A |H_W(\mathbf{v})|^2 + \sigma_F^2 \mathbf{v}^H \mathbf{D}_W \mathbf{v} \leq (\kappa - 1) \sigma_W^2, \quad (19c)$$

$$|v_m|^2 \leq s_m \beta_{\max}^2, \quad m = 1, \dots, M. \quad (19d)$$

The constraint $|v_m|^2 \leq s_m \beta_{\max}^2$ ensures that $v_m = 0$ for inactive elements with $s_m = 0$, while the amplification gain of each activated element with $s_m = 1$ is limited by $\beta_{\max}$.

Problem (P1) is non-convex because its objective function is fractional and it includes quadratic constraints with respect to $\mathbf{v}$. To address this difficulty, we introduce an augmented vector $\bar{\mathbf{v}} = [\mathbf{v}^T, 1]^T$ and a lifted matrix $\mathbf{V} = \bar{\mathbf{v}} \bar{\mathbf{v}}^H$. Originally, $\mathbf{V}$ should satisfy $\mathbf{V} \succeq 0$ and $\text{rank}(\mathbf{V}) = 1$; however, the rank-one constraint is non-convex. In semidefinite relaxation (SDR), this rank-one constraint is relaxed, and only $\mathbf{V} \succeq 0$ is imposed. Furthermore, by applying the Charnes-Cooper transformation $\mathbf{Y} = \tau \mathbf{V}$, $\tau > 0$, the denominator is normalized as

$$\sigma_F^2 \text{tr}(\bar{\mathbf{D}}_B \mathbf{Y}) + \sigma_B^2 \tau = 1. \quad (20)$$

Here, $\bar{\mathbf{D}}_B$ denotes the augmented matrix corresponding to $\mathbf{D}_B$. Similarly, $\bar{\mathbf{D}}_A$, $\bar{\mathbf{D}}_W$, and $\bar{\mathbf{I}}$ are defined. In addition, let $\mathbf{A}_B = \bar{\mathbf{c}}_B \bar{\mathbf{c}}_B^H$ and $\mathbf{A}_W = \bar{\mathbf{c}}_W \bar{\mathbf{c}}_W^H$. Then, the relaxed SDR problem is formulated as

$$(P2): \max_{\mathbf{Y}, \tau} P_A \text{tr}(\mathbf{A}_B \mathbf{Y}) \quad (21a)$$

$$\text{s.t. } \sigma_F^2 \text{tr}(\bar{\mathbf{D}}_B \mathbf{Y}) + \sigma_B^2 \tau = 1, \quad (21b)$$

$$P_A \text{tr}(\bar{\mathbf{D}}_A \mathbf{Y}) + \sigma_F^2 \text{tr}(\bar{\mathbf{I}} \mathbf{Y}) \leq \tau P_F^{\max}, \quad (21c)$$

$$P_A \text{tr}(\mathbf{A}_W \mathbf{Y}) + \sigma_F^2 \text{tr}(\bar{\mathbf{D}}_W \mathbf{Y}) \leq \tau (\kappa - 1) \sigma_W^2, \quad (21d)$$

$$[\mathbf{Y}]_{M+1, M+1} = \tau, \quad (21e)$$

$$[\mathbf{Y}]_{m, m} \leq \tau \beta_{\max}^2 s_m, \quad m = 1, \dots, M, \quad (21f)$$

$$\mathbf{Y} \succeq 0, \quad \tau > 0. \quad (21g)$$

Problem (P2) is a semidefinite programming problem and can be solved by convex optimization solvers. If the obtained solution is rank-one, the corresponding reflection vector $\mathbf{v}$ can be directly recovered. Otherwise, a feasible $\mathbf{v}$ is recovered using Gaussian randomization or an approximation based on the principal eigenvector.

C. FRIS Position Selection via CEO

The FRIS position selection vector $\mathbf{s}$ is a binary variable, and an exhaustive search requires evaluating $\binom{M}{M_o}$ possible candidates. This becomes impractical when M and M_o are large. Therefore, in this paper, we employ cross-entropy optimization (CEO) to stochastically search for a set of positions that improves the covert rate.

Let p_m denote the selection probability of the m -th candidate position, and let $\mathbf{p} = [p_1, p_2, \dots, p_M]^T$ be the selection probability vector. At each CEO iteration ℓ , according to $\mathbf{p}^{(\ell)}$, M_o distinct candidate positions are sampled without replacement to generate K feasible selection vectors $\{\mathbf{s}^{(k)}\}_{k=1}^K$. For each candidate $\mathbf{s}^{(k)}$, problem (P2) is solved to optimize the reflection coefficients, and the corresponding covert rate $R_B^{(k)}$ is then evaluated. The obtained candidates are sorted in descending order of $R_B^{(k)}$, and the top K_e candidates are selected as the elite set $\mathcal{E}$. The empirical selection frequency of the m -th position in the elite set is defined as

$$\hat{p}_m = \frac{1}{K_e M_o} \sum_{\mathbf{s}^{(k)} \in \mathcal{E}} s_m^{(k)}. \quad (22)$$

To avoid premature convergence, the selection probability is updated using the smoothing factor α_{ce} as

$$p_m^{(\ell+1)} = (1 - \alpha_{ce})p_m^{(\ell)} + \alpha_{ce}\hat{p}_m. \quad (23)$$

With this update, position sets that enhance the effective channel to Bob while suppressing leakage to Willie are increasingly likely to be selected.

D. Overall AO-CEO-SDR Algorithm and Convergence

The overall procedure of the proposed AO-CEO-SDR algorithm is summarized in Algorithm 1. In the outer alternating optimization (AO) loop, Alice's transmit power is updated in closed form for the current FRIS configuration, and then the FRIS position selection and reflection coefficients are updated with the transmit power held fixed. In the inner CEO loop, multiple candidate position selections are generated, and the reflection coefficients are optimized via SDR for each candidate. Then, the selection probabilities are updated based on the elite set.

Since the CEO is a stochastic search method, the proposed algorithm does not guarantee global optimality for the original mixed-integer non-convex problem. Therefore, this paper retains the best feasible solution obtained over the CEO and AO iterations. Let $R_{\text{best}}^{(t)}$ denote the best covert rate recorded after the t -th AO iteration, and let $R_{\text{cand}}^{(t)}$ denote the rate of the best candidate obtained in the current iteration. Then, we have

$$R_{\text{best}}^{(t+1)} = \max\{R_{\text{best}}^{(t)}, R_{\text{cand}}^{(t)}\} \geq R_{\text{best}}^{(t)}. \quad (24)$$

Therefore, the recorded best objective value is monotonically non-decreasing. Moreover, since P_A , the FRIS power, and the reflection amplitudes are bounded by the constraints, the achievable covert rate is also upper-bounded. Consequently, $R_{\text{best}}^{(t)}$ converges to a finite value.

Algorithm 1 Proposed AO-CEO-SDR Algorithm

Require: Channel coefficients, $\mathbf{J}$, $P_A^{\max}$, $P_F^{\max}$, ϵ , M_o , $\beta_{\max}$, CEO parameters.

Ensure: P_A , $\mathbf{s}$, β , θ .

- 1: Initialize $\mathbf{s}^{(0)}$, $\beta^{(0)}$, $\theta^{(0)}$, $\mathbf{p}^{(0)}$, and $R_{\text{best}} = 0$.
- 2: **repeat**
- 3: Construct $\mathbf{v}^{(t)} = \mathbf{s}^{(t)} \odot \beta^{(t)} \odot e^{j\theta^{(t)}}$.
- 4: Update $P_A^{(t+1)} = P_A(\mathbf{v}^{(t)})$.
- 5: **repeat**
- 6: Generate K feasible selections $\{\mathbf{s}^{(k)}\}_{k=1}^K$ according to $\mathbf{p}$.
- 7: Solve (P2) for each $\mathbf{s}^{(k)}$ and evaluate $R_B^{(k)}$.
- 8: Select the top K_e candidates and update $\mathbf{p}$.
- 9: **until** CEO convergence
- 10: Select the best candidate and update the best feasible solution.
- 11: **until** AO convergence
- 12: Return P_A , $\mathbf{s}$, β , and θ .

IV. SIMULATION RESULTS

In this section, we present numerical results to evaluate the performance of the proposed scheme. In the simulations, the locations of Alice, Bob, Willie, and the FRIS/RIS are set to $(0, 0)$, $(100, 0)$, $(80, -10)$, and $(50, 30)$, respectively. The carrier frequency is set to $f_c = 2.4$ GHz, and the noise powers at Bob, Willie, and the FRIS are all set to -80 dBm. The spatial correlation among the FRIS candidate elements is computed using the Jakes correlation model in (3). Unless otherwise specified, the covertness constraint is set to $\epsilon = 0.1$. We compare the proposed scheme with two benchmark schemes: random FRIS and conventional RIS [7]. Random FRIS selects the FRIS position at random and optimizes the remaining value. The RIS benchmark uses uniformly deployed reflecting elements over the same physical aperture.

Fig. 2(a) shows the average covert rate versus the maximum transmit power of Alice, $P_A^{\max}$. Here, we set $M_{\text{total}} = 16$ and $M_o = 4$. The proposed optimized FRIS scheme achieves the highest covert rate among all the schemes. This is because the proposed scheme jointly optimizes the FRIS element positions, reflection coefficients, and transmit power, thereby enhancing the effective channel toward Bob while suppressing signal leakage toward Willie. In addition, the random FRIS scheme outperforms the RIS scheme in some cases, indicating that the spatial degrees of freedom inherent in the FRIS contribute to improved covert communication performance. On the other hand, the clear performance gap between the optimized and random FRIS schemes demonstrates the importance of optimizing position selection to fully exploit the FRIS's potential.

Fig. 2(b) shows the average covert communication rate when the number of candidate FRIS elements is fixed at $M_{\text{total}} = 64$, and the number of activated elements M_o is varied. The proposed optimized FRIS scheme achieves a higher covert rate than the RIS scheme for all values of M_o . This is because the FRIS has degrees of freedom to select reflection positions

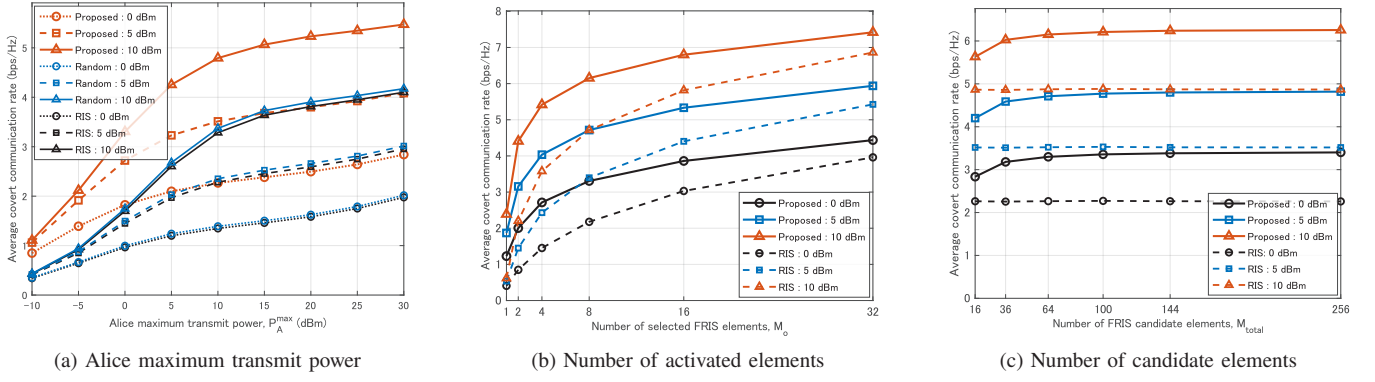


Fig. 2. Average covert communication rate under different system parameters.

in addition to controlling amplitudes and phases. However, as M_o becomes large relative to M_{total} , the freedom to select only particularly favorable elements from the candidate elements is relatively reduced. It can also be observed that the gain of the optimized FRIS scheme is more pronounced in the region where a small number of activated elements is used.

Fig. 2(c) shows the average covert rate when the number of activated elements is fixed at $M_o = 8$ and the number of candidate FRIS elements M_{total} is varied. The proposed scheme achieves a higher average covert rate as M_{total} increases, since more candidate elements provide greater spatial flexibility for forming favorable reflected links while mitigating leakage to the warden. However, the performance improvement gradually decreases as M_{total} becomes large, and the rate tends to saturate. In the RIS scheme, because fixed reflecting elements are used, the average covert rate remains nearly unchanged when the number and arrangement of the elements do not change, even as M_{total} increases.

V. CONCLUSION

In this paper, we investigated an FRIS-assisted covert communication system in which Alice transmits confidential information to Bob via an FRIS in the presence of Willie. To improve the covert rate, we formulated a joint optimization problem for Alice's transmit power, FRIS element selection, and reflection coefficients, subject to the FRIS power constraint and the covertness constraint. Since the formulated problem is a mixed-integer non-convex problem, we employed an AO-CEO-SDR algorithm that combines closed-form transmit power control, CEO-based element selection, and SDR-based reflection coefficient optimization. Numerical simulation results demonstrated that the proposed optimized FRIS scheme achieves a higher average covert rate than the random FRIS scheme and the conventional RIS scheme.

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