Covert Communication with Relay Selection

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***Abstract*—In this letter, we investigate covert communication in relay networks with relay selection. We consider the scenario that while forwarding the source's message, the selected relay opportunistically transmits its own message to the destination covertly. We derive the probability of detection error (PDE) and the average covert rate (ACR) in a closed form, based on which we analyse the effects of system parameters on the performance of the covert communication. Our analysis indicates that applying relay selection causes a decrease in the PDE, however, it can provide an ACR gain when the transmission rate of the source increases.**

***Index Terms*—covert communication, detection error, relay selection, average covert rate.**

I. Introduction

Covert communication or low probability of detection (LPD) communication has recently emerged as a new transmission technology to address privacy and security in wireless networks[1]. Covert communication aims to perform a wireless communication with a low probability of being detected, i.e., hiding the wireless communication. It is desired in many application scenarios, such as covert military operations, location tracking in vehicular ad hoc networks, intercommunication of sensor networks or Internet of Things (IoT)[2], and unmanned aerial vehicle (UAV) networks[3].

The information-theoretic limits of covert communication were studied in some pioneering works [4]-[6]. It was proved that the maximum amount of information can be transmitted covertly over n channel uses is $\mathcal{O}(\sqrt{n})$ bits, which indicates that the asymptotic covert rate decreases to 0 as n approaches infinity, i.e., $\lim_{n\to\infty}\mathcal{O}(\sqrt{n})/n = 0$. Considering that the warden has uncertainty on the receiver's noise power, the authors in [7] and [8] proved that a positive covert rate can be achieved. Moreover, the interference uncertainty[9],[10] and the channel uncertainty[11],[12] were also studied in covert communication.

Recently, extensive research activities were carried out to study covert communication in context of relay networks. In [13], the channel uncertainty in the link between the relay and the warden was exploited to achieve a positive covert rate. Hu et al. [2] considered the scenario that relay uses amplify-and-forward (AF) to opportunistically transmit its own message to the destination with a low probability of being detected by the source, and proposed the rate-control and power-control schemes for transmitting the covert information. Further, the study was extended to the relay network with energy harvesting strategy[14].

For multiple-relay networks, relay selection (RS) has been regarded as an effective technique to achieve spacial diversity gain. However, to the best of our knowledge, the performance behavior of covert communication incorporating relay selection is still unknown. Therefore, in this letter, we investigate covert communication in a relay selection system, where the relay with the best relay-to-destination link is selected to forward the information from the source, and it can also opportunistically transmit its own message covertly to the destination. We derive the probability of detection error (PDE) and the average covert rate (ACR) in a closed form, and then analyse the effects of system parameters on the performance of covert communication. Our analysis indicates that although relay selection can provide diversity gain, it causes a decrease in the PDE, and degrades the ACR when the transmission rate of the source is low. However, the spatial diversity benefit becomes dominant when the transmission rate of the source increases, and thus an ACR gain can be achieved.

II. System Model and Transmission Scheme

We consider a multiple-relay network, consisting of one source S, one destination D, and N decode-and-forward (DF) relays, denoted by R_i ($i = 1, \dots, N$). Each node is equipped with a single antenna. The direct link between S and D does not exist due to deep fading. The channel coefficient of the link $a \to b$ ($a, b \in \{S, R_i, D\}$) is denoted by h_{ab}, which is an independent, zero-mean circularly symmetric complex Gaussian random variable with unit variance. It is assumed that the ith relay R_i only knows its h_{SR_i} and h_{R_iD}, while S only knows all h_{SR_i} and D only knows all h_{R_iD}, $i = 1, \dots, N$[2]. A block fading environment is assumed, where the channel coefficients are constant within one block, but change independently from one block to another.

We consider a partial relay selection scheme based on the instantaneous channel conditions of the relay-to-destination links. The relay with the highest instantaneous signal-to-noise ratio (SNR) at the destination, denoted by R_k ($k \in \{1, \dots, N\}$), is selected to forward the information from the source[15]. In more detail, for DF relaying, assuming each relay transmits with power P_R and the noise power at D is denoted by n_D, the instantaneous received SNR at D for the ith relay, $i = 1, \dots, N$, can be given by $\gamma_i = P_R|h_{R_iD}|^2/n_D$. Thus, the selected relay R_k can be determined by $k = \arg\max_{i\in\{1,\dots,N\}} |h_{R_iD}|^2$. In the relay selection phase, each relay starts a timer, which is an inverse proportional function

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with respect to $|h_{R_iD}|^2$. The relay whose timer expires first is the selected relay R_k, and it notifies other nodes via a flag signal. Thus, we can have

$$|h_{R_kD}|^2 = \max_{i\in\{1,\dots,N\}} |h_{R_iD}|^2. \tag{1}$$

The selected relay R_k works in the half-duplex mode. The transmission from S to D takes place in two phases. We consider a fixed-rate transmission from S to D [2]. In the first phase, S transmits its information to R_k with a fixed-rate r_{SD}. The received signal at R_k is given by

$$y_{R_k}(i) = \sqrt{P_S} h_{SR_k} x_s(i) + n_{R_k}(i), \tag{2}$$

where P_S is the transmit power of S, $x_s(i)$ is the normalized signal transmitted by S in the ith channel use, which satisfies $E\{|x_s(i)|^2\} = 1$, $i = 1,\dots,n$, n is the number of channel uses during each phase, and $n_{R_k}(i)$ is the additive white Gaussian noise (AWGN) at R_k with mean zero and variance $\sigma^2_{R_k}$. In the second phase, whether R_k starts its transmission depends on two necessary conditions. The first one is that R_k can decode x_s successfully, i.e.,

$$\gamma_{R_k} = \frac{P_S|h_{SR_k}|^2}{\sigma^2_{R_k}} \geq \gamma_{th}, \tag{3}$$

where γ_{R_k} denotes the received SNR at R_k, and $\gamma_{th} = 2^{2r_{SD}} - 1$ denotes the SNR threshold. The second one is that D can decode the data successfully, i.e.,

$$\gamma_{D,M} = \frac{P_M|h_{R_kD}|^2}{\sigma^2_D} \geq \gamma_{th}, \tag{4}$$

where $\gamma_{D,M}$ denotes the maximum received SNR at D, P_M is the maximum transmit power of R_k, and σ^2_D is the noise power at D. The two conditions can be checked by R_k. As long as one of the conditions is not met, which means that the outage occurs, R_k will not transmit. According to (3) and (4), we denote the condition for non-outage as

$$\bar{\mathbb{O}} = \{\gamma_{R_k} \geq \gamma_{th}\} \bigcap \{\gamma_{D,M} \geq \gamma_{th}\}. \tag{5}$$

When $\bar{\mathbb{O}}$ is met, R_k starts its transmission, which is divided into two cases, i.e., transmission without covert message and transmission with covert message.

When R_k only forwards the information from S, it decodes the data received in the first phase and encodes them with another codebook, and then transmits to D. The received signal at D in the ith channel use is given by

$$y_{D,0}(i) = \sqrt{P_{R_k,0}} h_{R_kD} x_R(i) + n_D(i), \tag{6}$$

where $x_R(i)$ is the normalized signal transmitted by R_k in the ith channel use, which satisfies $E\{|x_R(i)|^2\} = 1$, $i = 1,\dots,n$, $n_D(i)$ is the AWGN at D with mean zero and variance σ^2_D, and $P_{R_k,0}$ is the transmit power of R_k without transmitting the covert message. Since we consider a fixed-rate transmission, R_k only has to ensure that the received SNR at D is equal to the SNR threshold γ_{th}. Thus, $P_{R_k,0}$ is given by

$$P_{R_k,0} = \frac{\gamma_{th}\sigma^2_D}{|h_{R_kD}|^2}. \tag{7}$$

When R_k transmits with covert message, the received signal in the ith channel use at D is given by

$$y_{D,1}(i) = \sqrt{P_{R_k,1}} h_{R_kD} x_R(i) + \sqrt{P_C} h_{R_kD} x_C(i) + n_D(i), \tag{8}$$

where $P_{R_k,1}$ is the transmit power of R_k for forwarding $x_R(i)$ which carrying the source's information, P_C is the fixed transmit power of R_k for transmitting $x_C(i)$ which carrying the covert information of R_k. $x_C(i)$ is normalized and satisfies $E\{|x_C(i)|^2\} = 1$, $i = 1,\dots,n$.

When D receives $y_{D,1}$, it first decodes x_R treating x_C as an interference. The signal-to-interference-plus-noise ratio (SINR) for decoding x_R is given by

$$\gamma_{D,1} = \frac{P_{R_k,1}|h_{R_kD}|^2}{P_C|h_{R_kD}|^2 + \sigma^2_D}. \tag{9}$$

To ensure $\gamma_{D,1} = \gamma_{th}$, $P_{R_k,1}$ is given by

$$P_{R_k,1} = \gamma_{th}P_C + \frac{\gamma_{th}\sigma^2_D}{|h_{R_kD}|^2}. \tag{10}$$

Consider the maximum power constraint at R_k, i.e., $P_{R_k,1} + P_C \leq P_M$, the necessary condition for R_k to perform its covert transmission is given by

$$\mathbb{A} = \left\{ |h_{R_kD}|^2 \geq \frac{\gamma_{th}\sigma^2_D}{P_M - (\gamma_{th}+1)P_C} \triangleq g \right\}. \tag{11}$$

After decoding x_R, D subtracts it from the received signal, and thus the SNR for decoding x_C is given by

$$\gamma_C = \frac{P_C|h_{R_kD}|^2}{\sigma^2_D}. \tag{12}$$

III. Performance Analysis

A. Probability of Detection Error (PDE) at Source

When R_k starts its transmission in the second phase, S will detect whether R_k transmits its covert message. The received signal at S in the second phase is expressed as

$$y_S(i) = \begin{cases} \sqrt{P_{R_k,0}} h_{R_kS} x_R(i) + n_S(i), & H_0 \\ \sqrt{P_{R_k,1}} h_{R_kS} x_R(i) + \sqrt{P_C} h_{R_kS} x_C(i) + n_S(i), & H_1 \end{cases} \tag{13}$$

where $n_S(i)$ is the AWGN at S with mean zero and variance σ^2_S, H_1 and H_0 denote the hypothesises that R_k transmits with or without covert message respectively, h_{R_kS} is the channel coefficient from R_k to S, which is equal to h_{SR_k} due to the channel reciprocity, and is known to S. The optimal detection scheme is a radiometer[2][13], i.e.,

$$T(n) = \frac{1}{n}\sum_{i=1}^{n} |y_S(i)|^2 \underset{H_0}{\overset{H_1}{\gtrless}} \tau, \tag{14}$$

where τ is the decision threshold. Assuming the blocklength is infinite, i.e., $n \to \infty$, $T(n)$ can be given by

$$T(n) = \begin{cases} P_{R_k,0}|h_{R_kS}|^2 + \sigma^2_S, & H_0 \\ P_{R_k,1}|h_{R_kS}|^2 + P_C|h_{R_kS}|^2 + \sigma^2_S, & H_1 \end{cases} \tag{15}$$

When the condition $\bar{\mathbb{O}}$ is guaranteed, R_k can start its transmission and S can start its detection. Thus, the probability of false alarm (FA) and the probability of miss detection (MD) are calculated under the condition $\bar{\mathbb{O}}$, which are given by the following lemma.

Lemma 1: For a given τ, the probability of FA $\Pr(D_1|H_0)$ and the probability of MD $\Pr(D_0|H_1)$ under the condition $\bar{\mathbb{O}}$ can be given by

$$\Pr(D_1|H_0) = \begin{cases} 1, & \tau < \sigma^2_S \\ p_{FA}(\tau), & \sigma^2_S \leq \tau \leq t_1 \\ 0, & \tau > t_1 \end{cases}, \tag{16}$$

$$\Pr(D_0|H_1) = \begin{cases} 0, & \tau < t_2 \\ p_{MD}(\tau), & t_2 \le \tau \le t_3 \\ 1, & \tau > t_3 \end{cases}, \quad (17)$$

where D_1 and D_0 are the binary decisions, corresponding to R_k transmits with or without covert message respectively,

$$t_1 = P_M|h_{R_kS}|^2 + \sigma_S^2,$$
$$t_2 = (\gamma_{th}+1)P_C|h_{R_kS}|^2 + \sigma_S^2,$$
$$t_3 = [P_M + (\gamma_{th}+1)P_C]|h_{R_kS}|^2 + \sigma_S^2,$$
$$p_{FA}(\tau) = \frac{\left[1-\exp\left(-\frac{\gamma_{th}\sigma_D^2|h_{R_kS}|^2}{\tau-\sigma_S^2}\right)\right]^N - \left[1-\exp\left(-\frac{\gamma_{th}\sigma_D^2}{P_M}\right)\right]^N}{1-\left[1-\exp\left(-\frac{\gamma_{th}\sigma_D^2}{P_M}\right)\right]^N},$$
$$p_{MD}(\tau) = \frac{1-\left[1-\exp\left(-\frac{\gamma_{th}\sigma_D^2|h_{R_kS}|^2}{\tau-(\gamma_{th}+1)P_C|h_{R_kS}|^2-\sigma_S^2}\right)\right]^N}{1-\left[1-\exp\left(-\frac{\gamma_{th}\sigma_D^2}{P_M}\right)\right]^N}.$$

Proof: With (7), (14) and (15), $\Pr(D_1|H_0)$ under the condition $\bar{\mathbb{O}}$ can be expressed by

$$\Pr(D_1|H_0) = \Pr\left\{\frac{\gamma_{th}\sigma_D^2}{|h_{R_kD}|^2}|h_{R_kS}|^2 + \sigma_S^2 \ge \tau \middle| \bar{\mathbb{O}}\right\} \quad (18)$$

Then, with (3), (4) and (5), (18) can be calculated as

$$\Pr(D_1|H_0) = \begin{cases} 1, & \tau < \sigma_S^2 \\ \dfrac{\Pr\left\{\frac{\gamma_{th}\sigma_D^2}{P_M} \le |h_{R_kD}|^2 \le \frac{\gamma_{th}\sigma_D^2|h_{R_kS}|^2}{\tau-\sigma_S^2}\right\}}{\Pr\left\{|h_{R_kD}|^2 \ge \frac{\gamma_{th}\sigma_D^2}{P_M}\right\}}, & \sigma_S^2 \le \tau \le t_1 \\ 0, & \tau > t_1 \end{cases}. \quad (19)$$

According to (1), the cumulative distribution function (CDF) of $|h_{R_kD}|^2$ can be given by $F_{|h_{R_kD}|^2}(x) = (1-e^{-x})^N$. Substituting it into (19), (16) is achieved.

With (10), (14) and (15), $\Pr(D_0|H_1)$ under the condition $\bar{\mathbb{O}}$ can be expressed by

$$\Pr(D_0|H_1) = \Pr\left\{\left[(\gamma_{th}+1)P_C + \frac{\gamma_{th}\sigma_D^2}{|h_{R_kD}|^2}\right]|h_{R_kS}|^2 + \sigma_S^2 \le \tau \middle| \bar{\mathbb{O}}\right\}. \quad (20)$$

Then, with (3), (4) and (5), (20) can be calculated as

$$\Pr(D_0|H_1) = \begin{cases} 0, & \tau < t_2 \\ \dfrac{\Pr\left\{|h_{R_kD}|^2 \ge \frac{\gamma_{th}\sigma_D^2|h_{R_kS}|^2}{\tau-(\gamma_{th}+1)P_C|h_{R_kS}|^2-\sigma_S^2}\right\}}{\Pr\left\{|h_{R_kD}|^2 \ge \frac{\gamma_{th}\sigma_D^2}{P_M}\right\}}, & t_2 \le \tau \le t_3 \\ 1, & \tau > t_3 \end{cases}. \quad (21)$$

Substituting $F_{|h_{R_kD}|^2}(x) = (1-e^{-x})^N$ into (21), (17) is achieved. ■

Assuming R_k will transmit a covert message with probability ρ when the necessary condition $\mathbb{A}$ is met, the PDE can be given by the following theorem.

Theorem 1: Given τ and ρ, the PDE can be given by

$$\xi = \Pr(D_1|H_0)\Pr(H_0) + \Pr(D_0|H_1)\Pr(H_1)$$
$$= \begin{cases} 1-\beta, & \tau < \sigma_S^2 \\ (1-\beta)p_{FA}(\tau), & \sigma_S^2 \le \tau \le t_2 \\ \beta p_{MD}(\tau) + (1-\beta)p_{FA}(\tau), & t_2 \le \tau \le t_1 \\ \beta p_{MD}(\tau), & t_1 \le \tau \le t_3 \\ \beta, & \tau > t_3 \end{cases}, \quad (22)$$

where $\beta = \rho\left[1-\left(1-\exp(-g)\right)^N\right]\Big/\left[1-\left(1-\exp(-\frac{\gamma_{th}\sigma_D^2}{P_M})\right)^N\right]$

Proof: S starts its detection as long as $\bar{\mathbb{O}}$ is met, and R_k will transmit a covert message with probability ρ when $\mathbb{A}$ is met. With (3), (4), (5) and (11), $\Pr(H_1)$ can be calculated by

$$\Pr(H_1) = \rho\Pr(\mathbb{A}|\bar{\mathbb{O}}) = \rho \times \frac{\Pr(\mathbb{A}\bigcap\bar{\mathbb{O}})}{\Pr(\bar{\mathbb{O}})}$$
$$= \frac{\rho\Pr\{|h_{R_kD}|^2 \ge g\}}{\Pr\left\{|h_{R_kD}|^2 \ge \frac{\gamma_{th}\sigma_D^2}{P_M}\right\}} \triangleq \beta. \quad (23)$$

Substituting $F_{|h_{R_kD}|^2}(x)$ into (23), β in (22) is achieved, and thus we have $\Pr(H_1) = \beta$, $\Pr(H_0) = 1-\beta$. From Lemma 1, it is obvious that $t_3 > t_1$ and $t_3 > t_2$. Considering the maximum power constraint at R_k, i.e., $P_{R_k,1} + P_C \le P_M$, with (10), we can have $(\gamma_{th}+1)P_C < P_M$, which indicates that $t_1 > t_2$. Thus, with $\Pr(H_1)$ and $\Pr(H_0)$, combining (16) and (17), the result in Theorem 1 can be achieved. ■

Obviously, ξ given by Theorem 1 can be minimized by optimizing τ at S. From (22), it is easy to see that $(1-\beta)p_{FA}(\tau)$ is a decreasing function with respect to τ, and $\beta p_{MD}(\tau)$ is an increasing function with respect to τ. Meanwhile, ξ is a continuous function of τ. Hence, the optimal value of τ to minimize ξ falls into the interval $t_2 \le \tau \le t_1$, i.e.,

$$\tau_{opt} = \arg\min_{t_2 \le \tau \le t_1}[\beta p_{MD}(\tau) + (1-\beta)p_{FA}(\tau)] \quad (24)$$

(24) can be solved by numerical search, and then the optimal PDE can be obtained, i.e., $\xi_{opt} = \beta p_{MD}(\tau_{opt}) + (1-\beta)p_{FA}(\tau_{opt})$.

B. Average Covert Rate (ACR)

The ACR is derived in the following theorem.

Theorem 2: Given a fixed transmit power P_C, the ACR achieved by the covert communication in the relay selection system with N relays can be given by

$$R_{C,avg} = \rho\exp\left(-\frac{\gamma_{th}\sigma_{R_k}^2}{P_S}\right)\frac{N}{\ln 2}\sum_{k=0}^{N-1}\binom{N-1}{k}(-1)^k$$
$$\times\frac{\exp(-(k+1)g)}{k+1}\left[\ln\left(1+\frac{P_C g}{\sigma_D^2}\right) - \exp(\lambda)\mathrm{Ei}(-\lambda)\right], \quad (25)$$

where $\lambda = (k+1)(g + \frac{\sigma_D^2}{P_C})$, $\mathrm{Ei}(x) = -\int_{-x}^{\infty}\frac{e^{-t}}{t}dt$ is the exponential integral function.

Proof: The covert rate is defined as $R_C = \log_2(1+\gamma_C)$, and it can be achieved when $\bar{\mathbb{O}}$ and $\mathbb{A}$ are met. Thus, taking ρ into account, the ACR can be derived by

$$R_{C,avg} = \rho\int_{\frac{\gamma_{th}\sigma_{R_k}^2}{P_S}}^{\infty} f_{|h_{SR_k}|^2}(x)dx$$
$$\times\int_g^{\infty}\log_2\left(1+\frac{P_C y}{\sigma_D^2}\right)f_{|h_{R_kD}|^2}(y)dy, \quad (26)$$

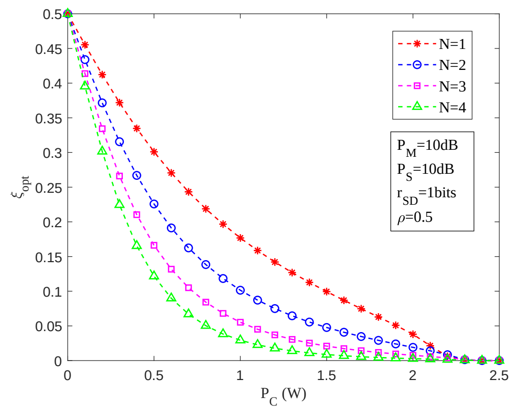


Fig. 1. ξ_{opt} versus P_C for different number of relays with $P_M = 10$dB, $P_S = 10$dB, $\rho = 0.5$, $r_{SD} = 1$bits, $\sigma_S^2 = \sigma_{R_k}^2 = \sigma_D^2 = 1$, and $|h_{R_k S}|^2 = 1$.

where $f_{|h_{SR_k}|^2}(x) = e^{-x}$ and $f_{|h_{R_k D}|^2}(y) = N(1-e^{-y})^{N-1}e^{-y}$ are the probability density function (PDF) of $|h_{SR_k}|^2$ and $|h_{R_k D}|^2$ respectively.

By using the binomial expansion $(1-e^{-y})^{N-1} = \sum_{k=0}^{N-1}\binom{N-1}{k}(-1)^k e^{-ky}$ and the variable substitution $y' = P_C(y-g)/\sigma_D^2$, after some algebraic manipulations, we have

$$R_{C,avg} = \rho \exp\left(-\frac{\gamma_{th}\sigma_{R_k}^2}{P_S}\right)\frac{N}{\ln 2}\sum_{k=0}^{N-1}\binom{N-1}{k}(-1)^k e^{-(k+1)g} \times \frac{\sigma_D^2}{P_C}\int_0^\infty \ln\left(y'+1+\frac{P_C g}{\sigma_D^2}\right)\exp\left(-\frac{(k+1)\sigma_D^2}{P_C}y'\right)dy' \tag{27}$$

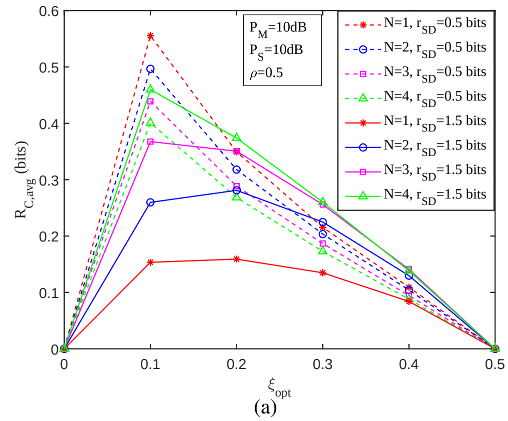
Then, making use of [16, Eq.(4.337.1)], (25) in Theorem 2 can be obtained. ■

IV. Numerical Results

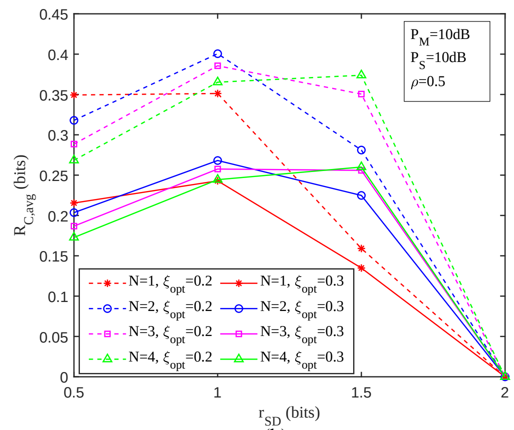
In this section, numerical results are presented to investigate the effects of system parameters on the performance of the covert communication in the relay selection system, and some useful insights are also provided.

Fig.1 depicts ξ_{opt} versus P_C for different number of relays. The covert constraint in the considered system is given by[2] $\xi_{opt} \geq \min\{\beta, 1-\beta\} - \epsilon$, where $\epsilon \geq 0$. For $\rho = 0.5$, $\beta \leq 0.5$, hence, the maximum value of ξ_{opt} is 0.5. As can be observed, ξ_{opt} monotonically decreases as P_C increases, hence, the maximum possible value of P_C depends on the covert constraint. We can see that with the same value of P_C, ξ_{opt} decreases as the number of relay increases, which indicates that the diversity gain provided by relay selection causes a decrease in the uncertainty of the detection. Intuitively, this is due to the fact that from the source's point of view the possible transmit power range for transmitting x_R decreases.

Fig.2(a) depicts $R_{C,avg}$ versus ξ_{opt} for different number of relays. We can see that, in the case $r_{SD} = 0.5$ bits, increasing the number of relays degrades the ACR, while the performance behavior is reversed in the case $r_{SD} = 1.5$ bits. Fig.2(b) depicts $R_{C,avg}$ versus r_{SD}. It also shows that when r_{SD} is low, applying relay selection degrades the ACR. However, the spacial diversity benefit becomes dominant when r_{SD} increases, i.e., benefitting from the diversity gain, the selected relay has more chance to perform the covert transmission, and thus an ACR gain can be achieved.



(a)



(b)

Fig. 2. (a) $R_{C,avg}$ versus ξ_{opt}. (b) $R_{C,avg}$ versus r_{SD}. $P_M = 10$dB, $P_S = 10$dB, $\rho = 0.5$, $\sigma_S^2 = \sigma_{R_k}^2 = \sigma_D^2 = 1$, and $|h_{R_k S}|^2 = 1$.

V. Conclusion

In this letter, we investigate covert communication in a relay selection system. The PDE and the ACR are derived in a closed-form, based on which we analyse the performance behavior of the covert communication. Our results show that the diversity gain provided by relay selection causes a decrease in the PDE, however, it can provide an ACR gain when the transmission rate of the source increases.

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