Placement Optimization of UAV Relaying for Covert Communication

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***Abstract*—Covert communication has attracted growing interests as a new security technique, which focuses on concealing the signal transmission. Owing to the high flexibility, unmanned aerial vehicles (UAVs) can be utilized to realize long-distance covert transmission. In this correspondence, we propose a UAV relaying scheme to assist the covert communication between two terrestrial nodes. Due to the high risk of eavesdropping in line-of-sight (LoS) channels, we assume that the UAV adopts the Gaussian signalling to confuse the warden's detection. First, we divide the transmission into two phases. Then, in both phases, the requirement of covertness is derived to optimize the transmit power and blocklength. With different distance between the transmitter and warden, the location of UAV is optimized to maximize the effective throughput under the constraint of transmit power and blocklength. Simulation results show the effectiveness of the proposed UAV relaying scheme to guarantee the covert transmission.**

***Index Terms*—Covert communication, unmanned aerial vehicle, relay, location optimization, finite blocklength.**

I. Introduction

Owing to the ubiquitous wireless connectivity, the security concerns of signal transmission are raised in both civilian and military applications [1]. Most of the traditional security techniques only concern whether the transmitted information (rather than the signal) is eavesdropped. However, the exposure of transmission signal itself can also cause serious security risk in some specific scenarios. In order to hide the existence of the signal transmission, covert communication, an emerging security technique, has attracted increasing research interests.

In covert communications, the transmitter is expected to send message to the receiver without being detected by the warden. Bash *et al*. found the information-theoretic limits of covert transmission in [2]. With n channels used, at most $\mathcal{O}(\sqrt{n})$ bits can be transmitted covertly. Based on Bash's results, a series of studies on covert communications have been carried out [3]–[5]. Yan *et al*. concluded in [3] that the Gaussian signalling is the optimal transmitting form to achieve the covertness from the perspective of information theory. In [4], Khurram *et al*. derived the optimal threshold to for the detection of the warden. Yang *et al*. proposed a covert wireless network with a full-duplex multi-antenna receiver in [5], where the secrecy capacity increases with the number of antennas. We can notice that these works are based on the infinite channels used when $n \to \infty$. In fact, with the rapid development of internet of things (loT), low-latency and high-reliability communications have drawn great attentions. Yan *et al*. described a delay-intolerant scheme in [6], and the optimal number of channel uses for covert communication was derived to maximize the effective covert throughput (ECT). In [7], a new metric named covert age of information was proposed by Yang *et al*. in the short-packet communication with finite blocklength. In addition, Zhou *et al*. verified that the performance of the delay-constraint covert communication can be enhanced by properly using IRS [8].

Recently, unmanned aerial vehicle (UAV) has brought a great upsurge in communications because of its flexibility, easy deployment and low consumption [9]–[11]. Benefiting from the high quality of line-of-sight (LoS) channels, UAVs can perform as a base station [12] or work as relays to assist the long-distance transmission [13]. However, the superior LoS channel also leads to the high risk of being interception in UAV-aided covert networks [14]. Against this challenge, Chen *et al*. in [15] adopted a multi-antenna jammer to assist the UAV-aided covert network. Yan *et al*. jointly derived the optimal transmit power and hovering location of UAV to maximize the signal-to-noise ratio (SNR) of receiver with the requirement of covertness in [16]. Zhou *et al*. in [17] considered a full-duplex UAV receiver to gather the information from a scheduled user, and utilize artificial noise to confuse the detection of the unscheduled users.

To our best knowledge, the UAV relay can be used to extend the range of covert transmission. However, it is only considered in a few related works [18]. Chen *et al*. jointly optimized the blocklength and transmit power in [18] to maximize the ECT against a flying warden, with the fixed placement of UAV. Motivated by this, in this correspondence, we utilize a UAV relay to assist the covert transmission of two terrestrial nodes with a ground warden. To avoid the unwanted

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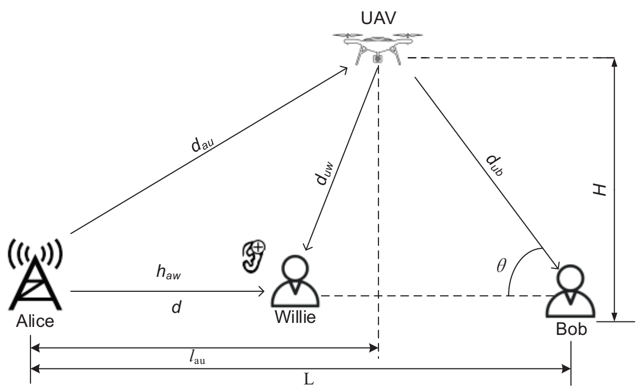

Fig. 1. Covert communication from Alice to Bob assisted by a UAV relay under the detection of Willie

detection by warden, the UAV utilizes Gaussian signalling for transmission. With the optimal blocklength and transmit power, the SNRs of UAV and receiver are obtained to optimize the hovering location, and the ECT can be maximized with different distance between the transmitter and warden.

The rest of the paper is organized as follows. The system model is described in Section II. Section III analyzes the detection at warden and derives the requirement of covertness. The optimal blocklength, transmit power and hovering location of UAV are derived in Section IV. Simulation results are presented in Section V with the conclusion drawn in Section VI.

II. System model

Consider a covert communication network as illustrated in Fig. 1, where a transmitter Alice expects to send message to a remote receiver Bob under the detection of a warden Willie, who aims at determining whether Alice is transmitting or not. Due to the fact that the distance between Alice and Bob is long and their channel is poor, we utilize a UAV relay to assist the covert communication between Alice and Bob. Assume that the decode-and-forward (DF) relaying is adopted, and the transmission can be divided into two phases. In the first phase, Alice transmits the signal with the probability of 0.5 to the UAV with the finite number of channel uses n. Once Alice determines to transmit, in the second phase, the UAV relay will decode and forward the signal to Bob with the same channel uses. Otherwise, the UAV relay keeps silence.

In the system, the distance between Alice and Bob is L, and the height of UAV is H. Assume that the air-ground channels can be approximated as LoS links because the UAV relay is located high enough [19]. Under this assumption, the channel coefficients of UAV follow the free-space path-loss model as

$$h_{ij} = \sqrt{\beta_0 d_{ij}^{-2}} = \sqrt{\beta_{ij}}, ij \in \{au, uw, ub\}, \tag{1}$$

where β_0 denotes the channel power gain at the unit distance of 1 m, and d_{ij} represents the distance between the nodes according to the subscript. The ground-ground channel coefficient from Alice to Willie consists of both large-scale pass loss with the exponent $\alpha > 2$ and small-scale fading, which can be expressed as

$$h_{aw} = \sqrt{\beta_0 d_{aw}^{-\alpha}} g_{aw} = \sqrt{\beta_{aw}} g_{aw}, \tag{2}$$

where g_{aw} is subject to the quasi-state Rayleigh fading of $\mathcal{CN}(0,1)$. All the devices are equipped with a single antenna. Assume that Alice and the UAV relay have the information of Willie's location, and thus its channel state information can be estimated [16]. The complex additive white Gaussian noise (AWGN) at Willie, UAV and Bob can be denoted as n_w, n_u and n_b, respectively, where $n_w \sim \mathcal{CN}(0,\sigma_w^2)$, $n_u \sim \mathcal{CN}(0,\sigma_u^2)$ and $n_b \sim \mathcal{CN}(0,\sigma_b^2)$. For simplicity, assume that $\sigma_m^2 = \sigma^2$ for $m \in \{u, w, b\}$.

III. Detection at Willie

In this section, we present the detection of Willie in the two phases of relaying, respectively.

A. Willie's Detection of Alice

In the first phase, Alice transmits the signal $x_a[i], i = 1, 2, \cdots, n$, with the fixed transmit power P_a. In order to detect whether there exists the transmission from Alice, the goal of Willie is to identify the binary assumptions as

$$\begin{cases} \mathbb{H}_0 : y_{aw}[i] = n_w[i], \\ \mathbb{H}_1 : y_{aw}[i] = \sqrt{P_a \beta_0 d_{aw}^{-\alpha}} g_{aw} x_a[i] + n_w[i], \end{cases} \tag{3}$$

where the distance from Alice to Willie is $d_{aw} = d$, $\mathbb{H}_0$ means that Alice keeps silence, and $\mathbb{H}_1$ denotes that Alice is transmitting. Note that g_{aw} and n_w both follow the complex Gaussian distribution, which are independent of each other, and we have

$$\begin{cases} \mathbb{H}_0 : y_{aw}[i] \sim \mathcal{CN}(0,\sigma_w^2), \\ \mathbb{H}_1 : y_{aw}[i] \sim \mathcal{CN}(0, P_a\beta_{aw} + \sigma_w^2). \end{cases} \tag{4}$$

The average received power T_{aw} can be represented as

$$T_{aw} = \frac{1}{n}\sum_{i=1}^{n} |y_{aw}[i]|^2 \underset{D_0}{\overset{D_1}{\gtrless}} \Gamma, \tag{5}$$

where D_0 and D_1 denote the detection results when Alice keeps silence and Alice is transmitting, respectively. The detection threshold at Willie is Γ. There are two error situations in the detection. When Alice keeps silence and the result of detection is transmitting, this is named as the false alarm, $\mathbb{P}_{FA} = Pr(D_1|\mathbb{H}_0) = Pr(T_{aw} > \Gamma|\mathbb{H}_0)$. In contrast, when Alice is transmitting and the detection is that Alice keeps silence, this is known as the miss detection, $\mathbb{P}_{MD} = Pr(D_0|\mathbb{H}_1) = Pr(T_{aw} < \Gamma|\mathbb{H}_1)$.

Thus, the total error probability of Willie can be given by

$$\mathbb{P}_e = \pi_0 \mathbb{P}_{FA} + \pi_1 \mathbb{P}_{MD} \geq 1 - \epsilon, \tag{6}$$

where $\epsilon > 0$ indicates the requirement of covert communication. π_1 or π_0 denotes the priori probability of transmitting or not.

Assume that Willie has the perfect knowledge of P_a and g_{aw}. Then, the optimal detection threshold Γ^* can be given by the likelihood ratio test as

$$\Gamma^* = \frac{\sigma_w^2\left(\sigma_w^2 + P_a\beta_{aw}\right)}{P_a\beta_{aw}} \ln\left(\frac{\sigma_w^2 + P_a\beta_{aw}}{\sigma_w^2}\right). \tag{7}$$

Considering the distribution function of the received signal in (4), we have

$$\begin{cases}\mathbb{H}_0 : T_{aw} = \lim_{n\to N} \frac{\sigma_w^2\chi^2(2n)}{n}, \\ \mathbb{H}_1 : T_{aw} = \lim_{n\to N} \frac{(P_a\beta_{aw}+\sigma_w^2)\chi^2(2n)}{n},\end{cases} \tag{8}$$

where N is the maximum transmitted symbols and $\chi^2(2n)$ denotes the chi-square distribution with $2n$ degrees of freedom. Considering the optimal test at Willie with the detection threshold Γ^* and equal priori probability $\pi_0 = \pi_1 = 0.5$, we have

$$\begin{aligned}\mathbb{P}_e &= \mathbb{P}_{FA} + \mathbb{P}_{MD} \\ &= Pr(T_{aw} > \Gamma^*|\mathbb{H}_0) + Pr(T_{aw} < \Gamma^*|\mathbb{H}_1), \\ &= 1 - \frac{\gamma(n, \frac{n\Gamma^*}{\sigma_w^2})}{(n-1)!} + \frac{\gamma(n, \frac{n\Gamma^*}{P_a\beta_{aw}+\sigma_w^2})}{(n-1)!},\end{aligned} \tag{9}$$

where $\gamma(\cdot,\cdot)$ is denoted by the incomplete gamma function as

$$\gamma(n,x) = \int_0^x e^{-t}t^{n-1}\,dt. \tag{10}$$

For this optimal test, (9) can be expressed as

$$\mathbb{P}_e = 1 - \mathcal{V}_T(\mathbb{P}_{0_{aw}}, \mathbb{P}_{1_{aw}}) \geq 1 - \epsilon, \tag{11}$$

where $\mathbb{P}_{0_{aw}}$ and $\mathbb{P}_{1_{aw}}$ denote the probability distributions (4) of the signal received at Willie from Alice under $\mathbb{H}_0$ and $\mathbb{H}_1$, respectively. $\mathcal{V}_T(\mathbb{P}_{0_{aw}}, \mathbb{P}_{1_{aw}})$ represents the total variation distance between $\mathbb{P}_{0_{aw}}$ and $\mathbb{P}_{1_{aw}}$. By using the Pinsker's inequality [2], (11) can be simplified as

$$1 - \mathcal{V}_T(\mathbb{P}_{0_{aw}}, \mathbb{P}_{1_{aw}}) \geq \sqrt{\frac{1}{2}D(\mathbb{P}_{0_{aw}}||\mathbb{P}_{1_{aw}})} \geq 1 - \epsilon, \tag{12}$$

where $D(\mathbb{P}_{0_{aw}}||\mathbb{P}_{1_{aw}})$ is the relative entropy between $\mathbb{P}_{0_{aw}}$ and $\mathbb{P}_{1_{aw}}$, which is denoted as

$$D(\mathbb{P}_{0_{aw}}||\mathbb{P}_{1_{aw}}) = \int_x \mathbb{P}_{0_{aw}}(x) \ln\frac{\mathbb{P}_{0_{aw}}(x)}{\mathbb{P}_{1_{aw}}(x)}\,dx. \tag{13}$$

Thus, the constraint of covert communication in the first phase can be given by

$$D(\mathbb{P}_{0_{aw}}||\mathbb{P}_{1_{aw}}) \leq 2\epsilon^2, \tag{14}$$

which can be also expressed as

$$n\left[\ln\left(\frac{P_a\beta_{aw} + \sigma_w^2}{\sigma_w^2}\right) - \frac{P_a\beta_{aw}}{P_a\beta_{aw} + \sigma_w^2}\right] \leq 2\epsilon^2. \tag{15}$$

B. Willie's Detection of UAV

In the second phase, the UAV acts as a relay to retransmit the signal to Bob under the detection of Willie. The UAV forwards the signal $x_u[i]$ with a Gaussian signalling random variable ξ, where the variance $\mathbb{E}[|x_u[i]|^2] = 1$. Thus, we have $\xi x_u[i] \sim \mathcal{CN}(0, P_u)$, where P_u denotes the transmit power of the relay. Willie needs to identify the binary assumptions as

$$\begin{cases}\mathbb{H}_0 : y_{uw}[i] = n_w[i], \\ \mathbb{H}_1 : y_{uw}[i] = \sqrt{\beta_0 d_{uw}^{-2}}\xi x_u[i] + n_w[i].\end{cases} \tag{16}$$

Similar to (8), the average received power T_{uw} at Willie from the relay can be expressed as

$$\begin{cases}\mathbb{H}_0 : T_{uw} = \lim_{n\to N} \frac{\sigma_w^2\chi^2(2n)}{n}, \\ \mathbb{H}_1 : T_{uw} = \lim_{n\to N} \frac{(P_u\beta_{uw}+\sigma_w^2)\chi^2(2n)}{n}.\end{cases} \tag{17}$$

To be consistent with the first phase, we adopt the same ϵ in Willie's detection of the UAV relaying. In this case, we have

$$D(\mathbb{P}_{0_{uw}}||\mathbb{P}_{1_{uw}}) \leq 2\epsilon^2, \tag{18}$$

where $D(\mathbb{P}_{0_{uw}}||\mathbb{P}_{1_{uw}})$ is the relative entropy between $\mathbb{P}_{0_{uw}}$ and $\mathbb{P}_{1_{uw}}$. (18) can be also expressed as

$$n\left[\ln\left(\frac{P_u\beta_{uw} + \sigma_w^2}{\sigma_w^2}\right) - \frac{P_u\beta_{uw}}{P_u\beta_{uw} + \sigma_w^2}\right] \leq 2\epsilon^2. \tag{19}$$

IV. Optimization for Alice and UAV Relay

In this section, the effective throughput from Alice to Bob is maximized while satisfying the covert constraints.

A. Problem Formulation

During the transmission, the received signals $y_{au}[i]$ and $y_{ub}[i]$ can be represented as

$$\begin{cases}y_{au}[i] = \sqrt{P_a\beta_0 d_{au}^{-2}}x_a[i] + n_u[i], \\ y_{ub}[i] = \sqrt{\beta_0 d_{ub}^{-2}}\xi x_u[i] + n_b[i],\end{cases} \tag{20}$$

where the SNRs of UAV and Bob can be denoted as $\gamma_{au} = P_a\beta_{au}/\sigma^2$ and $\gamma_{ub} = P_u\beta_{ub}/\sigma^2$, respectively.

Considering the finite blocklength of transmission and the non-trivial decoding error probability, the transmission rate and the effective throughput can be respectively expressed as [20]

$$R_k = \log_2(1+\gamma_k) - \sqrt{\frac{\gamma_k(\gamma_k+2)}{n(\gamma_k+1)^2}}\frac{Q^{-1}(\delta)}{\ln(2)}, \tag{21}$$

$$\eta_k = nR_k(1-\delta), \tag{22}$$

where $k \in \{au, ub\}$, γ_k is the received SNR, δ is the requirement of decoding error probability, and $Q^{-1}(\cdot)$ is the inversion of Q function.

In order to evaluate the performance of covert communication, we define the achievable effective throughput from Alice to Bob as

$$\eta = \min(\eta_{au}, \eta_{ub}), \tag{23}$$

which should be maximized while ensuring that the probability of detection error is large enough in both phases. Thus, the optimization problem can be formulated as

$$\max_{\mathbf{P},n,l_{au}} \quad \min(\eta_{au}, \eta_{ub}), \tag{24a}$$

$$s.t. \; D(\mathbb{P}_{0_{aw}}||\mathbb{P}_{1_{aw}}) \leq 2\epsilon^2, \tag{24b}$$

$$D(\mathbb{P}_{0_{uw}}||\mathbb{P}_{1_{uw}}) \leq 2\epsilon^2, \tag{24c}$$

$$n \leq N, \tag{24d}$$

where $\mathbf{P} = \{P_u, P_a\}$ denotes the transmit power, and l_{au} represents the horizontal distance between Alice and UAV.

B. Optimization of Blocklength and Power

According to Theorem 1 in [6], the optimal channel uses can be calculated by $n^* = N$. Thus, the general optimal received power can be derived as

$$P^* = \left(P^* + \sigma_w^2\right)\left[\ln\left(\frac{P^* + \sigma_w^2}{\sigma_w^2}\right) - \frac{2\epsilon^2}{N}\right]. \tag{25}$$

Then, the optimal values of P_a and P_u can be given by

$$\begin{cases} P_a^* \beta_{aw} = P^*, \\ P_u^* \beta_{uw} = P^*. \end{cases} \tag{26}$$

When the optimal transmit power is adopted, the received SNRs of UAV and Bob can be rewritten as $\gamma_{au} = P^* d^\alpha / (\sigma^2 d_{au}^2)$ and $\gamma_{ub} = P^* d_{uw}^2 / (\sigma^2 d_{ub}^2)$, respectively.

C. Optimization of UAV Location

Assume that δ is a constant and the effective throughputs η_{au} and η_{ub} are monotonically increasing with their SNRs γ_{au} and γ_{ub} according to Proposition 4 in [18]. Therefore, we need to compare γ_{au} and γ_{ub} to obtain the optimal position of UAV. Define $\theta = \arctan(H/(L - l_{au}))$ as the elevation angle of UAV to Bob. The range of θ is $[\theta_{\min}, \pi/2]$, where $\theta_{\min} = \arctan(H/L)$ means the minimum elevation angle. According to the geometry, we have

$$\begin{cases} d_{au} = \sqrt{L^2 + (H/\sin\theta)^2 - 2LH\cot\theta}, \\ d_{ub} = H/\sin\theta, \\ d_{uw} = \sqrt{(L-d)^2 + (H/\sin\theta)^2 - 2(L-d)H\cot\theta}. \end{cases} \tag{27}$$

Thus, γ_{au} can be rewritten as

$$\gamma_{au} = \frac{P^*}{\sigma^2} \frac{d^\alpha}{L^2 + (H/\sin\theta)^2 - 2LH\cot\theta}, \tag{28}$$

where the denominator of γ_{au} monotonically increases with respect to θ while the numerator is a constant. Thus, the maximum and minimum values of γ_{au} can be denoted by $\gamma_{au}|_{\theta_{\min}} = \gamma_{au}^{\max}$ and $\gamma_{au}|_{\pi/2} = \gamma_{au}^{\min}$, respectively.

Similarly, γ_{ub} can be given by

$$\gamma_{ub} = \frac{P^*}{\sigma^2} \frac{(L-d)^2 + (H/\sin\theta)^2 - 2(L-d)H\cot\theta}{(H/\sin\theta)^2}. \tag{29}$$

Then, we can obtain the monotonicity of γ_{ub} with the following lemma.

Lemma 1: When $\tan(2\theta_{\min}) \geq \tan\theta_c \geq 0$, γ_{ub} monotonically increases with θ. When $\tan\theta_c \geq \tan(2\theta_{\min}) \geq 0$, γ_{ub} decreases with $\theta \in [\theta_{\min}, \theta_c/2]$ and increases with $\theta \in [\theta_c/2, \pi/2]$.

Table I
Optimal location of UAV in different scenarios.

Condition	**Optimal location**
$\tan\theta_c \leq \tan(2\theta_{\min})$, $\gamma_{au}^{\max} \leq \gamma_{ub}^{\min}$ or $\tan\theta_c \geq \tan(2\theta_{\min})$, $\gamma_{au}^{\max} \geq \gamma_{ub}^{\max_1}$, $\gamma_{au}^{\min} \leq \gamma_{ub}^{\max_2}$, $\gamma_{ub}^{\max_1} \geq \gamma_{ub}\|_{\theta_i}$	$\theta = \arctan(H/L)$
$\tan\theta_c \geq \tan(2\theta_{\min})$, $\gamma_{au}^{\max} \geq \gamma_{ub}^{\max_1}$, $\gamma_{au}^{\min} \leq \gamma_{ub}^{\max_2}$, $\gamma_{ub}^{\max_1} \leq \gamma_{ub}\|_{\theta_i}$ or $\tan\theta_c \leq \tan(2\theta_{\min})$, $\gamma_{au}^{\max} \geq \gamma_{ub}^{\min}$, $\gamma_{au}^{\min} \leq \gamma_{ub}^{\max}$	$\theta = \theta_i$
$\gamma_{au}^{\min} \geq \gamma_{ub}^{\max}$	$\theta = \pi/2$

Proof: In order to prove the monotonicity of γ_{ub}, the derivative of γ_{ub} with respect to θ can be expressed as

$$\begin{aligned} \frac{\partial \gamma_{ub}}{\partial \theta} &= \frac{P^*}{\sigma^2} \frac{(L-d)^2 \sin 2\theta - 2H(L-d)\cos 2\theta}{H^2} \\ &= \frac{P^*}{\sigma^2} \frac{2(L-d)\sqrt{H^2 + ((L-d)/2)^2} \sin(2\theta - \theta_c)}{H^2}, \end{aligned} \tag{30}$$

where θ_c can be denoted as

$$\tan\theta_c = \frac{2H}{L-d}. \tag{31}$$

In addition, the existence of the stagnation point depends on $\theta_c/2 \in [\theta_{\min}, \pi/2]$.

Considering (30), $\partial\gamma_{ub}/\partial\theta \geq 0$ and $\sin(2\theta - \theta_c) \geq 0$ have the same solution with respect to θ. Thus, when $\tan(2\theta_{\min}) \geq \tan\theta_c \geq 0$, it means that $\sin(2\theta - \theta_c) \geq 0$ holds due to the fact that $\theta_{\min}$ and θ_c lie in $[0, \pi/2]$. Meanwhile, $\partial\gamma_{ub}/\partial\theta \geq 0$ holds. Similarly, when $\tan\theta_c \geq \tan(2\theta_{\min}) \geq 0$, $\partial\gamma_{ub}/\partial\theta$ is negative for $\theta \in [\theta_{\min}, \theta_c/2]$ and positive for $\theta \in [\theta_c/2, \pi/2]$. ■

According to Lemma 1, when $\tan(2\theta_{\min}) \geq \tan\theta_c \geq 0$, the minimum and maximum of γ_{ub} can be denoted by $\gamma_{ub}|_{\theta_{\min}} = \gamma_{ub}^{\min}$ and $\gamma_{ub}|_{\pi/2} = \gamma_{ub}^{\max}$, respectively. When $\tan\theta_c \geq \tan(2\theta_{\min}) \geq 0$, we denote $\gamma_{ub}|_{\theta_{\min}} = \gamma_{ub}^{\max_1}$, $\gamma_{ub}|_{\theta_c/2} = \gamma_{ub}^{\min}$, and $\gamma_{ub}|_{\pi/2} = \gamma_{ub}^{\max_2}$.

With different distance between Alice and Willie, four scenarios are discussed as follows.

1) $tan\theta_c \leq tan(2\theta_{\min})$ and $\gamma_{au}^{\max} \leq \gamma_{ub}^{\min}$: In this scenario, we have

$$\tan\theta_c = \frac{2H}{L-d} \leq \tan(2\theta_{\min}) = \frac{2LH}{L^2 - H^2}, \tag{32}$$

$$\gamma_{au}^{\max} = \frac{P^*}{\sigma^2} \frac{d^\alpha}{H^2} \leq \gamma_{ub}^{\min} = \frac{P^*}{\sigma^2} \frac{H^2 + d^2}{H^2 + L^2}, \tag{33}$$

where (32) can be simplified to $H^2 \geq Ld$. When (32) and (33) hold, γ_{ub} is always larger than γ_{au} due to the monotonicity derived in Lemma 1. At this point, the ECT is the same as η_{au}. Thus, we conclude that the optimal location of UAV is just above Alice.

2) $tan\theta_c \leq tan(2\theta_{\min})$, $\gamma_{au}^{\max} \geq \gamma_{ub}^{\min}$ and $\gamma_{au}^{\min} \leq \gamma_{ub}^{\max}$: Following Scenario 1), we still hold $H^2 \geq Ld$. Based on this, assume $\gamma_{au}^{\max} \geq \gamma_{ub}^{\min}$ and $\gamma_{au}^{\min} \leq \gamma_{ub}^{\max}$, which can be expressed as

$$\gamma_{au}^{\max} = \frac{P^*}{\sigma^2} \frac{d^\alpha}{H^2} \geq \gamma_{ub}^{\min} = \frac{P^*}{\sigma^2} \frac{H^2 + d^2}{H^2 + L^2}, \tag{34}$$

$$\gamma_{au}^{\min}=\frac{P^*}{\sigma^2}\frac{d^\alpha}{H^2+L^2}\le\gamma_{ub}^{\max}=\frac{P^*}{\sigma^2}\frac{H^2+(L-d)^2}{H^2}. \quad (35)$$

Due to the monotonicity and continuity of γ_{au} and γ_{ub}, they intersect at $\gamma_{au}|_{\theta_i}=\gamma_{ub}|_{\theta_i}$, where θ_i means the elevation angle of the intersection. Note that $\gamma=\min(\gamma_{au},\gamma_{ub})$ is determined by the smaller one of γ_{au} and γ_{ub}, and we can conclude that γ increases with $\theta\in[\theta_{\min},\theta_i]$, and decreases with $\theta\in[\theta_i,\pi/2]$. Therefore, it can be found that the optimal location of UAV lies at the position relative to $\theta=\theta_i$.

3) $tan\theta_c\ge tan(2\theta_{\min})$, $\gamma_{au}^{\max}\ge\gamma_{ub}^{\max_1}$ and $\gamma_{au}^{\min}\le\gamma_{ub}^{\max_2}$: With the increase of d, we have $H^2\le Ld$. In this case, γ_{ub} does not monotonously vary with θ, and $\gamma_{au}^{\max}$ is always larger than $\gamma_{ub}^{\max_1}$ as

$$\gamma_{au}^{\max}=\frac{P^*}{\sigma^2}\frac{d^\alpha}{H^2}\ge\gamma_{ub}^{\max_1}=\frac{P^*}{\sigma^2}\frac{H^2+d^2}{H^2+L^2}. \quad (36)$$

Recalling that α is larger than 2, (36) can be proved by

$$\frac{\gamma_{au}^{\max}}{\gamma_{ub}^{\max_1}}\ge\frac{d^2(H^2+L^2)}{H^2(H^2+d^2)}\ge\frac{H^2d^2+H^4}{H^4+H^2d^2}=1. \quad (37)$$

Therefore, the situation with $\gamma_{au}^{\max}\le\gamma_{ub}^{\max_1}$ is not considered. The condition of $\gamma_{au}^{\min}\le\gamma_{ub}^{\max_2}$ is the same as (35). Similar to Scenario 2), γ_{au} intersects with γ_{ub}. However, the monotonicity of γ is different. There are two points that can be selected as the optimal location, $\theta=\theta_{\min}$ and $\theta=\theta_i$, which is determined by the magnitude relationship between $\gamma_{ub}^{\max_1}$ and $\gamma_{ub}|_{\theta_i}$. Thus, $\max\{\gamma_{ub}^{\max_1},\gamma_{ub}|_{\theta_i}\}$ is derived as the optimal γ, and we can obtain the corresponding optimal location.

4) $\gamma_{au}^{\min}\ge\gamma_{ub}^{\max}$: In this scenario, $\gamma_{au}\ge\gamma_{ub}$ holds. This is because $\gamma_{au}^{\max}\ge\gamma_{ub}^{\max_1}$ holds for $H^2\le Ld$ as proved in Scenario 3), and γ_{ub} monotonically increases with θ for $H^2\ge Ld$. Thus, γ is equal to γ_{ub} in this situation, and the optimal location of UAV is right above Bob.

Based on the above derivations, we can obtain the optimal location of UAV in different scenarios according to θ, as summarized in Table I.

V. Simulation Results

In this section, we present simulation results to verify the above analysis. Assume that the distance between Alice and Bob is $L=800$ m and the UAV is hovering at $H=200$ m. The maximum transmitted symbols in a signal transmission is $N=200$. The path-loss exponent from Alice to Willie is $\alpha=3.4$ and the channel power gain at the unit distance of 1 m is $\beta_0=-60$ dB. In addition, the noise power at receivers are set as $\sigma^2=-60$ dBm. The decoding error probability is $\delta=0.1$ at both UAV and Bob.

Fig. 2 illustrates the effective SNR γ between Alice and Bob versus ϵ with different Willie's locations d. It is expected that γ increases with ϵ, since when ϵ gets larger, the transmit power derived by (25) increases. We can also observe that the performance with the optimal location in Table I significantly outperforms that with the other locations of UAV. When d increases from $d=40$ m in Scenario 2 to $d=80$ m in Scenario 3, the optimal location gets closer to Bob. In addition, Scenario 1 and Scenario 4 are not shown here, since the results of the optimal location are consistent with the curves when the UAV is above Alice and Bob, respectively.

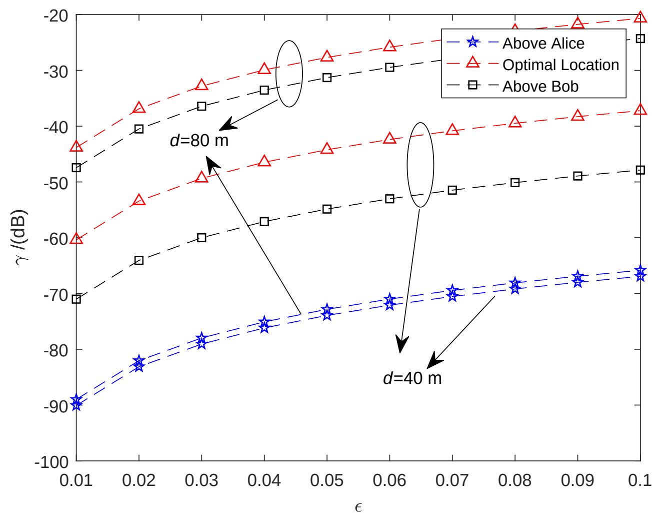

Fig. 2. The effective γ versus ϵ with different locations of Willie.

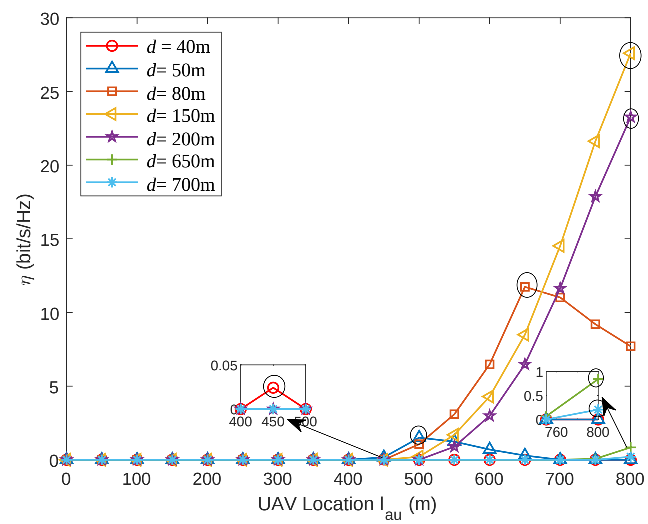

Fig. 3. The ECT η versus the locations of UAV and Willie.

The impact of UAV's location l_{au} and Willie's location d on the ECT η between Alice and Bob is shown in Fig. 3, with the optimal locations of UAV circled. First, we observe that η approaches zero when $d=40$ m in Scenario 2 due to the short detection distance between Alice and Willie. Then, when $d=80$ m, we can see that η first increases and then decreases with l_{au}, subject to Scenario 3. In Scenario 4 when $d=150$ m / 200 m, the increase of d limits the transmit power of UAV, resulting the decrease of η. When $d=650$ m/ 700 m, the short distance between Willie and Bob will also lead to the failure of covert communication.

Then, we investigate the influence of the path-loss exponent from Alice to Willie α on the ECT η between Alice and Bob in Fig. 4. We set the distance between Alice and Bob as $d=100$ m. From the results, we can see that the optimal location moves towards Bob when the path-loss exponent α increases, which is similar to the d. This can be explained

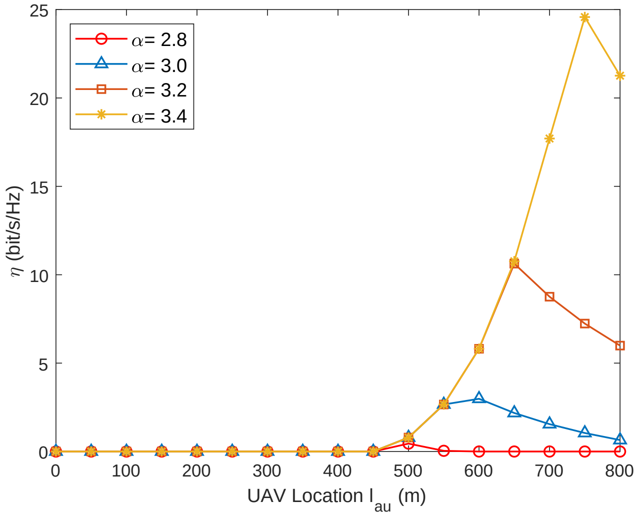

Fig. 4. The ECT η versus the path-loss exponent from Alice to Willie α.

in (26). The transmit power P_a increases with α due to the worse detection scenario. Thus, γ_{au} increases but γ_{ub} remains unchanged, which leads to the movement of optimal location and the increase of the optimal ECT.

VI. Conclusion

In this correspondence, we have proposed a two-phase covert communication scheme with finite blocklength assisted by a UAV relay. The transmission is divided into two phases due to the UAV relay, where Alice utilizes the channel uncertainty in the first phase, and the UAV performs Gaussian signalling in the second phase to mislead the detection of warden. With the optimal detection by the warden, the transmit power at Alice and UAV, the blocklength, and the hovering location in different scenarios according to d are jointly optimized to maximize the ECT, while satisfying the requirement of covertness. Simulation results show the effectiveness of the covert communication in the proposed UAV relaying scheme.

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