Placement Optimization of UAV Relaying for Covert Communication

Linhang Jiao, Ran Zhang, Mingqian Liu, Member, IEEE, Qiaozhi Hua, Nan Zhao, Senior Member, IEEE, Arumugam Nallanathan, Fellow, IEEE, and Xianbin Wang, Fellow, IEEE

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 $O(\sqrt{n})$ 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 $n \rightarrow \infty$. In fact, with the rapid development of internet of things (IoT), 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
detection by warden, the UAV utilizes Gaussian signalling for transmission. With the optional 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 and the transmission can be divided into two phases. In the second phase, the UA V relay will decode and forward the signal to Bob with the same power that Alice determined to transmit.

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

\[ h_{ij} = \sqrt{\beta_0 d_{ij}^{-\alpha}} = \sqrt{\beta_{ij}}, \quad ij \in \{ au, uw, ub \}, \]

where \( \beta_0 \) 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

\[ h_{aw} = \sqrt{\beta_0 d_{aw}^{-\alpha}} g_{aw} = \sqrt{\beta_{aw}} g_{aw}, \]

where \( g_{aw} \) is subject to the quasi-state Rayleigh fading of \( CN(0, 1) \). 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 \( n_w \sim CN(0, \sigma_w^2) \), \( n_u \sim CN(0, \sigma_u^2) \) and \( n_b \sim CN(0, \sigma_b^2) \). 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 \( x_a[i], i = 1, 2, \ldots, n \), 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

\[
\begin{align*}
\mathbb{H}_0 : y_{aw}[i] &= n_w[i], \\
\mathbb{H}_1 : y_{aw}[i] &= \sqrt{P_a \beta_0 d_{aw}^{-\alpha} g_{aw} x_a[i]} + n_w[i].
\end{align*}
\]

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

\[
\begin{align*}
\mathbb{H}_0 : y_{aw}[i] &\sim CN(0, \sigma_w^2), \\
\mathbb{H}_1 : y_{aw}[i] &\sim CN(0, P_a \beta_0 + \sigma_w^2).
\end{align*}
\]

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

\[
T_{aw} = \frac{1}{n} \sum_{i=1}^{n} |y_{aw}[i]|^2 \geq \frac{D_1}{D_0},
\]

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 \( \Gamma \). 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, \( P_{FA} = Pr(D_1 | \mathbb{H}_0) = Pr(T_{aw} > \Gamma | \mathbb{H}_0) \). In contrast, when Alice is transmitting and the detection is that Alice keeps silence, this is known as the miss detection, \( P_{MD} = Pr(D_0 | \mathbb{H}_1) = Pr(T_{aw} < \Gamma | \mathbb{H}_1) \).

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

\[
P_e = \pi_0 P_{FA} + \pi_1 P_{MD} \geq 1 - \epsilon,
\]

where \( \epsilon > 0 \) indicates the requirement of covert communication. \( \pi_1 \) or \( \pi_0 \) 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 $\Gamma^*$ can be given by the likelihood ratio test as

$$\Gamma^* = \frac{\sigma_w^2 \left( \chi^2(2n) \right)}{\lambda_a \chi^2(2n)} \ln \left( \frac{\sigma_w^2 + \lambda_a \chi^2(2n)}{\sigma_w^2} \right).$$

(7)

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

$$\begin{cases}
\mathbb{P}_0(T_{aw} < \Gamma^* | \mathbb{H}_0) = \frac{\gamma(n, \frac{n \Gamma^*}{\sigma_w})}{(n-1)!} + \frac{\gamma(n, \frac{n \Gamma^*}{\sigma_w + \sigma_w^*})}{(n-1)!}, \\
\mathbb{P}_1(T_{aw} < \Gamma^* | \mathbb{H}_1) = \frac{\gamma(n, \frac{n \Gamma^*}{\sigma_w})}{(n-1)!} + \frac{\gamma(n, \frac{n \Gamma^*}{\sigma_w + \sigma_w^*})}{(n-1)!},
\end{cases}$$

(9)

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

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

(10)

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

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

(11)

where $\mathbb{P}_{0_{aw}}$ and $\mathbb{P}_{1_{aw}}$ denote the probability distributions of the signal received at Willie from Alice under $\mathbb{H}_0$ and $\mathbb{H}_1$, respectively. $\mathbb{V}_T(\mathbb{P}_{0_{aw}}, \mathbb{P}_{1_{aw}})$ 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

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

(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

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

(13)

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

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

(14)

which can be also expressed as

$$n \left[ \ln \left( \frac{\lambda_a \chi^2(2n)}{\sigma_w^2} \right) - \frac{\lambda_a \chi^2(2n)}{\sigma_w^2} \right] \leq 2\epsilon^2.$$  

(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 $\xi$, where the variance $\text{var}[x_u[i]] = 1$. Thus, we have $x_u[i] \sim \mathcal{CN}(0, P_u)$, where $P_u$ denotes the transmit power of the relay. Willie needs to identify the binary assumptions as

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

(16)

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

$$\begin{cases}
\mathbb{H}_0 : T_{uw} = \lim_{n \to \infty} \frac{\sigma_w^2 \chi^2(2n)}{n}, \\
\mathbb{H}_1 : T_{uw} = \lim_{n \to \infty} \frac{\sigma_w^2 \chi^2(2n)}{n} \left( \frac{\lambda_a \chi^2(2n)}{\sigma_w^2} + \frac{\sigma_w^2}{\sigma_w^2} \right).
\end{cases}$$

(17)

To be consistent with the first phase, we adopt the same $\epsilon$ in Willie’s detection of the UAV relaying. In this case, we have

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

(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

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

(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

$$\begin{cases}
y_{au}[i] = \sqrt{\lambda_a} d_{aw}^2 x_u[i] + n_0[i], \\
y_{ub}[i] = \sqrt{\lambda_0} d_{ub}^2 \xi x_u[i] + n_0[i],
\end{cases}$$

(20)

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

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

(21)

$$\eta_k = n R_k (1 - \delta),$$

(22)

where $k \in \{au, ub\}$, $\gamma_k$ is the received SNR, $\delta$ is the requirement of decoding error probability, and $Q^{-1}($) 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

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

(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

\[
\begin{align*}
\max_{P_n, \eta_{au}} & \min_{\eta_{lb}} (\eta_{au} - \eta_{lb}), \\
\text{s.t.} & \quad D(P_{\eta_{au}} \mid P_{1_{\text{au}}}) \leq 2e^2, \\
& \quad D(P_{\eta_{lb}} \mid P_{1_{\text{lb}}}) \leq 2e^2, \\
& \quad n \leq N,
\end{align*}
\]

(24a)

(24b)

(24c)

(24d)

where \( P = \{ P_u, P_a \} \) 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 calculated as

\[
P^* = \left( P^* + \sigma^2_w \right) \left[ \ln \left( \frac{P^* + \sigma^2_w}{\sigma^2_w} \right) - \frac{2e^2}{N} \right].
\]

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

\[
\begin{align*}
& P_u^* \beta_{au} = P^*, \\
& P_a^* \beta_{au} = P^*.
\end{align*}
\]

(25)

(26)

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

### C. Optimization of UAV Location

Assume that \( \delta \) is a constant and the effective throughputs \( \eta_{au} \) and \( \eta_{ub} \) are monotonically increasing with their SNRs \( \gamma_{au} \) and \( \gamma_{ub} \) according to Proposition 4 in [18]. Therefore, we need to compare \( \gamma_{au} \) and \( \gamma_{ub} \) 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 \( \theta \) is \([\theta_{\min}, \pi/2]\), where \( \theta_{\min} = \arctan(H/L) \) means the minimum elevation angle. According to the geometry, we have

\[
\begin{align*}
d_{au} &= \sqrt{L^2 + (H / \sin \theta)^2} - 2HL \cot \theta, \\
d_{ub} &= H / \sin \theta, \\
d_{au} &= \sqrt{(L - d)^2 + (H / \sin \theta)^2} - 2(L - d)H \cot \theta.
\end{align*}
\]

(27)

Thus, \( \gamma_{au} \) can be rewritten as

\[
\gamma_{au} = \frac{P^* d^2}{\sigma^2} \frac{L^2 + (H / \sin \theta)^2 - 2LH \cot \theta}{H^2}
\]

(28)

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

Similarly, \( \gamma_{ub} \) can be given by

\[
\gamma_{ub} = \frac{P^* (L - d)^2 + (H / \sin \theta)^2 - 2(L - d)H \cot \theta}{(H / \sin \theta)^2}
\]

(29)

Thus, we can obtain the monotonicity of \( \gamma_{ub} \) with the following lemma.

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

**Proof:** In order to prove the monotonicity of \( \gamma_{ub} \), the derivative of \( \gamma_{ub} \) with respect to \( \theta \) can be expressed as

\[
\frac{\partial \gamma_{ub}}{\partial \theta} = \frac{P^* (L - d)^2 \sin 2\theta - 2H(L - d) \cos 2\theta}{\sigma^2} = \frac{P^* 2(L - d)H^2 + (L - d)^2 \sin(2\theta - \theta_c)}{\sigma^2 \theta_c}
\]

(30)

where \( \theta_c \) can be denoted as

\[
\tan \theta_c = \frac{2H}{L - d}.
\]

(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 \( \theta \). 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 \( \theta_c \) 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 \( \gamma_{ub} \) can be denoted by \( \gamma_{ub}|_{\theta = \theta_{\min}} = \gamma_{ub}^{\min} \) and \( \gamma_{ub}|_{\theta = \pi/2} = \gamma_{ub}^{\max} \), respectively. When \( \tan \theta_c \geq \tan(2\theta_{\min}) \geq 0 \), we denote \( \gamma_{ub}|_{\theta = \theta_{\min}} = \gamma_{ub}^{\max} \), \( \gamma_{ub}|_{\theta = \theta_c / 2} = \gamma_{ub}^{\min} \), and \( \gamma_{ub}|_{\theta = \pi/2} = \gamma_{ub}^{\max} \).

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

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

\[
\begin{align*}
\tan \theta_c &= \frac{2H}{L - d} \leq \tan(2\theta_{\min}) = \frac{2HL}{L^2 - H^2}, \\
\gamma_{ub}^{\max} &= \frac{P^* d^2}{\sigma^2 H^2} \leq \gamma_{ub}^{\min} = \frac{P^* d^2}{\sigma^2 H^2 + L^2},
\end{align*}
\]

(32)

(33)

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

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

\[
\begin{align*}
\gamma_{ub}^{\max} &= \frac{P^* d^2}{\sigma^2 H^2} \geq \gamma_{ub}^{\min} = \frac{P^* d^2}{\sigma^2 H^2 + L^2},
\end{align*}
\]

(34)
Due to the monotonicity and continuity of $\gamma_{au}$ and $\gamma_{ub}$, they intersect at $\gamma_{au}(\theta_i) = \gamma_{ub}(\theta_i)$, where $\theta_i$ means the elevation angle of the intersection. Note that $\gamma = \min(\gamma_{au}, \gamma_{ub})$ is determined by the smaller one of $\gamma_{au}$ and $\gamma_{ub}$, and we can conclude that $\gamma$ 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) $\tan \theta_i \geq \tan(2\theta_{min})$, $\gamma_{au}^{\max} \geq \gamma_{ub}^{\max}$, and $\gamma_{au}^{\min} \geq \gamma_{ub}^{\min}$.

With the increase of $d$, we have $H^2 \leq Ld$. In this case, $\gamma_{ub}$ does not monotonously vary with $\theta$, and $\gamma_{au}^{\min}$ is always larger than $\gamma_{ub}^{\min}$

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

(35)

Recalling that $\alpha$ is larger than 2, (36) can be proved by

$$\gamma_{au}^{\max} \geq \frac{H^2 (d^2 + L^2)}{H^2 (H^2 + d^2)} \geq \frac{H^2 d^2 + H^4}{H^4 + H^2 d^2} = 1.$$  

(37)

Therefore, the situation with $\gamma_{au}^{\max} \leq \gamma_{ub}^{\max}$ is not considered. The condition of $\gamma_{au}^{\min} \geq \gamma_{ub}^{\min}$ is the same as (35). Similar to Scenario 2), $\gamma_{au}$ intersects with $\gamma_{ub}$. However, the monotonicity of $\gamma$ 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 $\gamma_{ub}^{\max}$ and $\gamma_{ub}(\theta_i)$. Thus, max{\gamma_{ub}^{\max}, \gamma_{ub}(\theta_i)} is derived as the optimal $\gamma$, and we can obtain the corresponding optimal location.

4) $\gamma_{au}^{\min} \geq \gamma_{ub}^{\max}$. In this scenario, $\gamma_{au} \geq \gamma_{ub}$ holds. This is because $\gamma_{au}^{\max} \geq \gamma_{ub}^{\max}$ holds for $H^2 \leq Ld$ as proved in Scenario 3), and $\gamma_{ub}$ monotonically increases with $\theta$ for $H^2 \geq Ld$. Thus, $\gamma$ is equal to $\gamma_{ub}$ 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 $\theta$, 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 $\gamma$ between Alice and Bob versus $\epsilon$ with different Willie’s locations $d$. It is expected that $\gamma$ increases with $\epsilon$, since when $\epsilon$ 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.

The impact of UAV’s location $l_{au}$ and Willie’s location $d$ on the ECT $\eta$ between Alice and Bob is shown in Fig. 3, with the optimal locations of UAV circled. First, we observe that $\eta$ 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 $\eta$ 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 $\eta$. 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 $\alpha$ on the ECT $\eta$ 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 $\alpha$ increases, which is similar to the $d$. This can be explained.
and the increase of the optimal ECT. \(w\) is worse detection scenario. Thus, \(d\) location in different scenarios according to power at Alice and UAV, the blocklength, and the hovering warden. With the optimal detection by the warden, the transmit signalling in the second phase to mislead the detection of uncertainty in the first phase, and the UAV performs Gaussian due to the UAV relay, where Alice utilizes the channel by a UAV relay. The transmission is divided into two phases covert communication scheme with finite blocklength assisted in (26). The transmit power \(P_a\) increases with \(\alpha\) due to the worse detection scenario. Thus, \(\gamma_{au}\) increases but \(\gamma_{ub}\) 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 coverness. Simulation results show the effectiveness of the covert communication in the proposed UAV relaying scheme.

REFERENCES


