Regulating Covert Communication Capacity with Full-Duplex Receiver Against Location-Uncertain Eavesdropper

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***Abstract*—Covert communication enforces the transmitted signal to be indistinguishable from other signals under wireless environment, making it difficult for an eavesdropper to detect and intercept the message. The most common approach within covert systems is the augmentation of artificial noise (AN), ensuring reliable transmission. However, this strategy becomes problematic when the eavesdropper's position is uncertain, as continuous amplification of interference power can precipitate a substantial decline in covert communication capacity. In this paper, we investigate the covert communication between legitimate transmitter (i.e., Alice) and full duplex receiver (i.e., Bob) in the presence of the location uncertainties of the eavesdropper (i.e., Willie). We first derive the sufficient condition for achieving covert communication through robustness analysis. Then, we derive the effective throughput to measure the covert communication capacity. Afterward, by using joint optimization technology, the optimal AN power of Bob and the number of antennas for Alice are jointly designed to maximize the effective throughput subject to a covertness constraint. Theoretical analysis indicates that reducing the AN power while increasing the number of antennas helps to improve the system capacity, the effective throughput between Alice and Bob is inversely proportional to the distance between them. Finally, the validity of our analytical approach is corroborated by simulation results.**

***Index Terms*—Covert communication, FD-receiver, Location uncertainty, Low probability of detection**

I. Introduction

With the emergence of the 6th generation (6G) mobile networks era, a vast and unparalleled volume of sensitive and confidential data is transmitted through wireless mediums. Due to the inherent vulnerabilities (.e.g, privacy leakage) of wireless transmission, ensuring the security of 6G has become increasingly paramount. Acting as an strategical technology, covert communication has gained increasing attention in recent years especially when applied in wireless electronic adversary scenarios [1]. A typical convert communication system (as illustrated in Fig. 1) mainly refers to three kinds of roles: the legitimate transmitter (Alice), the legitimate receiver (Bob), and the illegitimate eavesdropper (Willie). Therein, Alice needs to dependably transmit a message to Bob under the oversight of Willie. Different from most of security schemes that prioritize to protect the information content, covert communication aims to conceal the entire communication process to achieve superior security by exploiting the inherent randomness of wireless physical layer channel.

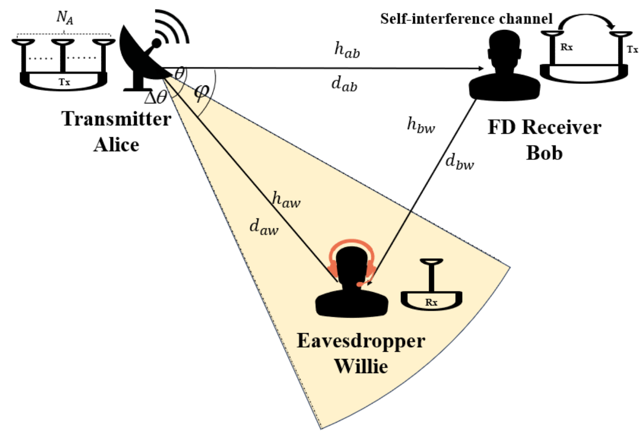

Fig. 1: Illustration of covert communication.

In practical scenarios like military missions, to flexibly regulate the covert communication capacity, using a full-duplex receiver to replace independent interference units has been perceived as an efficient method to reduce communication costs and escape the detection [2], [3]. However, most of existing studies assume the locations of Alice, Bob and Willie are fixed and known, while Willie tends to actively hide his location information from being exposed in real scenarios. This will bring high errors for regulating the covert communication capacity when deployed in the outdoor area. Additionally, the mobility of Willie may decrease the effectiveness of inference signals generated by the full-duplex receiver, so that the adversary still can successfully eavesdrop private information.

To deal with above challenges, this work focuses on regulating covert communication capacity with full-duplex receiver against location-uncertain eavesdropper. Main contributions of our work are summarized as follows:

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979-8-3503-7099-7/24/$31.00

- The sufficient condition for achieving covert communication is provided by robustness analysis in the FD system. Hence, the covert transmission in the worst-case scenario can be guaranteed.
- To measure the covert communication capacity more accurately, we derive the effective throughput and model the covert communication capacity regulation as a multi-parameter optimization problem.
- The optimal power of artificial noises and the number of antennas to maximize the effective throughput are given by joint optimization. It demonstrates proposed optimization solutions are applicable against location-uncertain Willie.

II. Related Works

A. Covert communication with full-duplex receiver

Full-duplex receivers were initially introduced in [4] for achieving covert communication using controlled artificial noise. Building on this work, Shahzad *et al*. [2] demonstrated that when the covert transmission probability and artificial noise power can be jointly optimized, the prior transmission probability of 0.5 is not always the best choice for achieving the maximum possible covertness. Subsequently, Zheng *et al*. [3] studied covert communications with a full-duplex receiver in non-coherent rayleigh fading. Yang *et al*. [5] explored critical covert rate performance in a full-duplex device-to-device cellular network consisting of a base station. Through the analysis of previous work, we can conclude that covert performance can be significantly enhanced via optimization of AN power. However, most above studies assume spatial errors in Willie's location distribution, whereas in actual covert transmission networks, such analytical methods are often insufficiently precise, causing definite computational errors.

B. Regulation of covert communication capacity

The groundbreaking study by Bash *et al*. [6] established the fundamental limits of covert data transmission capacity in the presence of additive white Gaussian noise (AWGN) channels. Subsequently, this research has been expanded to encompass discrete memoryless channels (DMCs) and multiple access channels (MACs) [7]. Notably, the scholars in [8] showcased that a positive covert rate can be accomplished in scenarios where the warden remains unaware of the background noise power. The authors in [9] present novel optimization problems for solving the covert communications problem when Alice has uncertainty about the channel distribution information (CDI) on the channel from herself to warden Willie. However, the existing methods take not the effects of uncertainty in the location of Willie into account. To this end, we present a efficient covert communication capacity regulation countermeasures against location-uncertain Willie.

III. System Model

We examine a wireless communication setting in which Bob (i.e., the full-duplex receiver) operates in full-duplex mode, while Alice (i.e., the multi-antenna transmitter) aims to transmit covertly to Bob, assisted by Bob's generated artificial noise (AN). Meanwhile, Willie (i.e., the location-uncertain eavesdropper) endeavors to detect this covert transmission.

We assume that the actual distances between Alice to Bob, Alice to Willie, and Bob to Willie are denoted by d_{ab}, d_{aw}, and d_{bw}, respectively. In addition to the eavesdropper's power may be uncertain for the legitimate communication system, we consider the probable location of the Willie in an uncertain area (UA), and analyze the covert performance in this case. We consider that the region of UA is a sector, the angle between the legitimate link and the eavesdropping link (φ) satisfies the following relation

$$\theta \leqslant \varphi \leqslant \theta + \Delta\theta \tag{1}$$

In our focused scenario, we consider the line-of-sight (LOS) AWGN channel model, where Alice equips N_a antennas and Bob is equipped with a dual-antenna setup. Utilizing the channel state information (CSI) of the link between Alice and Bob, Bob strategically chooses one antenna to receive the covert message while employing the other antenna to transmit artificial noise (AN), thereby disrupting Willie's detection efforts. The transmit power of Alice is denoted by P_a, which is fixed and publicly known by Bob and Willie. In contrast, Willie only knows the average power of Bob P_b follows a uniform distribution with the probability density function (pdf) [10] as follows:

$$f_{P_b}(x) = \begin{cases} \frac{1}{P_U - P_L}, & 0 \leq P_L \leq P_b \leq P_U \leq P_{\max} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

where P_U and P_L represent the upper and lower bounds of the power uncertainty range, and $P_{\max}$ signifies the maximum permissible power that Bob can generate.

We make the assumption that the wireless channel experiences independent quasi-static Rayleigh fading. h_{ab}, h_{aw}, and h_{bw} are the channel coefficients for the channel from Alice to Bob, Alice to Willie, and the Bob to Willie, respectively. Furthermore, the self-interference channel coefficient of Bob is represented by h_{bb}. We consider that these coefficients are all independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and unit variance $\mathcal{CN}(0,1)$. Hence, the channel vectors can be expressed as $\mathbf{h}_{aw} \triangleq \left[h_{a_1 w}, \cdots, h_{a_{N_a} w}\right]^T$ between Alice and Willie, $\mathbf{h}_{ab} \triangleq \left[h_{a_1 b}, \cdots, h_{a_{N_a} b}\right]^T$ between Alice and Bob. If Alice transmits, the signal received by Bob is given as

$$r_b[n] = \mathbf{w}\mathbf{h_{ab}}\sqrt{\frac{P_a}{d_{ab}^{\alpha}}} s_a[n] + h_{bb}\sqrt{\lambda P_b} s_b[n] + v_b[n] \tag{3}$$

where $\mathbf{w}$ is the precoding vector, $s_a[\cdot]$ is the normalized signal transmitted by Alice satisfying the $\mathbb{E}\left[s_a(n)s_a^{\dagger}(n)\right] = 1$, $s_b[\cdot]$ is the AN signal transmitted by Bob satisfying the $\mathbb{E}\left[s_b(n)s_b^{\dagger}(n)\right] = 1$. $v_b[n] \sim \mathcal{CN}\left(0, \sigma_b^2\right)$ denotes the aggregate received interference following Gaussian distribution. $\alpha(\alpha \geq 2)$ indicates the path loss exponent. $\lambda(0 \leq \lambda \leq 1)$ is a factor corresponding to different self-interference cancellation levels, $\lambda = 0$ denotes the best case that all the self-interference can be cancelled in particular.

IV. Metrics of Covert Communication

In the presence of FD receiver Bob, Willie endeavors to discern the presence or absence of Alice's transmission by differentiating between the null hypothesis ($\mathcal{H}_0$) and the alternative hypothesis ($\mathcal{H}_1$):

$$\begin{aligned}&\mathcal{H}_0 : r_w[n] = h_{bw}\sqrt{\frac{P_b}{d_{bw}^{\alpha}}}s_b[n] + v_w[n]\\&\mathcal{H}_1 : r_w[n] = \mathbf{wh_{aw}}\sqrt{\frac{P_a}{d_{aw}^{\alpha}}}s_a[n] + h_{bw}\sqrt{\frac{P_b}{d_{bw}^{\alpha}}}s_b[n] + v_w[n]\end{aligned} \tag{4}$$

where $v_w[n]$ represents the AWGN at Willie with a variance of σ_w^2. Based on the principle of signal detection estimation, Willie aimed at minimizing detection errors through the Likelihood Ratio test, which can be expressed by Neyman-Pearson criterion as follows:

$$\mathcal{T}(r_w) = \frac{1}{N_s}\sum_{n=1}^{N_s} r_w[n] * r_w[n] \underset{\mathcal{D}_1}{\overset{\mathcal{D}_0}{\lessgtr}} \gamma \tag{5}$$

where $\mathcal{T}(r_w)$ denotes the average power received at Willie, while γ represents a predetermined threshold. We utilize $\mathcal{D}_0$ and $\mathcal{D}_1$ to signify the decision that the received signal corresponds to interference and the decision that the received signal comprises the signal from Alice along with interference, respectively. Subsequently, when considering the scenario with an increasing number of channel uses, i.e., as $n \to \infty$, the average received power at Willie can be expressed as:

$$\begin{aligned}&\mathcal{H}_0 : \mathcal{T}(r_w) = \tfrac{P_b|h_{bw}|^2}{d_{bw}^{\alpha}} + \sigma_w^2\\&\mathcal{H}_1 : \mathcal{T}(r_w) = \tfrac{P_a|\mathbf{wh_{aw}}|^2}{d_{aw}^{\alpha}} + \tfrac{P_b|h_{bw}|^2}{d_{bw}^{\alpha}} + \sigma_w^2\end{aligned} \tag{6}$$

Through the process of hypothesis testing conducted by Willie, we can compute the probabilities of false alarm (FA) and misdetection (MD). The performance of Willie's hypothesis can be measured by the detection error (DE) probability as the sum of P_{FA} and P_{MD}, i.e.,

$$\begin{aligned}P_{DE} &= P_{FA} + P_{MD} = \mathbb{P}(\mathcal{D}_1 \mid \mathcal{H}_0) + \mathbb{P}(\mathcal{D}_0 \mid \mathcal{H}_1)\\&= \mathbb{P}(\mathcal{T}(r_w) > \gamma \mid \mathcal{H}_0) + \mathbb{P}(\mathcal{T}(r_w) < \gamma \mid \mathcal{H}_1)\end{aligned} \tag{7}$$

In the context of covert communications, a lower bound on the minimum detection error probability is given by

$$P_{DE}^{*}* \geq \sqrt{1 - \frac{1}{2}\mathcal{D}(\mathbb{P}_0\|\mathbb{P}_1)} \tag{8}$$

where $\mathcal{D}(\mathbb{P}_0\|\mathbb{P}_1)$ is the KL divergence from $\mathbb{P}_0$ to $\mathbb{P}_1$. We have the following proposition to demonstrate the sufficient condition for achieving covert communication.

Proposition 1: Willie's P_{DE} has a non-zero probability when the relationship between power and distance satisfies the following mathematical relation

$$\frac{P_a}{P_U - P_L} \leqslant \frac{|h_{bw}|^2 \cdot d_{aw}^{\alpha}}{|\mathbf{wh_{aw}}|^2 \cdot d_{bw}^{\alpha}} \tag{9}$$

Proof: Fig. 2 shows three cases for Willie's signal detection. As shown in Fig. 2(c), P_{DE} is greater than 0 and which is independent of γ. Willie can realize the effective signal detection in this case. i.e.,

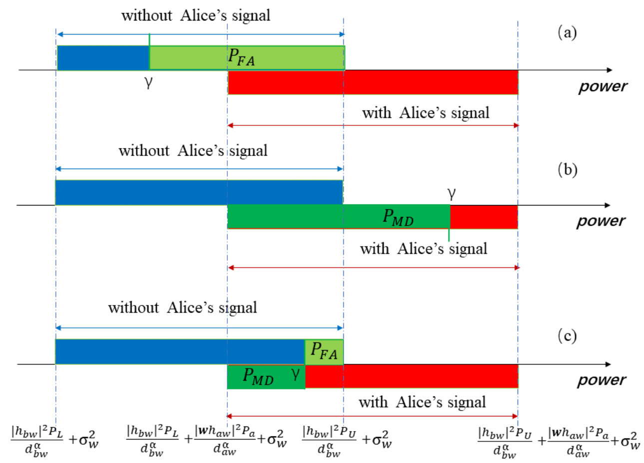


Fig. 2: Signal detection analysis of the Willie.

$$P_{DE} = P_{FA} + P_{MD} = 1 - \frac{P_a|\mathbf{wh_{aw}}|^2 d_{bw}^{\alpha}}{(P_U - P_L)|h_{bw}|^2 d_{aw}^{\alpha}} \tag{10}$$

Combing above three cases, collating assumptions condition and we obtain the conclusion in Proposition 1.

According to the robustness analysis technique, we should ensure reliable covert transmission of the system when Willie is in the optimal detection condition. In previous work [11], we have studied the impact of the power uncertainty range. In order to facilitate the later analysis, we assume that $P_L = 0$ and $P_U = P_{max}$. Substituting (10) into (9), the minimum P_{DE} at the optimal detection threshold is computed as follows:

$$P_{DE}^{*} = 1 - \frac{P_a|\mathbf{wh_{aw}}|^2 d_{bw}^{\alpha}}{P_{max}|h_{bw}|^2 d_{aw}^{\alpha}} \tag{11}$$

V. Proposed Optimization Method

In this section, we model the capacity regulation as a multi-parameter optimization problem and adopt P_{DE}^{*} in the (11) as the metrics of covert performance. On the basis of the above analysis, we focus on the signal-to-interference-plus-noise ratio (SINR) at Bob, which can be expressed as

$$SINR_b = \frac{P_a|\mathbf{wh_{ab}}|^2}{d_{ab}^{\alpha}\left(\lambda P_b|h_{bb}|^2 + \sigma_b^2\right)} \tag{12}$$

where $|\mathbf{wh_{ab}}|^2 \sim \Gamma(N_a, 1)$, $|h_{bb}|^2 \sim \exp(1)$. In order to compare with the control results, we use the covert communication transmission capacity C_{ab} to evaluate the transmission performance. The connection outage probability is used to measure the reliability performance of covert communication [12], which can be derived as

$$\begin{aligned}\delta_{ab} &= \mathbb{P}\left[C_{ab} < R_{ab}\right] = \mathbb{P}\left[SINR_b < 2^{R_{ab}} - 1\right] \\ &= 1 - \frac{1}{\lambda P_b}\sum_{m=0}^{N_a-1}\frac{\left(\left(2^{R_{ab}}-1\right)\cdot\frac{d_{ab}}{P_a}\right)^m}{\left(\frac{1+\lambda P_b\left(2^{R_{ab}}-1\right)\cdot\frac{d_{ab}}{P_a}}{\lambda P_b}\right)^{m+1}}\end{aligned} \tag{13}$$

where R_{ab} represents the predetermined transmission rate from Alice to Bob. Transmission outage occurs when $C_{ab} < R_{ab}$. Meanwhile, we can derive the effective throughput to measure the covert communication capacity, which is given by

$$\eta = R_{ab} = R_{ab}\left(1 - \left(1 + \frac{P_a}{\left(\lambda P_b + \sigma_b^2\right)\left(2^R - 1\right)d_{ab}^a}\right)^{-N_a}\right) \tag{14}$$

Proposition 2: Increasing the number of transmitter antennas or decreasing the AN power lead to a higher effective covert throughput.

Proof: We first define that

$$t \triangleq \left(1 + \frac{P_a}{\left(\lambda P_b + \sigma_b^2\right)\left(2^{R_{ab}} - 1\right)d_{ab}^a}\right) > 1 \tag{15}$$

taking the first derivative of η w.r.t N_a and P_b, we have

$$\frac{\partial\eta}{\partial N_a} = \frac{R_{ab}\ln t}{t^{N_a}} > 0 \tag{16}$$

$$\frac{\partial\eta}{\partial P_b} = -\frac{N_a P_a}{t^{N_a+1}d_{ab}^{\alpha}\left(2^{R_{ab}}-1\right)\left(\lambda P_b + \sigma_b^2\right)^2} < 0 \tag{17}$$

Consequently, we conclude that η monotonically increases with N_a and monotonically decreases with P_b. Similarly, we can prove that $\partial\eta/\partial d_{ab} < 0$, i.e., the effective throughput between Alice and Bob is inversely proportional to the distance between them.

In this section, we optimize P_b and N_a in order to maximize the effective covert throughput at Bob in the considered scenario. Specifically, we can formulate the multi-parameter optimization problem in the considered scenario as follows:

$$\mathbf{P}: \quad \underset{P_b, N_a}{\text{maximize}}\{\eta\} \tag{18a}$$

$$\text{s.t. } P_{DE}^* \geq 1 - \epsilon \tag{18b}$$

$$0 \leq P_b \leq P_{\max} \tag{18c}$$

$$1 \leq N_a \leq N_{\max} \tag{18d}$$

$$\theta \leqslant \varphi \leqslant \theta + \Delta\theta \tag{18e}$$

Constraint (18b) demonstrates the covert communication requirement in the worst-case. Constraint (18c) sets the bounds of the FD receiver's AN power. Constraint (18d) sets the maximum number of available antennas. Constraint (18e) gives the uncertain area of the Willie.

Proposition 3: By joint optimization technology, the maximum effective throughput when ignore σ_b^2 is given by

$$\eta^* = R_{ab}\left(1 - \left(1 + \frac{\epsilon}{\lambda\sin^{\alpha}\theta\left(2^{R_{db}} - 1\right)d_{ab}^{\alpha}}\right)^{-N_{\max}}\right) \tag{19}$$

Proof: Substituting (11) into (18b), we can transform the covert communication constraint as

$$P_b \geqslant f(\tau) = \frac{P_a}{\epsilon}\left(\tau^2 - 2\tau\cos\varphi + 1\right)^{\frac{\alpha}{2}} \tag{20}$$

where $\tau \triangleq \frac{d_{\text{ab}}}{d_{\text{aw}}}$. From the expression of (20), we have the first-order derivative of $f(\tau)$ against τ as

$$\frac{\partial f(\tau)}{\partial\tau} = \frac{2P_a}{\epsilon}(\tau - \cos\varphi)\left(\tau^2 - 2\tau\cos\varphi + 1\right)^{\frac{\alpha}{2}-1} \tag{21}$$

It is clear that $f(\tau)$ reaches minimum when $\tau = \cos\varphi$. Combining the conclusions in Proposition 2, the optimal N_a and the optimal P_b to maximize the effective throughput can be expressed as follows:

$$N_a^* = N_{\max} \tag{22}$$

$$P_b^* = \frac{P_a\sin^{\alpha}\theta}{\epsilon} \tag{23}$$

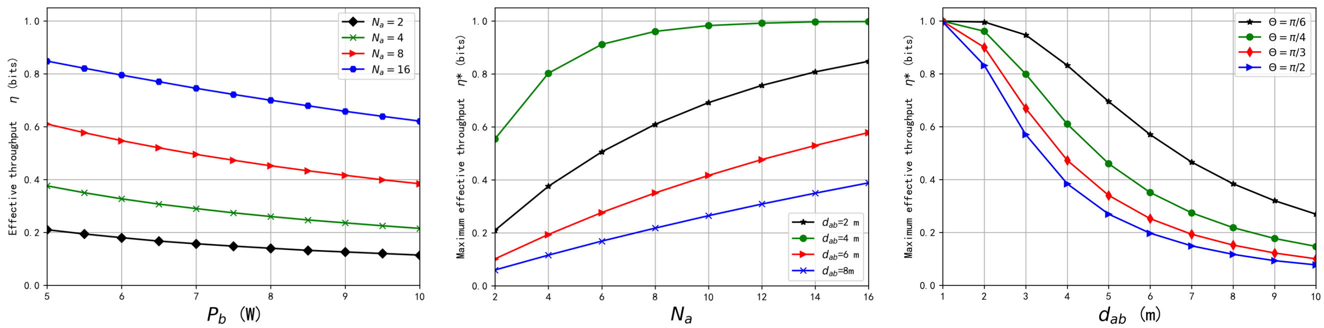
Finally, η^* is obtained by substituting (23) into (14) and we complete the proof.

VI. Simulation and Discussion

In this section, we present representative numerical results to verify the performance of the previous analysis. Without loss of generality, the main assumptions used in our simulations are summarized as follows: $\epsilon = 0.1$, $R_{ab} = 1$, $\sigma_b^2 = \sigma_w^2 = -104\text{dBm}$, $\lambda = 0.1$, $\alpha = 2$, $P_a = 1\text{W}$, $P_{max} = 10\text{W}$.

Fig. 3(a) draws the detection the effective covert throughput curve for the different AN power, respectively. It can be observed that η decreases with the increase of P_b, this is rather intuitive and which agrees with Proposition 2. Since increased interference power makes Willie's detection error prone, but the increase in P_b also interferes with the normal transmission process of the legal link, the AN is helpful for the transmission at first, but when the AN is too large, the performance deteriorates due to self-interference. Thus, with a fixed value of P_a in the feasible range, a higher value of λ (i.e., poorer self-interference cancellation) requires a lower value of $P_{\max}$ to satisfy the same rate requirement.

The impact of the number of antennas N_a on the maximum effective covert throughput η^* is investigated in Fig. 3(b). We can see that η^* monotonically increases with N_a and the increase tends to slow down as N_a becomes larger, this is due to the fact that in the multi-antenna system, each antenna transmits different covert information bits. As a result, the more antennas are involved in transmitting covert bit, the higher covert rate is achieved. In addition, the more antennas are configured, the more security gains can be obtained, and the safer the transmission, the less the possibility of transmission interruption, which is consistent with the analysis in



(a) η vs. P_b, where $d_{ab} = 4$m and $\theta = \frac{\pi}{4}$. (b) η^* vs. N_a, where $P_b = 5$W and $\theta = \frac{\pi}{4}$. (c) η^* vs. d_{ab}, where $P_b = 5$W and $N_a = 8$.

Fig. 3: The impact of variables in the proposed system on effective covert throughput.

Proposition 2. However, antenna resources are quite valuable in practical deployments, so we need to set a reasonable N_a to ensure transmission performance and resource utilization in covert communication.

We then investigate the relationship between η^* and the distance between Alice and Bob d_{ab}. As depicted in the Fig. 3(c), it indicates that η^* is a monotonically decreasing function of d_{ab}, this is due to that the increased distance between the legitimate communicating parties increases the risk of leakage, and the probability of interruption of transmission increases significantly when Willie has a strong priori sensing capabilities. Moreover, it is also observed that an increase of θ leads to a negative impact on η, which reminds us it can hardly communication covertly when the θ exceed a certain angle and the uncertain area of Willie is too large, this is due to the fact that the Bob tends to continuously increase the AN power to satisfy the covert requirement, the increasing probability of legitimate link interruption makes the maximum effective throughput decrease dramatically.

VII. Conclusion

In this paper, we have investigated a practical FD covert communication scenario in the case of the exact location of Willie is unknown to the legitimate transmission pair. We first derived the sufficient condition for achieving covert communication in the considered full-duplex system. We further set up the optimization model whose objective function is to maximize the effective throughput of covert communication model with the detection performance and position constraint. Finally, we analyzed the effect of the number of antennas and AN power on the covert transmission capability and obtain the maximum effective covert throughput, which also provides the guidance for the regulation in our realistic scenarios and help us to draw up a conventional scheme in covert communication. For future work, we intend to consider the covert scheme design in the scenarios where multiple mobile eavesdropping nodes exist.

Acknowledgement

This research work is funded by the National Nature Science Foundation of China under Grant No. 62202303, U20B2048, and 61831007, Shanghai Sailing Program under Grant No. 21YF1421700 and Shanghai Municipal Science and Technology Major Project under Grant 2021SHZDZX0102.

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