Joint Position and Power Control for Covert Communication in Dual-UAV Systems

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This paper investigates joint position and power control for downlink covert communication in a dual-UAV system, which consists of a UAV transmitter, a terrestrial receiver, a passive warden, and a cooperative UAV jammer. First, based on classical probability theory, the optimal detection threshold and the minimum detection error probability of Willie are analytically derived under the considered dual-UAV covert communication model. Then, by incorporating UAV mobility and controllable transmit power, closed-form expressions are obtained to characterize the optimal UAV positions and power control strategies under both transmission outage and covertness constraints. Finally, extensive numerical results are provided to validate the analytical findings and to demonstrate that the proposed joint position and power control scheme can substantially enhance the covert transmission performance of dual-UAV systems.

***Index Terms*—Covert communication, low detection probability communication, UAV position, power control, dual-UAV systems.**

I. INTRODUCTION

Unmanned aerial vehicle (UAV) communication systems rely on unmanned aerial vehicles to provide flexible and on-demand wireless connectivity for ground users, especially in scenarios where terrestrial infrastructures are unavailable, damaged, or overloaded. By leveraging their high mobility, adaptive deployment, and controllable altitude, UAVs can effectively enhance coverage, improve spectral efficiency, and support reliable communication links in dynamic environments. As a result, UAV communication systems are widely regarded as a key enabling technology for future wireless networks, playing an important role in emergency response, disaster recovery, intelligent transportation, and temporary hotspot coverage.

Due to the broadcast nature of the wireless medium and the long-distance transmission characteristics of LoS air-to-ground links, such systems are exposed to various potential adversaries and face serious security threats [1]. Covert communication is a promising technique to hide the very existence of wireless transmission among UAVs from potential malicious nodes, which provides a strong security guarantee for wireless transmissions in UAV communication systems [2]–[6]. Recently, some works have been conducted on the UAV covert communication [7]–[9]. The work in [7] investigates the impact of noise uncertainty in UAV-enabled covert communications and jointly optimizes the UAV trajectory and transmit power to maximize the covert rate. The work in [10] further considers a three-dimensional (3D) UAV covert communication system with finite-blocklength transmissions and develops a joint location design and power control strategy for covert rate maximization. The authors in [9] study the joint design of UAV location and jamming power in a full-duplex receiver-assisted UAV communication system to maximize the covert rate.

Although the aforementioned works have advanced the study of covert communications in UAV systems, they mainly exploit environmental noise or artificial noise (AN) generated by jammers deployed at fixed locations. These studies reveal the fundamental mechanisms of UAV covert communication and suggest that covert performance can be enhanced via UAV location optimization. Nevertheless, introducing a mobile UAV jammer provides additional design degrees of freedom and may further improve the covertness of UAV systems. How to jointly optimize the transmit powers and locations of the UAV transmitter and the UAV jammer to maximize covert communication performance remains largely underexplored.

To address the above issues, this paper considers a dual-UAV covert communication system comprising a transmitter (Alice), a receiver (Bob), a cooperative jammer (Jack), and a warden (Willie). For this system, we propose a covert scheme based on the UAVs' locations and transmit power control. Under this scheme, we derive the optimal detection threshold and the corresponding minimum detection error probability at Willie. Then, we provide the joint optimal design of UAVs' locations and transmit power to maximize the covert rate under the transmission outage constraint and the covertness constraint. Finally, extensive numerical results are provided to demonstrate the effectiveness of the proposed scheme in enabling covert communication for dual-UAV systems.

$Notation$: Lower-case letters, lower-case boldface letters, and upper-case boldface letters denote scalars, vectors, and matrices (e.g., a, $\mathbf{a}$, and $\mathbf{A}$), respectively. Moreover, $\mathbb{E}[\cdot]$, $\Pr\cdot$, and $|\cdot|$ stand for the expectation operator, probability operator, absolute value, and Euclidean norm, respectively.

II. SYSTEM MODEL

A. Communication Scenario

As shown in Fig. 1, we consider a dual-UAV covert communication system consisting of a UAV transmitter Alice, a

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terrestrial receiver Bob, a passive terrestrial warden Willie, and a friendly UAV Jack. In the system, Alice tries to transmit covert information to Bob subject to detection by Willie. To assist the covert transmission, Jack sends AN to confuse Willie's detection. Without loss of generality, we denote the horizontal location of Alice, Bob and Willie by $\mathbf{q}_a \triangleq [x_a, y_a]^T$, $\mathbf{q}_b \triangleq [x_b, y_b]^T$, $\mathbf{q}_w \triangleq [x_w, y_w]^T$ and $\mathbf{q}_j \triangleq [x_j, y_j]^T$ respectively.

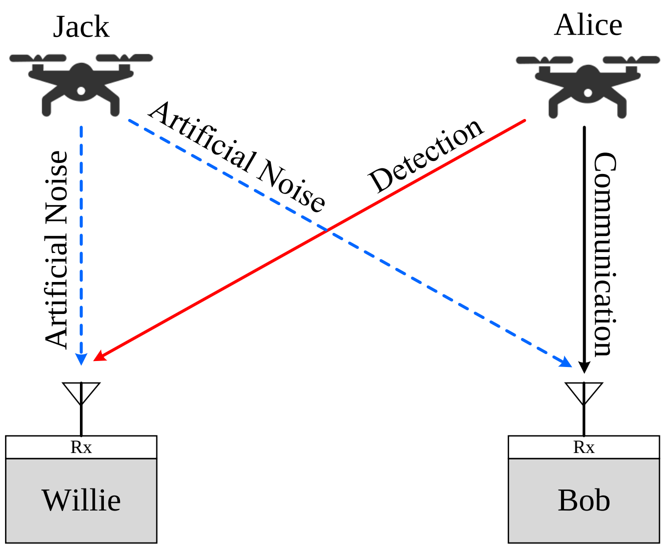

Fig. 1. System model.

In this paper, we assume that the UAVs fly at a fixed altitude H. Thus, the channel gains of UAV-terrestrial links can be expressed as

$$h_{us} = \sqrt{\beta_0 d_{us}^{-2}} = \sqrt{\frac{\beta_0}{||\mathbf{q}_u - \mathbf{q}_s||^2 + H^2}}, \quad (1)$$

where $u \in \{a, j\}$, $s \in \{b, w\}$. β_0 is the channel power gain at a reference distance 1m. The received signal at Bob in the i-th channel use is given by

$$y_b(i) = \sqrt{P_a} h_{ab} x_a(i) + \sqrt{P_j} h_{jb} x_j(i) + n_b(i), \quad (2)$$

where P_a denotes the transmit power of Alice. x_a denotes the signal transmitted by Alice, x_j denotes the AN transmitted by Jack. These two signals satisfy $\mathbb{E}[|x_a[i]|^2] = 1, \mathbb{E}[|x_j[i]|^2] = 1$. $n_b(i)$ is the AWGN at Bob following $n_b \sim \mathcal{CN}(0, \sigma_b^2)$. In this paper, Bob is assumed to have only statistical knowledge of the jamming signal. Consequently, Bob is unable to cancel the jamming and thus treats it as noise.

B. Detection at Willie

In covert communications, Willie determines whether Alice transmits the covert information to Bob based on the received signal from Alice. The signals $y_w(i)$ received at Willie can be given by

$$y_w(i) = \begin{cases} \sqrt{P_j} h_{jw} x_j(i) + n_w(i), & \mathcal{H}_0 \\ \sqrt{P_a} h_{aw} x_a(i) + \sqrt{P_j} h_{jw} x_j(i) + n_w(i), & \mathcal{H}_1 \end{cases}, \quad (3)$$

where $n_w(i)$ denotes the additive white Gaussian noise (AWGN) at Willie with $n_w \sim \mathcal{CN}(0, \sigma_w^2)$, and $\mathcal{H}_0$ and $\mathcal{H}_1$ denote the null hypothesis of no transmission and the alternative hypothesis that Alice transmits to Bob, respectively.

Without loss of generality, this paper considers the worst-case scenario for Alice's transmission, where Willie has complete knowledge of the location of all the nodes and the associated channel gains[1] The optimal decision rule for Willie that minimizes the total error rate is given by [11]

$$T_w \triangleq \frac{1}{n} \sum_{i=1}^{n} |y_w(i)|^2 \underset{\mathcal{D}_0}{\overset{\mathcal{D}_1}{\gtrless}} \gamma, \quad (4)$$

where T_w is the average power received at Willie, γ is the detection threshold of Willie, while $\mathcal{D}_0$ and $\mathcal{D}_1$ are the decisions in favor of $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively. As $n \to \infty$, T_w can be rewritten as

$$T_w = \begin{cases} |h_{jw}|^2 P_j + \sigma_w^2, & \mathcal{H}_0 \\ |h_{aw}|^2 P_a + |h_{jw}|^2 P_j + \sigma_w^2, & \mathcal{H}_1 \end{cases}, \quad (5)$$

According to (4), two types of detection errors may occur, namely, the false-alarm probability $P_F \triangleq \Pr\{\mathcal{D}_1 \mid \mathcal{H}_0\}$ and the miss-detection probability $P_M \triangleq \Pr\{\mathcal{D}_0 \mid \mathcal{H}_1\}$, which can be written as

$$\mathbb{P}_{\text{FA}} = \Pr\{|h_{jw}|^2 P_j + \sigma_w^2 \geq \gamma\}, \quad (6)$$

$$\mathbb{P}_{\text{MD}} = \Pr\{|h_{aw}|^2 P_a + |h_{jw}|^2 P_j + \sigma_w^2 \leq \gamma\}. \quad (7)$$

Then, the detection error probability of Willie is given by

$$\xi = P_F + P_M. \quad (8)$$

Assume that the jamming transmit power of Jack P_j follows a uniform distribution over the interval $[P_{j,\min}, P_{j,\max}]$, i.e., $P_j \sim U(P_{j,\min}, P_{j,\max})$. The probability density function (PDF) of P_j can be expressed as

$$f_{P_j}(x) = \frac{1}{P_{j,\max} - P_{j,\min}}, \quad P_j \in [P_{j,\min}, P_{j,\max}]. \quad (9)$$

Meanwhile, the transmit power P_j is assumed to be constrained by the average jamming power $P_{j,\text{avg}}$ of Jack, which is given by

$$P_{j,\min} + P_{j,\max} \leq P_{j,\text{avg}}. \quad (10)$$

C. Transmission Rate from Alice to Bob

The communication between legitimate nodes is required to ensure both the covertness requirement and the reliability requirement. In this subsection, the transmission outage probability between the legitimate nodes is derived, and the corresponding transmission performance is analyzed.

According to (2), the channel capacity can be expressed as

$$C_{ab} = \log_2 \left(1 + \frac{|h_{ab}|^2 P_a}{|h_{jb}|^2 P_j + \sigma_b^2} \right). \quad (11)$$

[1]If covert communication is achievable under this worst case, it is also achievable when Willie possesses only imperfect knowledge, with an even higher covert rate performance. This is because imperfect knowledge degrades Willie's detection capability, thereby allowing Alice to employ a higher covert transmit power.

Due to the presence of environmental noise and artificial jamming, the transmission from Alice to Bob may experience an outage. The transmission outage probability ζ is thus given by

$$\begin{aligned}\zeta &= \Pr\{C_{ab} < R_{ab}\} \\ &= \Pr\left\{P_j > \frac{|h_{ab}|^2 P_a}{|h_{jb}|^2(2^{R_{ab}}-1)} - \frac{\sigma_b^2}{|h_{jb}|^2}\right\}.\end{aligned} \tag{12}$$

From (3) and (12), the outage probability can be further expressed as

$$\zeta = \begin{cases} 0, & P_{j,\max} < \mu \\ \dfrac{P_{j,\max}-\mu}{P_{j,\max}-P_{j,\min}}, & P_{j,\min} \le \mu \le P_{j,\max}\ , \\ 1, & P_{j,\min} > \mu \end{cases} \tag{13}$$

where

$$\mu = \frac{|h_{ab}|^2 P_a}{|h_{jb}|^2(2^{R_{ab}}-1)} - \frac{\sigma_b^2}{|h_{jb}|^2}. \tag{14}$$

It can be observed from (13) that ζ increases monotonically with the transmission rate R_{ab}. Considering the reliability requirement for Alice–Bob communication, the outage probability is constrained by $\zeta \le \epsilon_b$, where ϵ_b denotes the maximum tolerable outage probability. When the transmission rate is maximized, the equality $\zeta = \epsilon_b$ always holds. Therefore, the achievable transmission rate from Alice to Bob can be expressed as

$$R_{ab} = \log_2\left(1 + \frac{|h_{ab}|^2 P_a}{|h_{jb}|^2\big(P_{j,\max} - \epsilon_b(P_{j,\max}-P_{j,\min})\big) + \sigma_b^2}\right). \tag{15}$$

III. Detection Performance at Willie

In this section, we first derive the probabilities of false alarm and miss detection at Willie, and then obtain the optimal detection threshold γ^* along with the corresponding minimum detection error rate ξ^*.

A. False Alarm Probability

Following (6), the false alarm probability can be given by

$$\mathbb{P}_{\text{FA}} = \begin{cases} 1, & \gamma < |h_{jw}|^2 P_{j,\min} + \sigma_w^2, \\ \tau_1, & |h_{jw}|^2 P_{j,\min} + \sigma_w^2 \le \gamma \le |h_{jw}|^2 P_{j,\max} + \sigma_w^2, \\ 0, & \gamma > |h_{jw}|^2 P_{j,\max} + \sigma_w^2, \end{cases} \tag{16}$$

where

$$\begin{aligned}\tau_1 &= \int_{\frac{\gamma-\sigma_w^2}{|h_{jw}|^2}}^{P_{j,\max}} \frac{x}{P_{j,\max}-P_{j,\min}}dx \\ &= \frac{P_{j,\max} - \frac{\gamma-\sigma_w^2}{|h_{jw}|^2}}{P_{j,\max}-P_{j,\min}}.\end{aligned} \tag{17}$$

B. Miss Detection Probability

Similarly, the miss detection rate P_M is given by

$$\mathbb{P}_{\text{MD}} = \begin{cases} 0, & \gamma-\kappa < |h_{jw}|^2 P_{j,\min}, \\ \tau_2, & |h_{jw}|^2 P_{j,\min} \le \gamma-\kappa \le |h_{jw}|^2 P_{j,\max}, \\ 1, & \gamma-\kappa > |h_{jw}|^2 P_{j,\max}, \end{cases} \tag{18}$$

where

$$\begin{aligned}\tau_2 &= \int_{P_{j,\min}}^{\frac{\gamma-\kappa}{|h_{jw}|^2}} \frac{x}{P_{j,\max}-P_{j,\min}}dx \\ &= \frac{\frac{\gamma-\kappa}{|h_{jw}|^2} - P_{j,\min}}{P_{j,\max}-P_{j,\min}}.\end{aligned} \tag{19}$$

$$\kappa = |h_{aw}|^2 P_a - \sigma_w^2. \tag{20}$$

C. Minimum Detection Error Probability

By substituting (16) and (18) into (8), the following expression can be obtained:

$$\xi = \begin{cases} 1, & \gamma < |h_{jw}|^2 P_{j,\min} + \sigma_w^2, \\ \tau_1, & |h_{jw}|^2 P_{j,\min} + \sigma_w^2 \le \gamma < |h_{jw}|^2 P_{j,\min} + \kappa, \\ \tau_1+\tau_2, & |h_{jw}|^2 P_{j,\min} + \kappa \le \gamma \le |h_{jw}|^2 P_{j,\max} + \sigma_w^2, \\ \tau_2, & |h_{jw}|^2 P_{j,\max} + \sigma_w^2 < \gamma \le |h_{jw}|^2 P_{j,\max} + \kappa, \\ 1, & \gamma > |h_{jw}|^2 P_{j,\max} + \kappa. \end{cases} \tag{21}$$

According to (17) and (19), τ_1 is a monotonically decreasing function of γ, while τ_2 increases monotonically with γ. Moreover, the sum $\tau_1+\tau_2 = 1 - \dfrac{|h_{aw}|^2 P_a}{|h_{jw}|^2(P_{j,\max}-P_{j,\min})}$ is independent of γ. Consequently, the optimal detection threshold of Willie can be determined as

$$\gamma^* \in \left[|h_{jw}|^2 P_{j,\min} + |h_{aw}|^2 P_a + \sigma_w^2; |h_{jw}|^2 P_{j,\max} + \sigma_w^2\right], \tag{22}$$

and the corresponding minimum detection error probability is given by

$$\xi^* = 1 - \frac{|h_{aw}|^2 P_a}{|h_{jw}|^2(P_{j,\max}-P_{j,\min})}. \tag{23}$$

According to (23), the covertness requirement can be expressed as $\xi^* > 1-\epsilon_w$, such that the optimal UAV location will be designed in the subsequent section.

IV. Covert Communiation Design

In this section, we propose the joint optimal design of UAVs' locations and transmit powers for maximizing the covert rate in the concerned system.

A. Optimal Jamming Power

First, we investigate the optimal value of $P_{j,\min}$. Take the first partial derivative of (23) with respect to $P_{j,\min}$, we can obtain

$$\frac{\partial \xi^*}{\partial P_{j,\min}} = -\frac{|h_{aw}|^2 P_a}{|h_{jw}|^2 (P_{j,\max} - P_{j,\min})}. \tag{24}$$

According to (24), within the domain $[0, P_{j,\max}]$, ξ^* decreases monotonically with $P_{j,\min}$. Furthermore, from (13), it can be observed that ζ also decreases monotonically with $P_{j,\min}$ when $P_{j,\min} \leq \mu \leq P_{j,\max}$. Therefore, to maximize ξ^* and minimize ζ, the optimal value of $P_{j,\min}$ is obtained as

$$P^*_{j,\min} = 0. \tag{25}$$

Substituting $P^*_{j,\min}$ into (23) and (4-22), respectively, yields

$$\xi^* = 1 - \frac{|h_{aw}|^2 P_a}{|h_{jw}|^2 P_{j,\max}}, \tag{26}$$

and

$$R_{ab} = \log_2 \left(1 + \frac{|h_{ab}|^2 P_a}{(1-\epsilon_b)|h_{jb}|^2 P_{j,\max} + \sigma_b^2} \right). \tag{27}$$

Now, we investigate the optimal value of $P_{j,\max}$. Take the first partial derivative of (23) with respect to $P_{j,\max}$, we have

$$\frac{\partial \xi^*}{\partial P_{j,\max}} = \frac{|h_{aw}|^2 P_a}{|h_{jw}|^2 (P_{j,\max} - P_{j,\min})}. \tag{28}$$

As shown in (28), ξ^* increases monotonically with $P_{j,\max}$. Moreover, from (13), it can be seen that ζ also increases monotonically with $P_{j,\max}$ when $P_{j,\min} \leq \mu \leq P_{j,\max}$. Therefore, increasing $P_{j,\max}$ enhances the system's covertness performance but simultaneously degrades its transmission performance. Consequently, the optimal value of $P_{j,\max}$ cannot be directly determined by the monotonicity of ξ^* and ζ.

Further analysis of (26) and (27) reveals that R_{ab} decreases with $P_{j,\max}$ but increases with P_a, whereas ξ^* increases with $P_{j,\max}$ but decreases with P_a. Based on this observation, the following lemma is introduced to further discuss the optimal value of $P_{j,\max}$.

Lemma 1: The ratio between the optimal transmit power of Alice and the optimal maximum transmit power of Jack can be expressed as

$$\frac{P_a^*}{P^*_{j,\max}} = \frac{\epsilon_w |h_{jw}|^2}{|h_{aw}|^2}, \tag{29}$$

where P_a^* and $P^*_{j,\max}$ denote the optimal transmit power of Alice and the optimal maximum transmit power of Jack, respectively.

Proof: According to (26), ξ^* decreases monotonically with $\frac{P_a}{P_{j,\max}}$. Under the covertness constraint, achieving a higher covert rate requires using a larger P_a, which forces the constraint $\xi^* \leq 1 - \epsilon_w$ to hold with equality. Therefore, (29) follows directly. ∎

Substituting (29) into (27) yields

$$R_{ab} = \log_2 \left(1 + \frac{\epsilon_w |h_{ab}|^2 |h_{jw}|^2}{(1-\epsilon_b)|h_{aw}|^2 |h_{jb}|^2 + \frac{|h_{aw}|^2 \sigma_b^2}{P_{j,\max}}} \right). \tag{30}$$

It can be observed from (30) that R_{ab} increases monotonically with $P^*_{j,\max}$. Combining (5) and (25), the optimal maximum transmit power of Jack is obtained as

$$P^*_{j,\max} = P_{j,\mathrm{avg}}. \tag{31}$$

Substituting (31) into (29) gives the optimal transmit power of Alice as

$$P_a^* = \frac{\epsilon_w |h_{jw}|^2 P_{j,\mathrm{avg}}}{|h_{aw}|^2}. \tag{32}$$

B. Optimal UAV Flight Position

Based on the optimal artificial noise power and transmit power, this subsection further investigates the optimal flight positions of the UAV nodes to maximize the covert rate of the system.

By substituting (25), (31), and (32) into (30), the achievable transmission rate can be expressed as

$$\begin{aligned} R_{ab} &= \log_2 \left(1 + \frac{\epsilon_w |h_{ab}|^2 |h_{jw}|^2}{(1-\epsilon_b)|h_{aw}|^2 |h_{jb}|^2 + \frac{|h_{aw}|^2 \sigma_b^2}{P_{j,\mathrm{avg}}}} \right) \\ &= \log_2 \left(1 + \frac{\epsilon_w |h_{ab}|^2 |h_{jw}|^2}{(1-\epsilon_b)|h_{aw}|^2 \left(|h_{jb}|^2 + \frac{\sigma_b^2}{(1-\epsilon_b)P_{j,\mathrm{avg}}} \right)} \right). \end{aligned} \tag{33}$$

Since Alice and Jack are two independent UAVs whose flight positions are mutually independent, the problem of maximizing the overall covert rate can be decomposed into the following two independent optimization problems:

$$\max_{\mathbf{q}_a} \frac{|h_{ab}|^2}{|h_{aw}|^2}, \tag{34}$$

$$\max_{\mathbf{q}_j} \frac{|h_{jw}|^2}{|h_{jb}|^2 + \frac{\sigma_b^2}{(1-\epsilon_b)P_{j,\mathrm{avg}}}}. \tag{35}$$

For simplicity, Bob is assumed to be located at the origin $\mathbf{q}_b = [0,0]^T P_{j,\mathrm{avg}}$, and Willie is positioned to the right of Bob with the same vertical coordinate, i.e., $\mathbf{q}_w = [x_w, 0]^T$. Accordingly, optimization problems (34) and (35) can be reformulated as

$$\max_{x_a, y_a} \quad \frac{(x_a - x_w)^2 + y_a^2 + H^2}{x_a^2 + y_a^2 + H^2}, \tag{36}$$

$$\max_{x_j, y_j} \quad \frac{\frac{1}{(x_j - x_w)^2 + y_j^2 + H^2}}{\frac{1}{x_j^2 + y_j^2 + H^2} + \eta}, \tag{37}$$

where $\eta = \frac{\sigma_b^2}{\beta_0 P_{j,\mathrm{avg}}(1-\epsilon_b)}$.

The solution to the optimization problem (36) corresponds to the maximum value of the objective function

$$f_a(x_a, y_a) = \frac{(x_a - x_w)^2 + y_a^2 + H^2}{x_a^2 + y_a^2 + H^2}. \tag{38}$$

The optimal solution to problem (36) can thus be obtained by analyzing the extrema of $f_a(x_a, y_a)$.

By analyzing the stationary points of $f_a(x_a, y_a)$, two critical points can be obtained as

$$\mathbf{q}_{a1} = [\frac{x_w - \sqrt{x_w^2 + 4H^2}}{2}, 0] \tag{39}$$

$$\mathbf{q}_{a2} = [\frac{x_w + \sqrt{x_w^2 + 4H^2}}{2}, 0] \tag{40}$$

Among them, $\mathbf{q}_{a1}$ corresponds to the maximum point, while $\mathbf{q}_{a2}$ yields the minimum of R_{ab}. Hence, the maximum value of $f_a(x_a, y_a)$ can be expressed as

$$f_a\left(\frac{x_w - \sqrt{x_w^2 + 4H^2}}{2}, 0\right) = 1 + \frac{x_w^2 + \sqrt{x_w^2\left(x_w^2 + 4H^2\right)}}{2H^2}. \tag{41}$$

The solution to the optimization problem (37) corresponds to the maximum of the objective function

$$f_j(x_j, y_j) = \frac{\frac{1}{(x_j - x_w)^2 + y_j^2 + H^2}}{\frac{1}{x_j^2 + y_j^2 + H^2} + \eta}. \tag{42}$$

To solve (37), the extrema of $f_j(x_j, y_j)$ are analyzed by setting its partial derivatives to zero:

$$\frac{\partial f_j}{\partial x_j} = -\frac{2\eta(x_j - x_w)\left(x_j^2 + y_j^2 + H^2\right)^2 + 2x_w\left(x_j x_w - x_j^2 + y_j^2 + H^2\right)}{\left(x_j^2 - 2x_j x_w + x_w^2 + y_j^2 + H^2\right)^2\left(1 + \eta\left(x_j^2 + y_j^2 + H^2\right)\right)^2}, \tag{43}$$

$$\frac{\partial f_j}{\partial y_j} = -\frac{2y_j\left((2x_j - x_w)x_w + \eta\left(x_j^2 + y_j^2 + H^2\right)^2\right)}{\left(x_j^2 - 2x_j x_w + x_w^2 + y_j^2 + H^2\right)^2\left(1 + \eta\left(x_j^2 + y_j^2 + H^2\right)\right)^2}. \tag{44}$$

According to (43), the equation $\frac{\partial f_j}{\partial x_j} = 0$ is a quintic polynomial with respect to x_j, which has no closed-form analytical solution. The optimal solution to problem (37) can thus be determined by finding the largest real root α of the following fifth-order equation:[2]

$$\rho_1 x + \rho_2 x^2 + \rho_3 x^3 + \rho_4 x^4 + \rho_5 x^5 + H^2 = 0, \tag{45}$$

where the coefficients are given by

$$\rho_1 = -\left(5H^2 + \eta H^4 + x_w^2 + 4\eta H^2 x_w^2\right), \tag{46a}$$

$$\begin{aligned}\rho_2 =& 10H^2 + 4\eta H^4 + 3x_w^2 - 14\eta H^2 x_w^2 \\ &+ 12\eta^2 H^4 x_w^2 + 3\eta x_w^4 + 6\eta^2 H^2 x_w^4,\end{aligned} \tag{46b}$$

$$\begin{aligned}\rho_3 =& -8\eta^3 H^6 x_w^2 + 2H^2\left(-5 + 18\eta x_w^2 + 3\eta^2 x_w^4\right) \\ &- 2\eta H^4\left(3 - 30\eta x_w^2 + 11\eta^2 x_w^4\right) \\ &- 3\left(x_w^2 - 7\eta x_w^4 + \eta^2 x_w^6\right),\end{aligned} \tag{46c}$$

$$\begin{aligned}\rho_4 =& x_w^2\left(1 + \eta x_w^2\right)^3 + 16\eta^3 H^6 x_w^2\left(-3 + 2\eta x_w^2\right) \\ &+ 4\eta H^4\left(1 - 15\eta x_w^2 + 5\eta^2 x_w^4 + 3\eta^3 x_w^6\right) \\ &+ H^2\left(5 - 14\eta x_w^2 - 6\eta^2 x_w^4 + 14\eta^3 xw^6 + \eta^4 x_w^8\right),\end{aligned} \tag{46d}$$

$$\rho_5 = -H^2\left(1 + \eta H^2\right)\left(1 + 2\eta x_w^2 + \eta^2\left(4H^2 x_w^2 + x_w^4\right)\right)^2. \tag{46e}$$

[2]All roots of the fifth-order equation are computed using the companion matrix eigenvalue method, following the implementation in MATLAB's roots() function.

The maximum of $f_j(x_j, y_j)$ is achieved at $\mathbf{q}_j = [\omega, 0]$, where ω is the real root of

$$\begin{aligned}&H^2 - H^2\alpha - \eta H^4\alpha - x_w^2\alpha - \eta H^2 x_w^2\alpha + \left(2x_w\alpha + 2\eta H^2 x_w\alpha\right)x \\ &+ \left(1 - \alpha - 2\eta H^2\alpha - \eta x_w^2\alpha\right)x^2 + 2\eta x_w\alpha x^3 - \eta\alpha x^4 = 0\end{aligned} \tag{47}$$

Finally, substituting (41) and α into (33), the maximum covert rate of the system can be obtained as

$$R_{ab}^* = \log_2\left(1 + \eta\left(1 + \alpha\frac{x_w^2 + \sqrt{x_w^2(x_w^2 + 4H^2)}}{2H^2}\right)\right). \tag{48}$$

V. Numerical Results

In this section, numerical results are provided to demonstrate the performance advantage of the proposed method. The maximum average jamming power of Jack is set to $P_{j,\text{avg}} = 20, \text{dBm}$. The channel power gain at the reference distance of $1, \text{m}$ is set to $\beta_0 = -70, \text{dB}$. The receiver noise powers at Bob and Willie are set to $\sigma_b^2 = \sigma_w^2 = -100, \text{dBm}$. The covertness and reliability requirements are set to $\epsilon_w = \epsilon_b = 0.05$. The UAV flight altitude is fixed at $H = 100, \text{m}$. The locations of Bob and Willie are set to $\mathbf{q}_b = [0, 0]^T$ and $\mathbf{q}_w = [50, 0]^T$, respectively.

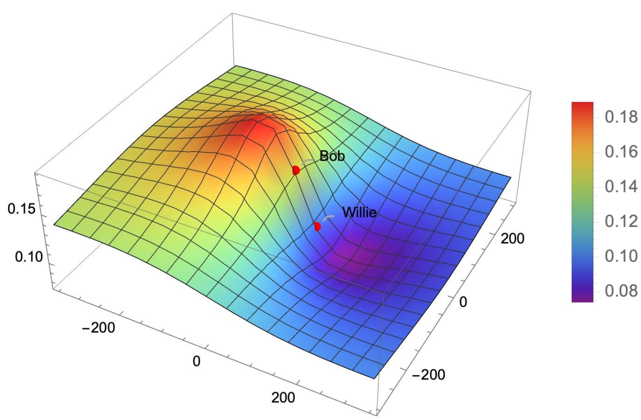

Fig. 2. Maxmum covert rate R_{ab}^* versus location of Alice $\mathbf{q}_a$.

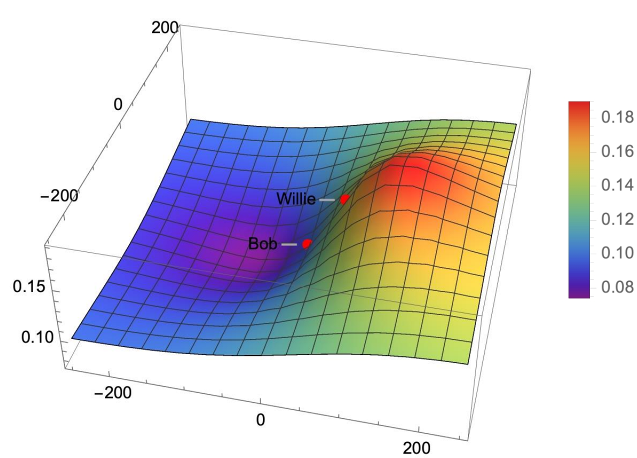

Fig. 3. Maximum covert rate R_{ab}^* versus location of Jack $\mathbf{q}_j$.

Fig. 2 illustrates the relationship between the maximum covert rate and the position of Alice when Jack is located at the optimal point. It can be observed that the maximum covert rate is significantly higher when Alice is positioned to the left of Bob than when Alice is on the right. The peak covert rate occurs along the line connecting Bob and Willie, specifically on the left side of Bob, which is consistent with the optimal solution of problem (36). The reasons can be explained as follows. Since Willie is located to the right of Bob, Alice tends to move farther away from Willie to degrade Willie's detection performance. At the same time, Alice also prefers to stay closer to Bob to enhance Bob's SINR. To maximize the covert rate, Alice should maintain a small distance from Bob while staying as far from Willie as possible.

Fig. 3 illustrates the relationship between the maximum covert rate and the position of Jack when Alice is located at the optimal point. It can be observed that the maximum covert rate is significantly higher when Jack is positioned to the right of Willie than when he is on the left. Similar to Fig. 2, the peak covert rate occurs along the line connecting Bob and Willie, specifically on the right side of Willie. This is because Jack tends to stay as close as possible to Willie while moving away from Alice, thereby enhancing the interference to Willie and further improving the covert rate.

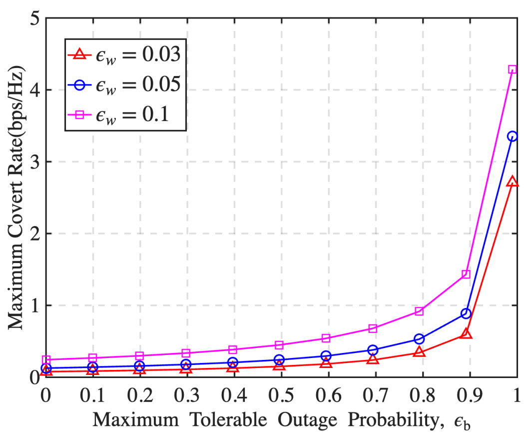

Fig. 4. Maximum covert rate R^*_{ab} versus maximum tolerable outage probability ϵ_b.

To explore the effects of the maximum tolerable outage probability ϵ_b on the maximum covert rate R^*_{ab}, we summarize in Fig. 4 how R^*_{ab} varies with ϵ_b for each setting of $\epsilon_w = \{0.03, 0.05, 0.1\}$. We can see from Fig. 4 that R^*_{ab} increases as ϵ_b increases. This is because a larger ϵ_b allows Bob to tolerate a higher jamming power, which weakens Willie's detection performance and enables Alice to increase covert transmit power.

The impact of the average jamming power $P_{j,\text{avg}}$ on the maximum covert rate R^*_{ab} is further investigated. Under each setting of $\epsilon_w = \{0.03, 0.05, 0.1\}$, Fig. 5 illustrates how R^*_{ab} varies with $P_{j,\text{avg}}$. We can see from Fig. 5 that as $P_{j,\text{avg}}$ increases, R^*_{ab} increases and then remains unchanged. The reason behind this phenomenon can be explained as follows. Note that the detection error probability of Willie and the transmission outage probability of the Alice–Bob link both

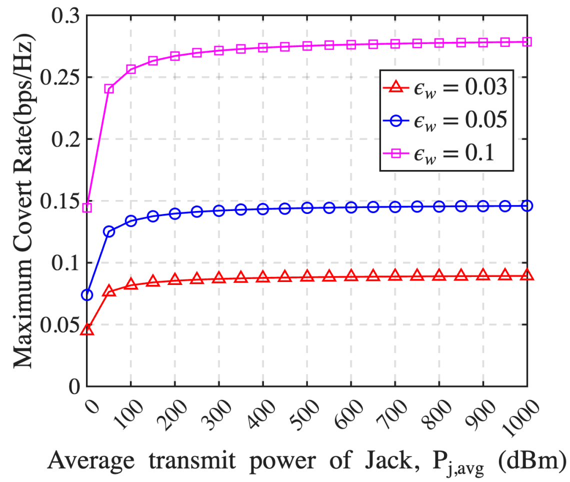

Fig. 5. Maximum covert rate R^*_{ab} versus average jamming power $P_{j,\text{avg}}$.

increase as $P_{j,\text{avg}}$ increases. The increase of the detection error probability dominates that of the transmission outage probability, which allows Alice to increase transmit power up to some threshold under the constraint of the covertness requirement, thus R^*_{ab} can increase to the maximum value.

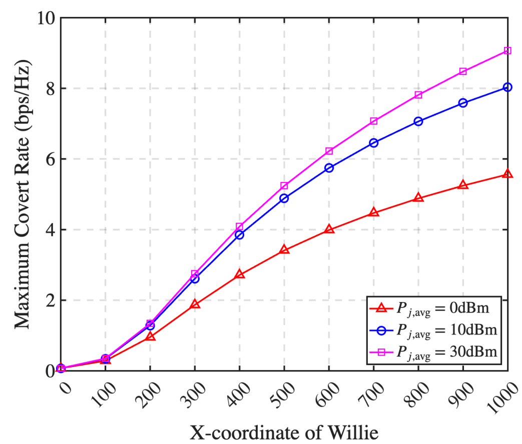

Fig. 6. Maximum covert rate R^*_{ab} versus location of Willie.

Fig. 6 depicts the variation of the maximum covert rate R^*_{ab} with respect to the distance x_w between Willie and Bob under three average jamming power levels, i.e., $P_{j,\text{avg}} = 0\text{dBm}$, $P_{j,\text{avg}} = 10\text{dBm}$, and $P_{j,\text{avg}} = 20\text{dBm}$. It can be observed that when Willie is located close to Bob, the average jamming power has a negligible impact on the maximum covert rate. In contrast, as the distance between Willie and Bob increases, the influence of the average jamming power on the system's maximum covert rate becomes more pronounced.

VI. Conclusion

This paper has studied the joint design of UAV locations and transmit power in a dual-UAV communication system. We derived the optimal detection threshold and Willie's minimum detection error probability, and characterized the optimal locations of the UAV transmitter and jammer under both the transmission-outage and covertness constraints. The results show that the proposed joint location and power design can substantially improve the covert rate of the dual-UAV system.

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