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UAV-IRS Assisted Covert Communication: Introducing Uncertainty via Phase Shifting

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Abstract—The line-of-sight (LoS) channels introduced by unmanned aerial vehicle (UAV) may lead to the threat of being detected, and thus fail the covert communication. This can be solved by intelligent reflection surface (IRS) to introduce additional randomness. In this letter, we propose a novel scheme via a UAV carrying an IRS to establish air-ground links to assist the covert transmission, where the phase shifts of IRS are randomized to preserve the covertness. In addition, the legitimate receiver can act as a jammer in the full-duplex mode to defuse the detection of a warden. An optimal detection threshold and the corresponding error detection probability are derived. Under this worst situation, the optimal transmit-to-jamming ratio is obtained to maximize the achievable transmission rate. Simulation results are presented to show the effectiveness of the proposed UAV-IRS assisted covert communication scheme.

Index Terms—Covert communication, intelligent reflecting surface, random phase shifting, unmanned aerial vehicle.

I. INTRODUCTION

Wireless links can result in the leakage of information. Different from physical layer security and encryption preventing decoding of malicious users, covert communication can provide another direction to realize the secure transmission [1]. In covert communications, the transmitter adopts different strategies to guarantee that the received signal varies randomly at the warden, and the covertness can be achieved. The very fundamental research in [2] has brought the blooming of covert communication related research, in which Bash *et al.* derived the square root limits. After this, a lot of research has been conducted regarding the practical scenarios [3], [4]. In [3], Chen *et al.* investigated the covert communication with the uncertain location of warden. In [4], Zheng *et al.* proposed to realize covert communication with the help of dynamically selected friendly jammers. Nevertheless, the channel may be blocked when the users are on the ground.

Unmanned aerial vehicle (UAV) has emerged as a potential multifunctional platform, owing to its characteristics of high mobility [5], easy configuration [6], and low cost [7], through which covert communication can overcome the terrestrial

blockage and provide better transmission [6], [8], [9]. Yan *et al.* utilized the UAV as a transmitter in [8] to conduct the covert communication, where the location and transmit power were jointly optimized to guarantee the covertness. Chen *et al.* applied a UAV relay in [6] to assist the covert transmission, where the covertness performance was investigated with Rician channel fading. In [9], Jiang *et al.* utilized the mobility of UAV to introduce randomness to Willie to achieve the covert transmission with terrestrial users.

However, the air-ground line-of-sight (LoS) links can not only benefit the legitimate transmission but also be leveraged by malicious wardens, leading to the deterioration or even failure of covert communications. Intelligent reflection surface (IRS) can tune the channel gains by adjusting the phase shifting matrix [10], [11]. It can be deployed near the transmitter to achieve a higher channel gain via adjusting its phase reflection coefficients without extra active relaying power required [12]–[14]. Therefore, the IRS carried by UAV can help to overcome the channel blockage and improve received signal power at each receiver in covert communications [5], [15], [16]. Lu *et al.* discussed different functions of IRS in covert communications in [5]. In [15], Wang *et al.* employed a UAV-IRS in a covert communication network to overcome the channel blockage between Alice and Bob, where the location uncertainty of Willie was investigated. In [16], Tatar Mamaghani and Hong studied the IRS-aided covert communication in a Terahertz UAV network, where the transmit and jamming power was randomized to introduce uncertainty to avoid detection.

Except for the advantages mentioned above, IRS can also be utilized to introduce randomness to the warden via randomizing its phase shifting matrix. This can help to overcome the risk brought by the LoS channels. In this letter, a UAV-IRS assisted covert communication scheme with a full-duplex receiver as the jammer is proposed, in which the random phase shifting matrix is randomly generated to introduce uncertainty. First, we analyze the error detection probability at the warden under the random phase shifts. Then, we derive the optimal detection threshold and the corresponding minimum error detection probability. Finally, we obtained the optimal transmit-to-jamming power ratio to maximize the achievable rate while meeting the covertness constraint.

II. SYSTEM MODEL

Consider that an IRS carried by a UAV is utilized to assist the covert communication from Alice to Bob to overcome

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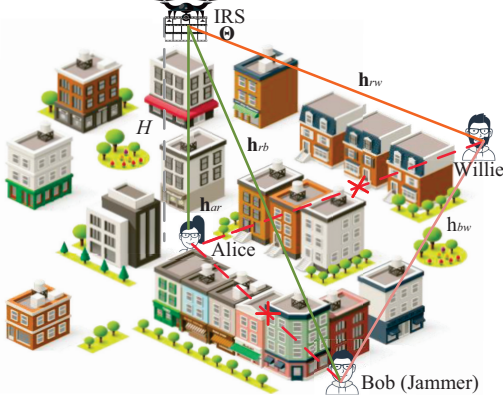


Fig. 1. UAV-IRS assisted covert communication.

the channel blockage, as shown in Fig. 1, where the direct channels from Alice to Bob and Willie are both blocked. Meanwhile, the IRS can leverage its phase shifts to introduce uncertainty to Willie. Assume that Alice a transmits to Bob b with the help of IRS r while avoiding the detection of Willie w , where the IRS is equipped on a UAV hovering at its lowest height H without blocks from other receivers. Owing to the multiplication of double path losses, i.e., from Alice to IRS and from IRS to Bob, the received signal will experience severe attenuation. A smaller composite path loss can be achieved when the IRS is closer to either Alice or Bob. Thus, we deploy the IRS just above Alice. Alice, Bob, Willie and IRS are located at $L_a = (x_a, y_a, z_a)$, $L_b = (x_b, y_b, 0)$, $L_w = (x_w, y_w, 0)$, and $L_r = (x_a, y_a, H)$, respectively.

Assume that Alice is equipped with a single transmit antenna and Willie has a single receiving antenna. Bob is equipped with two antennas, one for receiving and the other for jamming. He works in the full-duplex mode as a jammer to prevent Alice from being detected by Willie. Bob is jamming with the power of P_b , which also results in ϕP_b interference at himself. $0 < \phi \leq 1$ represents the portion of self-interference that cannot be eliminated. On the other hand, the IRS has N reflection elements, and its reflection matrix is denoted as $\Theta = \text{diag}(e^{j\theta_1}, \dots, e^{j\theta_N})$, where θ_i is the phase shift of the i th element. To guarantee the covertness of Alice's transmission, the IRS is designed to change its phase shifting matrix randomly, and we have $\Theta_{ii} \sim \mathcal{CN}(0, 1)$, $i = \{1, \dots, N\}$.

Assume that all of the air-ground channels follow LoS as

$$\mathbf{h}_{ij} = \sqrt{\frac{\rho_0}{d_{ij}^\alpha}} \mathbf{g}_{ij}, i, j \in \{ar, rw, rb\}, \quad (1)$$

where ρ_0 is the reference power gain at the distance of 1 m, d_{ij} denotes the distance between i and j , α is the air-ground path-loss exponent, and $\mathbf{g}_{ij}$ represents the link vector between i and j , i.e., $\mathbf{g}_{rw} \in \mathbb{C}^{1 \times N}$, $\mathbf{g}_{rb} \in \mathbb{C}^{1 \times N}$ and $\mathbf{g}_{ar} \in \mathbb{C}^{N \times 1}$. In addition, we have $|g_{ijk}| = 1$, $k = \{1, \dots, N\}$. The channel coefficient between Bob and Willie follows the large-scale path loss and quasi-static small-scale block Rayleigh fading, which can be described as

$$h_{bw} = \sqrt{\frac{\rho_0}{d_{bw}^\alpha}} g_{bw}, \quad (2)$$

where g_{bw} follows a complex Gaussian distribution with zero mean and unit variance. h_{bb} denotes the self-interference channel gain at Bob with $|h_{bb}| = 1$. Owing to the LoS channels, we assume that $\mathbf{h}_{rw}$, $\mathbf{h}_{rb}$ and $\mathbf{h}_{ar}$ are known at each node.

Alice transmits the signal $x[n]$ to Bob during each time slot with the transmit power P_a on the probability of π_1 , and Bob constantly emits the jamming signal $x_b[n]$ with the power P_b , where $\mathbb{E}(|x[n]|) = 1$ and $\mathbb{E}(|x_b[n]|) = 1$. Thus, the received signal at Bob can be described as

$$y_b[n] = \sqrt{P_a} \mathbf{h}_{rb} \Theta \mathbf{h}_{ar} x[n] + \sqrt{\phi P_b} h_{bb} x_b[n] + n_b[n], \quad (3)$$

where $n_b[n] \sim \mathcal{CN}(0, \sigma_b^2)$ is the additive white Gaussian noise (AWGN) received at Bob and follows.

Accordingly, the received signal-to-interference-plus-noise ratio (SINR) at Bob can be expressed as

$$\gamma_b = \frac{P_a |\mathbf{h}_{rb} \Theta \mathbf{h}_{ar}|^2}{\phi P_b |h_{bb}|^2 + \sigma_b^2}, \quad (4)$$

and the achievable transmission rate R_b from Alice to Bob can be denoted as

$$R_b = \log(1 + \gamma_b). \quad (5)$$

On the other hand, the received signal at Willie is under two conditions, which are $\mathcal{H}_1$ when Alice is transmitting and $\mathcal{H}_0$ when Alice is being silent. Thus, it can be described as

$$y_w[n] = \begin{cases} \sqrt{P_a} \mathbf{h}_{rw} \Theta \mathbf{h}_{ar} x[n] + \sqrt{P_b} h_{bw} x_b[n] + n_w[n], & \mathcal{H}_1, \\ \sqrt{P_b} h_{bw} x_b[n] + n_w[n], & \mathcal{H}_0, \end{cases} \quad (6)$$

where $n_w[n]$ is the AWGN at Bob following $n_w[n] \sim \mathcal{CN}(0, \sigma_w^2)$. Without loss of generality, we assume that $\sigma_b^2 = \sigma_w^2 = \sigma^2$.

III. HYPOTHESIS DETECTION AT WILLIE

Willie monitors the received power P_w and makes the decision on whether Alice is transmitting or not by comparing P_w with the preset detection threshold τ . If the received power P_w is higher than τ , Willie confirms that Alice is transmitting ($\mathcal{D}_1$). Otherwise, Willie considers that Alice is being silent ($\mathcal{D}_0$). The decision rule can be expressed as

$$P_w = \lim_{K \rightarrow \infty} \frac{1}{K} \sum_{n=1}^K |y_w[k]|^2 \underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\gtrless}} \tau, \quad (7)$$

where P_w can be derived as

$$P_w = \begin{cases} P_a |\mathbf{h}_{rw} \Theta \mathbf{h}_{ar}|^2 + P_b |h_{bw}|^2 + \sigma^2, & \mathcal{H}_1, \\ P_b |h_{bw}|^2 + \sigma^2, & \mathcal{H}_0. \end{cases} \quad (8)$$

Thus, besides the channel noise, the uncertainties can be generated by both the random phase shifting of IRS and the jamming signal from Bob.

Then, the probability distribution of P_w is analyzed in Lemma 1 under the two cases of $\mathcal{H}_0$ and $\mathcal{H}_1$.

Lemma 1: The probability density function (PDF) of $P_w - \sigma^2$ can be derived as

$$f(z) = \begin{cases} \frac{\lambda_a \lambda_b (e^{-\lambda_b z} - e^{-\lambda_a z})}{\lambda_a - \lambda_b}, & \mathcal{H}_1, \\ \lambda_b e^{-\lambda_b z}, & \mathcal{H}_0, \end{cases} \quad (9)$$

where $z = P_w - \sigma^2$.

Proof. As we can see from (8), both $\mathbf{h}_{rw}$ and $\mathbf{h}_{ar}$ are fixed while Θ_{ii} follows the complex Gaussian distribution. In addition, based on the linear algebra, $|\mathbf{h}_{rw}\Theta\mathbf{h}_{ar}|^2$ can be changed into

$$|\mathbf{h}_{rw}\Theta\mathbf{h}_{ar}|^2 = |[\Theta_{11}, \Theta_{22}, \dots, \Theta_{NN}] \text{diag}(\mathbf{h}_{rw}) \mathbf{h}_{ar}|^2 = |\boldsymbol{\theta}\mathbf{h}_{arw}|^2, \quad (10)$$

where $\boldsymbol{\theta} = [\Theta_{11}, \Theta_{22}, \dots, \Theta_{NN}]$ and $\mathbf{h}_{arw} = \text{diag}(\mathbf{h}_{rw}) \mathbf{h}_{ar}$. According to the distribution of Θ_{ii} , we can obtain the distribution of $P_a|\mathbf{h}_{rw}\Theta\mathbf{h}_{ar}|^2$ as

$$P_a|\mathbf{h}_{rw}\Theta\mathbf{h}_{ar}|^2 \sim \exp\left(\frac{1}{\frac{\rho_0}{d_{rw}^\alpha} \frac{\rho_0}{d_{ar}^\alpha} P_a \lambda}\right) = \exp(\lambda_a), \quad (11)$$

where $\lambda = |\text{diag}(\mathbf{g}_{rw}) \mathbf{g}_{ar}|^2$ is fixed.

Similarly, owing to $h_{bw} \sim \mathcal{CN}(0, 1)$, the distribution of $P_b|h_{bw}|^2$ can be concluded as

$$P_b|h_{bw}|^2 \sim \exp\left(\frac{1}{P_b \frac{\rho_0}{d_{bw}^\alpha}}\right) = \exp(\lambda_b). \quad (12)$$

Thus, the PDF of $P_w - \sigma^2$ under the case $\mathcal{H}_0$ can be presented as

$$f(z) = \lambda_b e^{-\lambda_b z} \quad (\mathcal{H}_0). \quad (13)$$

Accordingly, the cumulative distribution function (CDF) of $P_w - \sigma^2$ under the case $\mathcal{H}_1$ can be calculated as¹

$$\begin{aligned} F(z) &= \int_0^z \int_0^{-A+z} f(A)f(B) dA dB \\ &= 1 - \frac{\lambda_a e^{-\lambda_b z} - \lambda_a e^{-\lambda_a z}}{\lambda_a - \lambda_b}, \end{aligned} \quad (14)$$

where $z = A + B$, $A = P_a|\mathbf{h}_{rw}\Theta\mathbf{h}_{ar}|^2$ and $B = P_b|h_{bw}|^2$.

Then, we can derive the first-order derivative of $F(z)$ with respect to z as

$$f(z) = \frac{\lambda_a \lambda_b (e^{-\lambda_b z} - e^{-\lambda_a z})}{\lambda_a - \lambda_b} \quad (\mathcal{H}_1). \quad (15)$$

Lemma 1 is proved. $\square$

Furthermore, Willie may make mistakes when performing the detection, owing to the uncertainty brought by the legitimate system. There are two types of detection mistakes, i.e., false alarm (FA) and miss detection (MD). The probability of FA α is defined as that even though Alice is transmitting, Willie decides that Alice is being silent $\mathcal{D}_0$ according to the received power. On the other hand, the MD probability β is that when Alice is being silent, Willie decides that there is transmission going on $\mathcal{D}_1$. Thus, the error detection probability ξ can be concluded as the probability summation of FA and MD as

$$\xi = \alpha + \beta = \pi_1 \mathbb{P}\{\mathcal{D}_1|\mathcal{H}_0\} + (1 - \pi_1) \mathbb{P}\{\mathcal{D}_0|\mathcal{H}_1\}, \quad (16)$$

where $\mathbb{P}\{c|d\}$ represents the probability of c being true under the condition of d .

¹The probability of $\lambda_a = \lambda_b$ is extremely small, which is not discussed here.

According to Lemma 1 and the definition of FA, we can calculate α as

$$\begin{aligned} \alpha &= \mathbb{P}\{\mathcal{D}_0|\mathcal{H}_1\} = \mathbb{P}\{P_w \geq \tau|\mathcal{H}_0\} \\ &= \mathbb{P}\{P_b|h_{bw}|^2 + \sigma^2 \geq \tau\} = e^{-\lambda_b(\tau - \sigma^2)}. \end{aligned} \quad (17)$$

On the other hand, the probability of Willie making MD can be calculated as

$$\begin{aligned} \mathbb{P}\{\mathcal{D}_1|\mathcal{H}_0\} &= \mathbb{P}\{P_w \leq \tau|\mathcal{H}_0\} \\ &= \mathbb{P}\{P_a|\mathbf{h}_{rw}\Theta\mathbf{h}_{ar}|^2 + P_b|h_{bw}|^2 + \sigma^2 \leq \tau\} \\ &= \frac{\lambda_a \lambda_b}{\lambda_a - \lambda_b} \left(-\frac{1}{\lambda_b} e^{-\lambda_b x} + \frac{1}{\lambda_a} e^{-\lambda_a x} \right) \Big|_0^{\tau - \sigma^2} \\ &= 1 + \frac{\lambda_b e^{-\lambda_a(\tau - \sigma^2)} - \lambda_a e^{-\lambda_b(\tau - \sigma^2)}}{\lambda_a - \lambda_b}. \end{aligned} \quad (18)$$

Then, we analyze the error detection probability at Willie and obtain the optimal power detection threshold in Proposition 1.

Proposition 1: The optimal detection threshold τ^* of Willie can be concluded as

$$\tau^* = \frac{\log \lambda_a - \log \lambda_b}{\lambda_a - \lambda_b} + \sigma^2, \quad (19)$$

and the consequent optimal error detection probability ξ^* can be described as

$$\xi^* = 1 - t^{\frac{1}{1-t}}, \quad (20)$$

where $t = \frac{\lambda_b}{\lambda_a}$.

Proof. Willie needs to adjust the detection threshold τ properly to minimize his error detection probability ξ . To derive the optimal τ , we analyze the monotonicity of ξ . With the definitions in (16), (17) and (18), we have the first-order derivative of ξ with respect to τ as

$$\begin{aligned} \xi'(\tau) &= \frac{\lambda_a \lambda_b}{\lambda_a - \lambda_b} \left(e^{-\lambda_b(\tau - \sigma^2)} - e^{-\lambda_a(\tau - \sigma^2)} \right) \\ &\quad - \lambda_b e^{-\lambda_b(\tau - \sigma^2)}. \end{aligned} \quad (21)$$

According to the definitions of λ_a and λ_b in (11) and (12), respectively, when $\xi'(\tau) \geq 0$, we have

$$\tau \geq \frac{\log \lambda_a - \log \lambda_b}{\lambda_a - \lambda_b} + \sigma^2. \quad (22)$$

Therefore, we can know that ξ decreases when $\tau \leq \tau^*$, while increasing when $\tau \geq \tau^*$. Then, we can conclude that when $\tau = \tau^*$ as shown in (19), the minimum ξ can be derived as (20). $\square$

According to Proposition 1, Willie can change his detection threshold, which does not have to be the optimal value listed in (19). However, the optimal one in (19) can lead to the minimum error detection probability, which is the worst case for the legitimate system.

IV. COVERT COMMUNICATION STRATEGY

In this section, we analyze the maximum achievable transmission rate of Alice with respect to the transmit-to-jamming power ratio under the constraint of error detection probability larger than $1 - \epsilon$.

A. Problem Formulation

We aim to maximize the achievable transmission rate via jointly adjusting the transmit power of Alice and the jamming power of Bob to guarantee the error detection probability at Willie larger than $1 - \epsilon$. Therefore, the optimization problem can be formulated as

$$\mathbf{P} \ 1: \max_{P_a, P_b} R_b \quad (23a)$$

$$s.t. \quad P_a \leq P_{a_{max}}, \quad (23b)$$

$$P_b \leq P_{b_{max}}, \quad (23c)$$

$$\xi^* \geq 1 - \epsilon, \quad (23d)$$

where $P_{a_{max}}$ and $P_{b_{max}}$ are the maximum transmit and jamming power, respectively. $1 - \epsilon$ represents the minimum allowed error detection threshold.

From the definition of R_b and ξ^* , we can see that both R_b and ξ are related to P_a and P_b , leading to the coupling in the optimization. Therefore, we first analyze the monotonicity of R_b and ξ with respect to P_a and P_b , respectively.

The worst situation is when Willie can achieve his minimum error detection probability as shown in (20). First, to guarantee (23d), the minimum ξ needs to be larger than $1 - \epsilon$. Therefore, P 1 can be changed into

$$\mathbf{P} \ 1.1: \max_{P_a, P_b} \log \left(1 + \frac{P_a |\mathbf{h}_{rb} \mathbf{\Theta} \mathbf{h}_{ar}|^2}{\phi P_b |h_{bb}|^2 + \sigma_b^2} \right) \quad (24a)$$

$$s.t. \quad P_a \leq P_{a_{max}}, \quad (24b)$$

$$P_b \leq P_{b_{max}}, \quad (24c)$$

$$1 - t^{\frac{1}{1-t}} \geq 1 - \epsilon. \quad (24d)$$

The first-order derivative of R_b with respect to P_a can be derived as

$$\frac{\partial R_b}{\partial P_a} = -\frac{1}{1 + \gamma_b} \frac{|\mathbf{h}_{rb} \mathbf{\Theta} \mathbf{h}_{ar}|^2}{\phi P_b |h_{bb}|^2 + \sigma_b^2}, \quad (25)$$

from which we can easily conclude that $\frac{\partial R_b}{\partial P_a} \geq 0$. This indicates that R_b monotonically increases with P_a . To achieve a higher R_b , a larger P_a is required.

Then, the first-order derivative of R_b with respect to P_b can be derived as

$$\frac{\partial R_b}{\partial P_b} = \frac{1}{1 + \gamma_b} \frac{P_a |\mathbf{h}_{rb} \mathbf{\Theta} \mathbf{h}_{ar}|^2 \phi |h_{bb}|^2}{(\phi P_b |h_{bb}|^2 + \sigma_b^2)^2}, \quad (26)$$

where we can conclude that $\frac{\partial R_b}{\partial P_b} \leq 0$. This indicates that a smaller P_b can lead to a higher R_b .

In conclusion, the achievable transmission rate R_b can be increased by either increasing P_a or decreasing P_b .

On the other hand, we can analyze the monotonicity of ξ^* with respect to P_a and P_b to evaluate their influence on ξ^* , respectively. The first-order derivative of ξ^* with respect to P_a can be derived as

$$\frac{\partial \xi^*}{\partial P_a} = \frac{t^{\frac{t}{1-t}} (t - t \ln t - 1)}{(1 - t)^2} \frac{\rho_0 \lambda d_{bw}^{\alpha_g}}{P_b d_{rw}^{\alpha} d_{ar}^{\alpha}}, \quad (27)$$

where $\frac{t^{\frac{t}{1-t}} (t - t \ln t - 1)}{(1 - t)^2} \leq 0$. Thus, we can conclude $\frac{\partial \xi^*}{\partial P_a} \leq 0$, which indicates that ξ^* monotonically decreases with P_a .

Then, the first-order derivative of ξ^* with respect to P_b can be expressed as

$$\frac{\partial \xi^*}{\partial P_b} = -\frac{t^{\frac{t}{1-t}} (t - t \ln t - 1)}{(1 - t)^2} \frac{P_a \rho_0 \lambda d_{bw}^{\alpha_g}}{P_b^2 d_{rw}^{\alpha} d_{ar}^{\alpha}}. \quad (28)$$

Similarly, we can conclude $\frac{\partial \xi^*}{\partial P_b} \geq 0$, which indicates that ξ^* increases with P_b . Therefore, to increase ξ^* , we need to increase P_b or to decrease P_a .

After the above monotonicity analysis, we can derive the optimal solution to P 1.1, as given in Proposition 2.

Proposition 2: The optimal P_a -to- P_b ratio for P 1.1 can be expressed as

$$\left(\frac{P_a}{P_b} \right)^* = \frac{d_{rw}^{\alpha} d_{ar}^{\alpha}}{\rho_0 \lambda d_{bw}^{\alpha_g}} \xi^{*-1} (1 - \epsilon), \quad (29)$$

where $\xi^{*-1} (1 - \epsilon)$ denotes the reverse function of $\xi^* (t) = 1 - \epsilon$.

Proof. We can observe that ξ^* decreases with $\frac{P_a}{P_b}$ while R_b increases with $\frac{P_a}{P_b}$. To achieve a larger R_b , we need to increase $\frac{P_a}{P_b}$, but it also leads to a smaller ξ^* , which results in the failure of covert communication.

Therefore, we derive the upper limit of $\frac{P_a}{P_b}$ with the constraint (24d) satisfied, as shown in (29). This will achieve the largest achievable R_b with the covertness requirement (24d) satisfied. Proposition 2 is proved. $\square$

Remark: Proposition 2 demonstrates the optimal ratio of P_a and P_b . The maximum achievable R_b can be still improved via properly increasing P_b . With the optimal $\left(\frac{P_a}{P_b} \right)^*$, γ_b can be described as

$$\gamma_b = \frac{\left(\frac{P_a}{P_b} \right)^* |\mathbf{h}_{rb} \mathbf{\Theta} \mathbf{h}_{ar}|^2}{\phi |h_{bb}|^2 + \frac{\sigma^2}{P_b}}. \quad (30)$$

From (30), we can see that with $\left(\frac{P_a}{P_b} \right)^*$ fixed, a larger R_b can be still achieved by increasing P_a and P_b together under the constraints of (23c) and (23d).

V. SIMULATION RESULTS

In this section, we present numerical results to evaluate the effectiveness of the proposed UAV-IRS assisted covert communication scheme. Simulation parameters are set as follows unless otherwise stated. The locations of Alice, Bob, Willie, and IRS are assumed to be $L_a = (0, 0, 50)$, $L_b = (200, 0, 0)$, $L_w = (200, 100, 0)$ and $L_r = (0, 0, 120)$ in meters. The maximum allowed transmit power of Alice is set to $P_{a_{max}} = 0.5$ W and the maximum allowed jamming power at Bob is set to $P_{b_{max}} = 0.5$ W. The variance of noise power at both Bob and Willie is $\sigma^2 = -130$ dBm. The reference channel gain at the distance of 1 m is $\rho_0 = -20$ dB. The air-ground path-loss and the ground-to-ground path-loss exponent are set to $\alpha = 2$ and $\alpha_g = 5$, respectively. The self-interference cancellation factor at Bob is set to $\phi = -90$ dB.

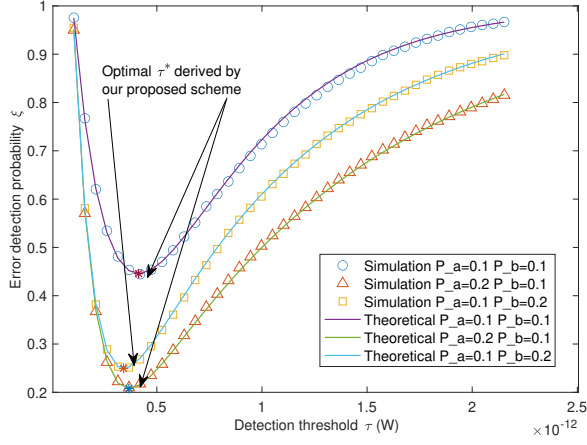


Fig. 2. Comparison of ξ under different value of τ , with different P_a and P_b considered.

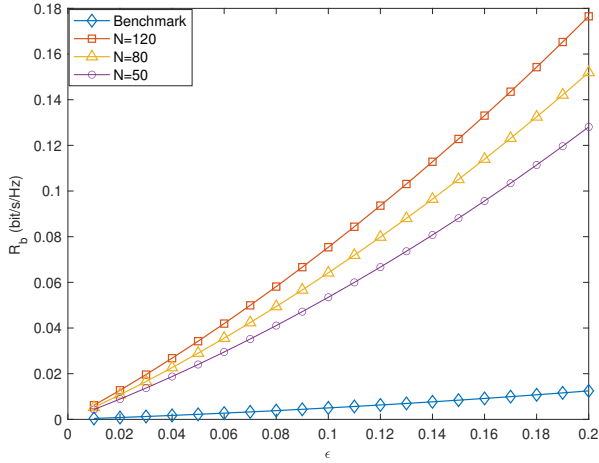


Fig. 3. Influence of ϵ and N on R_b , with a benchmark considered.

In Fig. 2, the impact of different power detection thresholds τ on the error detection probability ξ is investigated. The simulated and theoretical curves of ξ are also compared. From the results, we can see that the theoretical values can well match the simulated ones. In addition, the error detection probability ξ first decreases and then increases as τ gets larger. Furthermore, different cases of P_a and P_b also influence the results of ξ . The derived theoretically optimal detection threshold of each case matches the simulation results and lead to the minimum error detection probability accordingly.

The impact of ϵ on the maximum achievable transmission rate R_b is shown in Fig. 3, with different numbers of IRS elements. The optimal $\frac{P_a}{P_b}$ ratio is adopted in the simulation, where $P_a = 0.1$ W and P_b is set according to (29). From the results, we can see that the maximum achievable transmission rate R_b increases with ϵ . This is because bigger ϵ leads to less strict covertness constraint $1 - \epsilon$, and thus we can achieve higher R_b . In addition, a higher transmission rate can be achieved by increasing the number of reflection elements with the same covertness constraint ϵ . Finally, we compare with a benchmark to verify the effectiveness of our proposed scheme,

in which Alice adopts random power transmission and the UAV forwards its received signals without IRS. The results show that our proposed scheme can achieve a much higher transmission rate at Bob compared with the benchmark.

VI. CONCLUSION

This letter has proposed a UAV-IRS assisted covert communication scheme, where the random phase shifting is adopted at the IRS to introduce uncertainty and Bob performs full-duplex jamming to avoid detection. We first analyze the error detection probability, and then derive the closed-form detection threshold and the corresponding minimum error detection probability for Willie. Then, the transmit power and jamming power are jointly optimized under the worst situation with the optimal detection threshold of Willie. Simulation results are presented to evaluate the effectiveness of the proposed covert communication scheme.

REFERENCES

- [1] X. Chen, J. An, Z. Xiong, C. Xing, N. Zhao, F. R. Yu, and A. Nallanathan, "Covert communications: A comprehensive survey," *IEEE Communications Surveys & Tutorials*, vol. 25, no. 2, pp. 1173–1198, 2nd Quart. 2023.
- [2] B. A. Bash, D. Goeckel, and D. Towsley, "Limits of reliable communication with low probability of detection in AWGN channels," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 9, pp. 1921–1930, Sept. 2013.
- [3] X. Chen, W. Sun, C. Xing, N. Zhao, Y. Chen, F. R. Yu, and A. Nallanathan, "Multi-antenna covert communication via full-duplex jamming against a warden with uncertain locations," *IEEE Trans. Wireless Commun.*, vol. 20, no. 8, pp. 5467–5480, Aug. 2021.
- [4] T.-X. Zheng, Z. Yang, C. Wang, Z. Li, J. Yuan, and X. Guan, "Wireless covert communications aided by distributed cooperative jamming over slow fading channels," *IEEE Trans. Wireless Commun.*, vol. 20, no. 11, pp. 7026–7039, Nov. 2021.
- [5] X. Lu, E. Hossain, T. Shafique, S. Feng, H. Jiang, and D. Niyato, "Intelligent reflecting surface enabled covert communications in wireless networks," *IEEE Network*, vol. 34, no. 5, pp. 148–155, Sept./Oct. 2020.
- [6] X. Chen, J. An, N. Zhao, C. Xing, D. B. da Costa, Y. Li, and F. R. Yu, "UAV relayed covert wireless networks: Expand hiding range via drones," *IEEE Network*, vol. 36, no. 4, pp. 226–232, Jul./Aug. 2022.
- [7] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: opportunities and challenges," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 36–42, May. 2016.
- [8] S. Yan, S. V. Hanly, and I. B. Collings, "Optimal transmit power and flying location for UAV covert wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 11, pp. 3321–3333, Nov. 2021.
- [9] X. Jiang, Z. Yang, N. Zhao, Y. Chen, Z. Ding, and X. Wang, "Resource allocation and trajectory optimization for UAV-enabled multi-user covert communications," *IEEE Trans. Vehi. Tech.*, vol. 70, no. 2, pp. 1989–1994, Feb. 2021.
- [10] Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 106–112, Jan. 2020.
- [11] I. Al-Nahhal, O. A. Dobre, and E. Basar, "Reconfigurable intelligent surface-assisted uplink sparse code multiple access," *IEEE Commun. Lett.*, vol. 25, no. 6, pp. 2058–2062, Jun. 2021.
- [12] Y. Wu, S. Wang, J. Luo, and W. Chen, "Passive covert communications based on reconfigurable intelligent surface," *IEEE Wireless Commun. Lett.*, vol. 11, no. 11, pp. 2445–2449, Nov. 2022.
- [13] M. Cui, G. Zhang, and R. Zhang, "Secure wireless communication via intelligent reflecting surface," *IEEE Wireless Commun. Lett.*, vol. 8, no. 5, pp. 1410–1414, Oct. 2019.
- [14] X. Guan, Q. Wu, and R. Zhang, "Intelligent reflecting surface assisted secrecy communication: Is artificial noise helpful or not?," *IEEE Wireless Commun. Lett.*, vol. 9, no. 6, pp. 778–782, Jun. 2020.
- [15] C. Wang, X. Chen, J. An, Z. Xiong, C. Xing, N. Zhao, and D. Niyato, "Covert communication assisted by UAV-IRS," *IEEE Trans. Commun.*, vol. 71, no. 1, pp. 357–369, Jan. 2023.

- [16] M. T. Mamaghani and Y. Hong, "Aerial intelligent reflecting surface enabled terahertz covert communications in beyond-5G internet of things," *IEEE Internet Things J.*, vol. 9, no. 19, pp. 19012–19033, Oct. 2022.