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Covert communication for cooperative NOMA with two phases detection



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Abstract This paper investigates the covert communication of cooperative non-orthogonal multiple access (NOMA) systems, where the near user serves as a decode-and-forward (DF) relay and the far user receives the covert information from both the source and the near user. To improve the covertness performance, cooperative jamming and power randomness are adopted. Specifically, we derive detection error probability (DEP) of Willie and the minimum detection error probability (MDEP) at the optimal decision threshold for each phase. In addition, the reliability of the proposed system is investigated by deriving closed-form expressions for the outage probability (OP) of the two users. Under the covertness and reliability constraints, an optimization algorithm to maximize the effective covert rate is designed. Simulation results have confirmed the correctness of the theoretical analysis, and the proposed scheme can achieve a better covert communication.

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1. Introduction

With the widespread applications of smart devices, mobile internet and Internet of Things (IoT) are developing rapidly. The future 6th Generation (6G) mobile networks are facing the great challenges of massive connections, low latency and high spectral efficiency [1–3]. The traditional orthogonal multiple access (OMA) technology only allocates each orthogonal resource to one user, which limits the spectral efficiency and the number of access devices in the networks [4]. To solve

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the above problems, non-orthogonal multiple access (NOMA) has proposed as one of the potential technologies of 6G because it can improve the spectral efficiency and satisfy the simultaneous access of a large number of users [5]. Compared with OMA, NOMA can not only improve the system spectral efficiency, but also ensure fairness among the users by power domain multiplexing [6–9]. At the transmitter, NOMA allocates different powers to different users according to their channel conditions over the same time/frequency block. At the receiver, the successive interference cancellation (SIC) can be used to distinguish these users according to their channel conditions [10,11].

On the other hand, it is critical to facilitate the network coverage of NOMA users, and this can be effectively addressed by cooperative communications. Combining NOMA and cooperative communications can further improve the spectral efficiency [12]. In [13], a NOMA-based cooperative relay system was studied, and a unified framework for system performance evaluation was established. Based on the previous work, the authors of [14] studied the transmission security problem of two-user systems with the near user acting as decode-and-forward (DF) relay. In [15], the authors further considered the near user as a relay with different forwarding protocols and derived the outage probability (OP) under different forwarding protocols. For the scheme of relay-assisted NOMA communication, NOMA-based DF relaying performed better than the NOMA-based amplify-and-forward (AF) relaying scheme [16]. A. Salem et al. [17] analyzed the multi-antenna hybrid forwarding relays performance assisted by NOMA. Finally, Y.B. Kim et al. [18] showed that full-duplex cooperative NOMA has better performance than traditional cooperative NOMA due to the reduced transmit time.

Due to the inherent broadcasting characteristics of wireless communication and randomness of the fading channels, there is a risk for user information being detected during transmission. Therefore, how to ensure secure information transmission is a critical issue. In light of this fact, several research works have been conducted to investigate such security issue from the physical layer security (PLS) perspectives [19,20]. Unfortunately, the research works on PLS have mainly focused on the protection of communication contents. In some special communication scenarios, users aim to hide their communication behavior. To this end, a new secure performance evaluation metric with the name of covert communications is proposed. Covert communication aims to establish a reliable link between legitimate transmitters and receivers to ensure that transmitted information can not be detected by illegal users [21]. In recent years, researchers have carried out various investigations. In [22], the information-theoretic limit of covert communication over an additive white Gaussian noise (AWGN) channel was first proposed by B.A. Bash et al. which is called the square root law. It is the foundation for the theoretical study of covert communication [23,24]. To reduce the detection performance of the detector, the researchers further exploited various uncertainties of the fading channel and interference. In [25], the uncertainty of the fading channel was utilized to make Willie unable to accurately detect the information if transmitted or not. In [26], the authors further investigated the impact of the quality of channel state information (CSI) on Willie's detection performance under channel uncertainty. In [27], Hu et al. first investigated the use of artificial noise interference

by Willie to achieve covert communication. Tao et al. designed a covert communication scheme with the assist of energy harvesting jammers in [28]. With this idea, Peng et al. in [29] proposed a covert communication scheme for multi-antenna jamming, in which the optimal antenna is selected to transmit the jamming information. From the perspective of detection, the authors of [30] made a comprehensive analysis of the covert performance of the system with multiple detectors and jammers. Moreover, K. Shahzad et al. in [31] considered the joint optimization of the jamming power and the prior probability to achieve positive covert rate. It shows that equal probability transmission is not optimal scheme. In addition, the impact of communication time uncertainty on Willie was investigated in [32]. He et al. in [33] proposed schemes that can maximize the achievable rate under noise uncertainty. In [34], the authors analyzed the effects of fading channel and noise uncertainty on Willie's average detection error probability and system throughput.

It is possible to improve the security of the system by exploring the covert communication of cooperative transmission. Given this situation, Sun et al. [35] proposed a network structure that the relay can be switched between different operating modes to maximize the covert rate. Gao et al. in [36] investigated the covert communication performance of IoT systems with multiple relays and developed relay selection strategies to enhance covert capacity. In [37,38], Hu et al. proposed two relay-based transmission strategies from different perspectives, and derived the covert achievable rate from the relay to the destination. The authors of [39] considered a relay acting as a jammer to interfere Willie detection. It shows that cooperative jamming is beneficial to covert communication. On the other hand, the authors in [40] combines covert communication with NOMA to optimize the covert performance by optimizing the power allocation. In [41], the authors proposed a NOMA-based friendly jamming assisted covert transmission strategy in vehicular networks. Finally, the authors in [42] studied covert communication in NOMA systems and obtained the optimal power control parameter to achieve the maximum covert throughput.

1.1. Motivation and Contributions

Based on the preceding discussion, we find that Willie always performs single-phase detection for source or relay transmission. In fact, Willie can detect source-relay and relay-destination two-phase to improve the detection capability of information transmission. For instance, in [43], a scheme was proposed to achieve covert communication by limiting the transmission capability of each phase. M. Forouzesh et al. [44] considered the instantaneous secrecy rate in the presence of untrusted relays by satisfying the minimum detection error probability (MDEP) of two phases. Moreover, we consider the investigation of covert communication in NOMA networks, which can well satisfy the covertness, achieve a better covert communication, and also improve the information transmission rate. Therefore, the above works motivate us to investigate NOMA-assisted covert communication and two phase detections. We first obtain the optimal decision thresholds by analyzing the detection performance of the Willie, and then derive MDEPs of each phase for Willie. We also design an optimization scheme to maximize the effective covert rate

under covertness and reliability constraints. The following are the major contributions of this work:

- We propose a unified framework of the cooperative NOMA networks, and study the covert communication performance of the proposed framework. Specifically, to further investigate the effect of Willie's detection ability on the covert performance, we propose a two phases detection scheme. Then, binary hypothesis detection problems are designed for theoretical analysis.
- We derive analytical closed-form expressions for the optimal decision threshold and MDEP for each phase. Then, Willie's average MDEP is calculated and discussed. Our analysis shows that as the jamming power increases, average MDEP approaches one, which means that the Willie's decision is blind.
- We propose an optimization scheme to maximize the effective covert rate under the guaranteed covertness and reliability constraints. We find that with different transmit power and covert constraints, the system obtains different positive transmission rates, and the two-phase detection is also able to achieve covert communication compared to the one-phase detection.

1.2. Organization and Notations

The rest of the article is organized as follows. Section II details the system model and the metrics of covert communication. Section III derives the expressions for each of Willie's detection performance and each user's OP, and then optimizes the effective covert rate. The theoretical results are simulated and analyzed in Section IV. The paper is concluded in Section V.

Notations: $\mathcal{CN}(0, \sigma^2)$ is a complex Gaussian random variable with a variance of σ^2 and a mean of zero. The expectation operation of random variables is denoted by $\mathbb{E}(\cdot)$. $\Pr\{X\}$ denotes the probability of the random variable X . In addition, the probability density function (PDF) and cumulative distribution function (CDF) of random variables are $f_x(\cdot)$ and $F_x(\cdot)$, respectively. Finally, $\exp(\cdot)$ is the exponential function.

2. System Model

In this section, we first introduce the cooperative NOMA system with two-phase detection. Then, we present a detailed description of the transmission scheme. Finally, we describe the detection metrics for covert communication.

2.1. Communication Scenario

We consider a downlink cooperative NOMA system, as illustrated in Fig. 1, which consists of a source (S), a near user (U1) as the DF relay, a far user (U2) receiving covert information, and a detector Willie (W). In this study, Willie uses a radiometer (power detector) to detect whether covert information is transmitted. When Willie detects the covert information, it will launch a vicious attack on the network. S transmits superimposed information to the users in the first phase; U1 works as a DF relay to decode and forward the

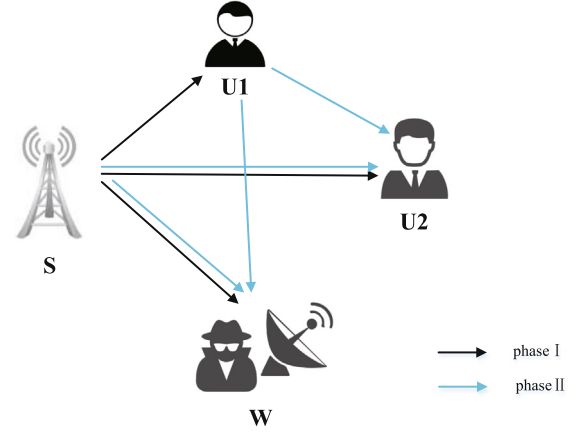


Fig. 1 System model.

received covert information, meanwhile S transmits the jamming signals to deceive Willie.

In this study, we have the following assumptions: *i)* All nodes are the single antenna devices and run in half-duplex (HD) mode; *ii)* Willie only knows the statistical CSI of the S-W link and U1-W link; *iii)* All channels experience independent and follow quasi-static Rayleigh fading. The channel gain between any two nodes is denoted by $h_i \sim \mathcal{CN}(0, \lambda_i)$, which is a complex Gaussian distribution with a mean zero and variance λ_i , where $i \in (SU1, SU2, SW, U1U2, U1W)$.

2.2. Transmission Scheme

The entire transmission is divided into two phases. In phase I, S transmits the superposed signal $x = \sqrt{P_{SU1}}x_1 + \sqrt{P_{SU2}}x_2$ to NOMA users with power P_S , where x_1 and x_2 are the corresponding signals of U1 and U2, with $\mathbb{E}(|x_1[k]|^2) = \mathbb{E}(|x_2[k]|^2) = 1$, $k \in (1, 2, \dots, K)$; $P_{SU1} = (1 - \alpha)P_S$ and $P_{SU2} = \alpha P_S$ are the allocated power to U1 and U2, with power allocation factor α . To ensure user fairness, the far user should be allocated more power than near users, which means that $0.5 < \alpha < 1$.

In phase II, S transmits a jamming signal to interfere with Willie. We assume that the transmitted jamming power P_j by S follows a uniform distribution in $[0, P_j^{\max}]$, whose PDF is by

$$f_{P_j}(x) = \begin{cases} \frac{1}{P_j^{\max}}, & 0 \leq x \leq P_j^{\max}, \\ 0, & \text{otherwise,} \end{cases} \quad (1)$$

where P_j^{\max} is the maximum jamming power of S. With a certain level of jamming power, as long as U1 forwards information, Willie receives the extra power and marks it directly as a covert transmission. Thus, to reduce Willie's detection performance, we consider P_j to be random.

2.3. Detection at Willie

The signals received at Willie in phase I and II can respectively written as

$$y_W^I = \begin{cases} \sqrt{P_{SU1}}h_{SW}x_1 + n_W^I, & H_0, \\ \sqrt{P_{SU1}}h_{SW}x_1 + \sqrt{P_{SU2}}h_{SW}x_2 + n_W^I, & H_1, \end{cases} \quad (2)$$

and

$$y_W^{\text{II}} = \begin{cases} \sqrt{P_j} h_{SW} x_j + n_W^{\text{II}}, & H_0, \\ \sqrt{P_j} h_{SW} x_j + \sqrt{P_r} h_{U1W} x_2 + n_W^{\text{II}}, & H_1, \end{cases} \quad (3)$$

where n_W^{I} and n_W^{II} are the AWGN terms at Willie in phase I and phase II with variance σ_W^2 , $n_W \sim \mathcal{CN}(0, \sigma_W^2)$. P_r denotes the forwarding power of U1. The null hypothesis indicates that S does not communicate covert information and is denoted by H_0 . The alternative hypothesis indicates that S transmits covert information with H_1 . For the convenience of analysis, we assume the H_0 and H_1 events with equal probability.

Willie utilizes the Neyman-Pearson criteria to determine whether covert information is transmitted, and the decision formula is defined by

$$T_W \stackrel{D_1}{\underset{D_0}{\geq}} \tau, \quad (4)$$

where T_W is denoted as the average received power of Willie, i.e., $T_W = \sum_{k=1}^K |y_W(k)|^2 / K$, and τ is the decision threshold. D_0 and D_1 are the judgement results of S to transmit covert information or not. We consider the case that Willie's observation time slot is sufficiently long, i.e., $K \rightarrow \infty$. Therefore, the average power received by Willie at each phase is expressed as

$$T_W^{\text{I}} = \begin{cases} P_{SU1} |h_{SW}|^2 + \sigma_W^2, & H_0, \\ P_{SU1} |h_{SW}|^2 + P_{SU2} |h_{SW}|^2 + \sigma_W^2, & H_1, \end{cases} \quad (5)$$

and

$$T_W^{\text{II}} = \begin{cases} P_j |h_{SW}|^2 + \sigma_W^2, & H_0, \\ P_j |h_{SW}|^2 + P_r |h_{U1W}|^2 + \sigma_W^2, & H_1. \end{cases} \quad (6)$$

The detection error probability (DEP) is the key metric for assessing the detector's detection capability, which is defined

$$\xi = P_{FA} + P_{MD}. \quad (7)$$

When ξ is smaller, Willie's detection performance is better while the system's covert transmission performance is worse. When there exists arbitrarily small $\varepsilon > 0$, satisfying $\xi \geq 1 - \varepsilon$, then the transmission of the system's covert information can be guaranteed. $P_{FA} = \Pr\{D_1|H_0\}$ is the false alarm probability (FAP), and $P_{MD} = \Pr\{D_0|H_1\}$ is the missed detection probability (MDP).

3. Performance of Covert Communication

In this section, we first analyze Willie's detection performance by deriving the closed-form expression of MDEP. Then, the exact expressions for the OP of U1 and U2 are derived to enable the system to establish a reliable communication link. Finally, the optimization scheme of the effective covert rate is designed under the covertness and reliability constraints.

3.1. Detection Performance at Willie

We investigate the covert performance in the worst scenario of the system since this is Willie's optimal detection performance. The FAPs and MDPs of the phases I and II are calculated sequentially, and the optimal decision threshold τ^* is obtained so that Willie obtains the MDEP ξ^* .

Theorem 1. For random threshold τ^{I} , Willie's FAP and MDP are given by

$$P_{FA}^{\text{I}} = \begin{cases} 1, & \tau^{\text{I}} < \sigma_W^2, \\ \exp\left(\frac{\sigma_W^2 - \tau^{\text{I}}}{P_{SU1} \lambda_{SW}}\right), & \tau^{\text{I}} \geq \sigma_W^2, \end{cases} \quad (8)$$

and

$$P_{MD}^{\text{I}} = \begin{cases} 0, & \tau^{\text{I}} < \sigma_W^2, \\ 1 - \exp\left(\frac{\sigma_W^2 - \tau^{\text{I}}}{(P_{SU1} + P_{SU2}) \lambda_{SW}}\right), & \tau^{\text{I}} \geq \sigma_W^2, \end{cases} \quad (9)$$

where P_{FA}^{I} and P_{MD}^{I} are denoted as FAP and MDP of the phase I, respectively.

Proof. : See Appendix A. \square

Note that **Theorem 1** presents the FAP and MDP for the entire threshold range. It can be seen that P_{FA}^{I} is a monotonically decreasing function with respect to τ^{I} , while P_{MD}^{I} is a monotonically increasing function. To minimize the DEP of Eq. (7) to obtain Willie's optimal decision threshold τ^{*} , we will derive it by the following **Theorem 2**.

Theorem 2. According to the decision formula given in Eq. (4), Willie's optimal decision threshold and MDEP are respectively given by

$$\tau^{*} = \frac{(1 - \alpha) P_S \lambda_{SW}}{\alpha} \ln\left(\frac{1}{1 - \alpha}\right) + \sigma_W^2, \quad (10)$$

and

$$\xi^{*} = 1 - \alpha(1 - \alpha)^{\frac{1-\alpha}{\alpha}}. \quad (11)$$

Proof. : According to Eqs. (7)–(9), the DEP expression at Willie of phase I is

$$\xi^{\text{I}} = \begin{cases} 1, & \tau^{\text{I}} < \sigma_W^2, \\ 1 - \exp\left(\frac{\sigma_W^2 - \tau^{\text{I}}}{(P_{SU1} + P_{SU2}) \lambda_{SW}}\right) + \exp\left(\frac{\sigma_W^2 - \tau^{\text{I}}}{P_{SU1} \lambda_{SW}}\right), & \tau^{\text{I}} \geq \sigma_W^2. \end{cases} \quad (12)$$

It is obvious that if $\tau^{\text{I}} < \sigma_W^2$, $\xi^{\text{I}} = 1$. This means that Willie is not able to identify the transmission of covert information at all. Therefore, we only need to consider the case $\tau^{\text{I}} \geq \sigma_W^2$. According to Eq. (12), the first derivative of ξ^{I} with respect to τ^{I} is obtained and let $\partial \xi^{\text{I}} / \partial \tau^{\text{I}} = 0$. We can obtain as

$$\frac{\partial \xi^{\text{I}}}{\partial \tau^{\text{I}}} = \frac{1}{(P_{SU1} + P_{SU2}) \lambda_{SW}} \exp\left(\frac{\sigma_W^2 - \tau^{\text{I}}}{(P_{SU1} + P_{SU2}) \lambda_{SW}}\right) - \frac{1}{P_{SU1} \lambda_{SW}} \exp\left(\frac{\sigma_W^2 - \tau^{\text{I}}}{P_{SU1} \lambda_{SW}}\right) = 0, \quad (13)$$

thus, the optimal τ^{*} is computed as

$$\tau^{*} = \frac{(P_{SU1} + P_{SU2}) P_{SU1} \lambda_{SW}}{P_{SU2}} \ln\left(\frac{P_{SU1} + P_{SU2}}{P_{SU1}}\right) + \sigma_W^2. \quad (14)$$

We can obtain that $\partial \xi^{\text{I}} / \partial \tau^{\text{I}} > 0$, if $\tau^{\text{I}} > \tau^{*}$ and $\partial \xi^{\text{I}} / \partial \tau^{\text{I}} < 0$, if $\tau^{\text{I}} < \tau^{*}$. Thus, ξ^{I} is a continuous function that declines and then grows with respect to τ^{I} . Substituting τ^{*} into Eq. (12), the minimum value of ξ^{*} is obtained as

$$\xi^{1*} = 1 - \frac{P_{SU2}}{P_{SU1} + P_{SU2}} \left(\frac{P_{SU1}}{P_{SU1} + P_{SU2}} \right)^{\frac{P_{SU1}}{P_{SU2}}}. \quad (15)$$

□

According to Eqs. (15) and (11) is obtained after some algebraic operations. The result shows that ξ^{1*} is only related to α . We derive it and get $\partial \xi^{1*} / \partial \alpha = (1 - \alpha)^{\frac{1-\alpha}{\alpha}} \ln(1 - \alpha) / \alpha$. Since $0.5 < \alpha < 1$, ξ^{1*} is a monotonically decreasing function of α . When $\alpha \rightarrow 1$, $\xi^{1*} \rightarrow 0$. It indicates that providing covert information more power makes it easier for Willie to detect covert transmission.

Theorem 3. *In phase II, for arbitrary threshold τ^{II} , Willie's FAP and MDP are given*

$$P_{FA}^{\text{II}} = \begin{cases} 1, & \tau^{\text{II}} < \sigma_W^2, \\ 1 - \frac{\tau^{\text{II}} - \sigma_W^2}{P_j^{\max} |h_{SW}|^2}, & \sigma_W^2 \leq \tau^{\text{II}} \leq \psi, \\ 0, & \tau^{\text{II}} > \psi, \end{cases} \quad (16)$$

and

$$P_{MD}^{\text{II}} = \begin{cases} 0, & \tau^{\text{II}} < \sigma_W^2, \\ \frac{\tau^{\text{II}} - \sigma_W^2 - P_r \lambda_{U1W}}{P_j^{\max} |h_{SW}|^2} + \frac{P_r \lambda_{U1W}}{P_j^{\max} |h_{SW}|^2} \exp\left(\frac{\sigma_W^2 - \tau^{\text{II}}}{P_r \lambda_{U1W}}\right), & \sigma_W^2 \leq \tau^{\text{II}} \leq \psi, \\ 1 - \frac{P_r \lambda_{U1W}}{P_j^{\max} |h_{SW}|^2} \left(\exp\left(\frac{\psi - \tau^{\text{II}}}{P_r \lambda_{U1W}}\right) - \exp\left(\frac{\sigma_W^2 - \tau^{\text{II}}}{P_r \lambda_{U1W}}\right) \right), & \tau^{\text{II}} > \psi, \end{cases} \quad (17)$$

where $\psi = P_j^{\max} |h_{SW}|^2 + \sigma_W^2$. P_{FA}^{II} and P_{MD}^{II} are denoted as FAP and MDP of phase II, respectively.

Proof. : See Appendix B. □

Theorem 3 shows that P_{FA}^{II} is a monotonically decreasing function about τ^{II} and P_{MD}^{II} is a function that first remains constant and then increases. According to Eq. (7), the DEP for phase II of Willie is written as

$$\xi^{\text{II}} = \begin{cases} 1, & \tau^{\text{II}} < \sigma_W^2, \\ 1 - \frac{P_r \lambda_{U1W}}{P_j^{\max} |h_{SW}|^2} \left(1 - \exp\left(\frac{\sigma_W^2 - \tau^{\text{II}}}{P_r \lambda_{U1W}}\right) \right), & \sigma_W^2 \leq \tau^{\text{II}} \leq \psi, \\ 1 - \frac{P_r \lambda_{U1W}}{P_j^{\max} |h_{SW}|^2} \left(\exp\left(\frac{\psi - \tau^{\text{II}}}{P_r \lambda_{U1W}}\right) - \exp\left(\frac{\sigma_W^2 - \tau^{\text{II}}}{P_r \lambda_{U1W}}\right) \right), & \tau^{\text{II}} > \psi. \end{cases} \quad (18)$$

From Willie's perspective, it needs to optimize the decision threshold in order to reduce the error probability, which is given by

$$\tau^{\text{II}*} = \arg \min_{\tau^{\text{II}}} \xi^{\text{II}}. \quad (19)$$

According to Eq. (18), if $\tau^{\text{II}} < \sigma_W^2$, $\xi^{\text{II}} = 1$. Therefore, we only need to consider the case $\tau^{\text{II}} \geq \sigma_W^2$. When $\sigma_W^2 \leq \tau^{\text{II}} \leq \psi$, ξ^{II} is a continuously decreasing function of τ^{II} . Therefore, the optimal detection threshold $\tau^{\text{II}*} = \psi$. When $\tau^{\text{II}} > \psi$, there is

$$\frac{d\xi^{\text{II}}}{d\tau^{\text{II}}} = \frac{1}{P_j^{\max} |h_{SW}|^2} \left(\exp\left(\frac{\psi - \tau^{\text{II}}}{P_r \lambda_{U1W}}\right) - \exp\left(\frac{\sigma_W^2 - \tau^{\text{II}}}{P_r \lambda_{U1W}}\right) \right). \quad (20)$$

Since Eq. (20) is constantly larger than 0, ξ^{II} is a continuously increasing function with respect to τ^{II} . The optimal decision threshold is $\tau^{\text{II}*} = \psi$. Therefore, Willie's optimal decision threshold should be set to $\tau^{\text{II}*} = \psi$. In summary, the best detection performance that Willie can obtain is given by

$$\xi^{\text{II}*} = 1 - \frac{P_r \lambda_{U1W}}{P_j^{\max} |h_{SW}|^2} \left(1 - \exp\left(-\frac{P_j^{\max} |h_{SW}|^2}{P_r \lambda_{U1W}}\right) \right). \quad (21)$$

In this study, Willie is assumed to be a bystander and to know only the statistical CSI of h_{SW} . Thus, we need to consider Willie's average MDEP at different $|h_{SW}|^2$, and choose the average MDEP i.e., $\mathbb{E}(\xi^{\text{II}*})$ as the covert metric. $\mathbb{E}(\xi^{\text{II}*}) \geq 1 - \varepsilon$ as a constraint on whether covert communication is possible. Hence, average MDEP is expressed as

$$\mathbb{E}(\xi^{\text{II}*}) = \int_0^\infty \xi^{\text{II}*} f_{|h_{SW}|^2}(x) dx. \quad (22)$$

After simple mathematical operations, the equation including $\int_0^\infty e^{-x}/x dx$ can be obtained. However, deriving an accurate equation for Willie's average MDEP $\mathbb{E}(\xi^{\text{II}*})$ is difficult, if not impossible. We can only analyze it by numerical search. Thus, in order to maximize the average MDEP of Willie, S and U1 are required to set the transmit power reasonably.

3.2. Outage Probability Analysis

When S transmits a superimposed signal with power P_S at phase I, the signals received by U1 and U2 can be represented as follows:

$$y_{U1} = \sqrt{P_{SU1}} h_{SU1} x_1 + \sqrt{P_{SU2}} h_{SU1} x_2 + n_1, \quad (23)$$

and

$$y_{U2}^{\text{I}} = \sqrt{P_{SU1}} h_{SU2} x_1 + \sqrt{P_{SU2}} h_{SU2} x_2 + n_2^{\text{I}}, \quad (24)$$

where y_{U2}^{I} denotes the signal received at U2 in phase I; $n_1 \sim \mathcal{CN}(0, \sigma_{U1}^2)$ and $n_2^{\text{I}} \sim \mathcal{CN}(0, \sigma_{U2}^2)$ are the complex Gaussian white noise of U1 and U2, respectively.

In phase II, we consider that U1 forwards the covert information and S transmits a jamming information. In a similar way, the received signal at U2 is given by

$$y_{U2}^{\text{II}} = \sqrt{P_j} h_{SU2} x_j + \sqrt{P_r} h_{U1U2} x_2 + n_2^{\text{II}}, \quad (25)$$

where y_{U2}^{II} denotes the signal received at U2 in phase II. n_2^{II} is AWGN at U2 in phase II with variance σ_{U2}^2 , $n_2^{\text{II}} \sim \mathcal{CN}(0, \sigma_{U2}^2)$. We assume that U2 has knowledge of the jamming information transmitted by S. Therefore, U2 eliminates the jamming information from the received signal, which means that $\sqrt{P_j} h_{SU2} x_j$ in Eq. (25) can be removed.

According to NOMA principle, the user firstly decodes the high power signal, and then removes this signal until it decodes its own signal. Thus, according to Eq. (23), U1 receives the superimposed signal, decodes U2's signal, and finally decodes its own signal. Then the signal-to-interference noise ratio (SINR) of U2's signal x_2 decoded at U1 is given by

$$\gamma_2^{U1} = \frac{P_{SU2}|h_{SU1}|^2}{P_{SU1}|h_{SU1}|^2 + \sigma_{U1}^2}. \quad (26)$$

After SIC, the residual signal's SINR is given as

$$\gamma_1^{U1} = \frac{P_{SU1}|h_{SU1}|^2}{\sigma_{U1}^2}, \quad (27)$$

where γ_2^{U1} and γ_1^{U1} are the SINR of U1 decoded signal x_2 and the SNR of U1 decoded by its own signal, respectively.

Similarly, according to Eq. (24), the SINR of U2 to detect its own signal is expressed as

$$\gamma_2^{U2^1} = \frac{P_{SU2}|h_{SU2}|^2}{P_{SU1}|h_{SU2}|^2 + \sigma_{U2}^2}. \quad (28)$$

In phase II, according to Eq. (25), U2 decodes its own signal, and its SINR is

$$\gamma_2^{U2^{II}} = \frac{P_r|h_{U1U2}|^2}{\sigma_{U2}^2}, \quad (29)$$

where $\gamma_2^{U2^1}$ and $\gamma_2^{U2^{II}}$ are the SINRs of U2 decoded by itself at phases I and II, respectively. To simplify the analysis, we set $\sigma_{U1}^2 = \sigma_{U2}^2 = \sigma_0^2$.

Theorem 4. *The OPs at U1 and U2 are given by*

$$P_{out}^{U1} = \begin{cases} 1, & \alpha \leq \frac{\mu_2}{1+\mu_2} \text{ or } \alpha = 1, \\ 1 - \exp\left(-\frac{G_2}{\lambda_{SU1}}\right), & \frac{\mu_2}{1+\mu_2} < \alpha \leq \frac{\mu_1 + \mu_1\mu_2}{\mu_1 + \mu_2 + \mu_1\mu_2}, \\ 1 - \exp\left(-\frac{G_1}{\lambda_{SU1}}\right), & \frac{\mu_1 + \mu_1\mu_2}{\mu_1 + \mu_2 + \mu_1\mu_2} \leq \alpha < 1, \end{cases} \quad (30)$$

and

$$P_{out}^{U2} = \begin{cases} 1, & \alpha \leq \frac{\mu_3}{1+\mu_3}, \\ \left(1 - \exp\left(-\frac{G_3}{\lambda_{SU2}}\right)\right) \times \left(1 - \exp\left(-\frac{\mu_3\sigma_0^2}{P_r\lambda_{U1U2}} - \frac{G_3}{\lambda_{SU1}}\right)\right), & \alpha > \frac{\mu_3}{1+\mu_3}, \end{cases} \quad (31)$$

where $G_1 = \frac{\mu_1\sigma_0^2}{(1-\alpha)P_S}$, $G_2 = \frac{\mu_2\sigma_0^2}{((1+\mu_2)\alpha - \mu_2)P_S}$, $G_3 = \frac{\mu_3\sigma_0^2}{((1+\mu_3)\alpha - \mu_3)P_S}$, and $\mu_1 = 2^{R_1} - 1$, $\mu_2 = 2^{R_2} - 1$, $\mu_3 = 2^{2R_2} - 1$. R_1 and R_2 is the pre-determined rate from S to U1 and U2.

Proof. : The outage event will occur at U1 in two cases: i) U1 cannot decode U2's signal successfully; and ii) U1 fails to decode its own signal. Hence, U1's OP be written as

$$\begin{aligned} P_{out}^{U1} &= 1 - \Pr\{\gamma_2^{U1} > \mu_2, \gamma_1^{U1} > \mu_1\} \\ &= 1 - \Pr\left\{\left((1+\mu_2)\alpha - \mu_2\right)|h_{SU1}|^2 > \frac{\mu_2\sigma_0^2}{P_S}, |h_{SU1}|^2 > \frac{\mu_1\sigma_0^2}{(1-\alpha)P_S}\right\}. \end{aligned} \quad (32)$$

Case 1: When $\alpha \leq \frac{\mu_2}{1+\mu_2}$ or $\alpha = 1$, we have $P_{out}^{U1} = 1$.

Case 2: When $\frac{\mu_2}{1+\mu_2} < \alpha \leq \frac{\mu_1 + \mu_1\mu_2}{\mu_1 + \mu_2 + \mu_1\mu_2}$, the OP can be derived as

$$\begin{aligned} P_{out}^{U1} &= 1 - \Pr\left\{|h_{SU1}|^2 > \frac{\mu_2\sigma_0^2}{((1+\mu_2)\alpha - \mu_2)P_S}\right\} \\ &= 1 - \exp\left(-\frac{G_2}{\lambda_{SU1}}\right). \end{aligned} \quad (33)$$

Case 3: When $\frac{\mu_1 + \mu_1\mu_2}{\mu_1 + \mu_2 + \mu_1\mu_2} < \alpha < 1$, we have

$$P_{out}^{U1} = 1 - \exp\left(-\frac{G_1}{\lambda_{SU1}}\right).$$

At U2, the information received within the two phases are processed by the selecting combining (SC) algorithm¹. Thus, the SINR of U2 is denoted as

$$\gamma_2^{U2} = \max\left(\gamma_2^{U2^1}, \min\left(\gamma_2^{U1}, \gamma_2^{U2^{II}}\right)\right). \quad (34)$$

When the near user U1 and the source transmission rate of both are less than the threshold rate, the outage will happen at U2. Hence, U2's OP be written as

$$\begin{aligned} P_{out}^{U2} &= \Pr\left\{\frac{1}{2}\log_2(1 + \gamma_2^{U2}) < R_2\right\} \\ &= \Pr\left\{\gamma_2^{U2^1} < \mu_3\right\} \times \left(1 - \Pr\left\{\gamma_2^{U1} \geq \mu_3\right\}\Pr\left\{\gamma_2^{U2^{II}} \geq \mu_3\right\}\right) \\ &= P_1 \times (1 - P_2 \times P_3). \end{aligned} \quad (35)$$

Using the same method as the OP of U1, the OP of U2 can be derived according to Eq. (31). \square

From the **Theorem 4**, it can be known that $G_1 = (\mu_1\sigma_0^2)/((1-\alpha)P_S)$ is a continuous increasing function of α , and $G_2 = (\mu_2\sigma_0^2)/(((1+\mu_2)\alpha - \mu_2)P_S)$ is a continuous decreasing function of α . In addition, $y = 1 - \exp(-x)$ is a continuous increasing function of x . We can obtain that P_{out}^{U1} is a continuous decreasing function of α when $\mu_2/(1+\mu_2) < \alpha \leq (\mu_1 + \mu_1\mu_2)/(\mu_1 + \mu_2 + \mu_1\mu_2)$, and when $(\mu_1 + \mu_1\mu_2)/(\mu_1 + \mu_2 + \mu_1\mu_2) \leq \alpha < 1$, P_{out}^{U1} is a continuous increasing function of α . Similarly, $G_3 = (\mu_3\sigma_0^2)/(((1+\mu_3)\alpha - \mu_3)P_S)$ is a continuous decreasing function of α , P_{out}^{U2} is a continuous decreasing function of α .

3.3. Optimal Effective Covert Rate

In the covert communication system, the system is usually required to meet the covert requirements of low probability detection while guaranteeing secure communication performance for legitimate users. We choose the effective covert rate as the performance evaluation metric, which defines the product of the probability of without outage of that link at a certain moment and the pre-determined rate [45]. The system's effective covert rate is expressed as

$$R_C = R_2(1 - P_{out}^{U2}). \quad (36)$$

Therefore, in order to maximize the effective covert rate of the system under the given covertness and reliability constraints, the optimization problem is set as follows

$$\begin{aligned} \max_{P_S} \quad & R_C, \\ \text{s.t.} \quad & \xi^{I*} \geq 1 - \varepsilon, \\ & \mathbb{E}(\xi^{II*}) \geq 1 - \varepsilon, \\ & P_{out}^{U1} \leq \delta_{th}, \end{aligned} \quad (37)$$

where δ_{th} are the pre-determined reliability constraint.

According to Eq. (36), R_2 is a pre-constant and R_C is a function of P_{out}^{U2} . In Eq. (31), we derive that P_{out}^{U2} is a continuous decreasing function of α and P_S . Thus, in order to maximize the R_C , the power allocation factor and the transmitted power

¹ In this study, we adopt SC detection as U2 since it has the low compute complete. However, the maximum ratio combination is also available in our analysis.

should be enhanced. For the two given covertness constraints, the ranges of α and P_S are derived. Similarly, the ranges of α and P_S are derived with satisfying the reliability constraint. On the other hand, we assume that Willie does not detected in phase II, which is compared Willie both phases are detected. However, the effective covert rate changed significantly.

4. Numerical Results

In this section, we analyze and investigate the effects of various parameters on the system covert performance. In this system, we make the following assumptions: $\lambda_{SW} = \lambda_{U1W} = \lambda_{SU1} = \lambda_{SU2} = \lambda_{U1U2} = 1$, the noise variance at different receptions are $\sigma_0^2 = \sigma_W^2 = 0$ dB and the pre-determined rates are $R_1 = R_2 = 1$ bps/Hz.

In phase I, it is assumed that $P_S = 0$ dB and $\alpha = 0.8$, then the PFA, MDP and DEP at different decision thresholds are shown in Fig. 2. In phase II, it is assumed that $P_r = 0$ dB, $P_j^{\max} = 0$ dB and $|h_{SW}|^2 = 1$, the PFA, MDP and DEP at different decision thresholds are shown in Fig. 3. The detection probability curves under the two phases are quite similar, as shown in Figs. 2 and 3. When the decision threshold is small, $P_{FA} = 1$. Since the decision threshold is small, the noise power is larger than the decision threshold, so it causes Willie to occur a false detection. With the increase of τ , the probability of Willie's false detection decreases. When the decision threshold is larger, the FAP finally becomes 0. It is obvious that the curve of MDP is opposite to the variation trend of FAP, which increases monotonically and finally approaches to 1. Due to the different variation of MDP and FAP, DEP first declines and then increases with the increase of τ . Thus, when the decision threshold is $\tau^{I*} = (1 - \alpha)P_S\lambda_{SW} \ln(1/(1 - \alpha))/\alpha + \sigma_W^2$ in Eq. (10) and $\tau^{II*} = P_j^{\max}|h_{SW}|^2 + \sigma_W^2$ in Eq. (19), Willie can obtain MDEPs for different phases.

Fig. 4 plots the variation curves of Willie's average MDEP with the maximum jamming power P_j^{\max} under phase II. We find that the average MDEP increases with the increase of P_j^{\max} . In addition, when P_j^{\max} is fixed, average MDEP decreases with the increase of U1's transmit power P_r . This is because increasing the jamming power reduces the detection of Willie and thus improves the covert performance of the system. In

addition, Willie is more likely to detect the transmission of covert information if the forwarding power P_r increases. Therefore, from the viewpoint of covertness, the jamming power should be increased as much as possible and decreased U1's forward power.

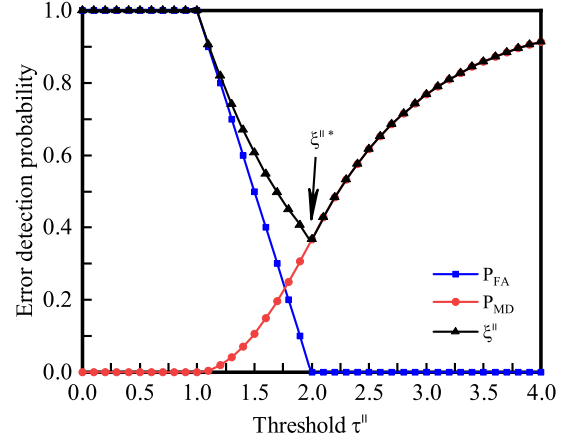


Fig. 3 The probability of different decision thresholds in the phase II.

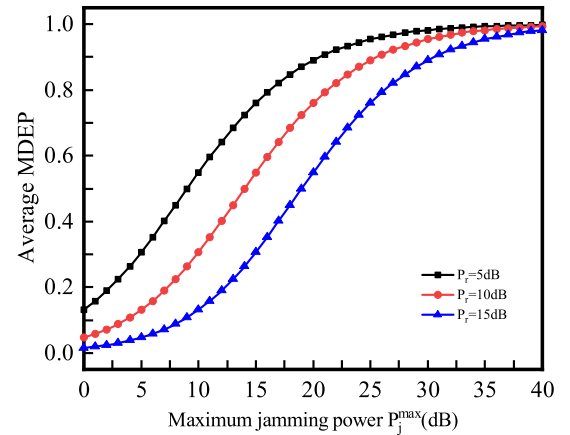


Fig. 4 Average MDEP versus P_j^{\max} for different values of P_r in the phase II.

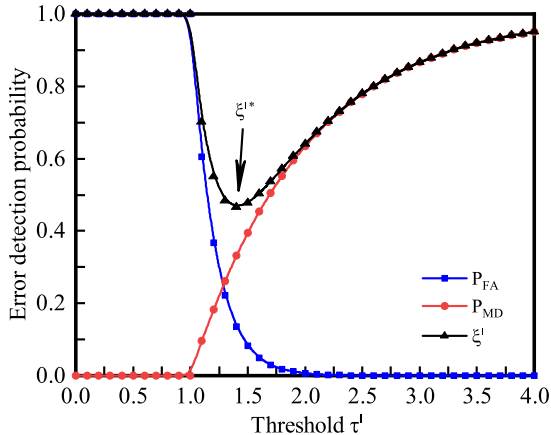


Fig. 2 The probability of different decision thresholds in the phase I.

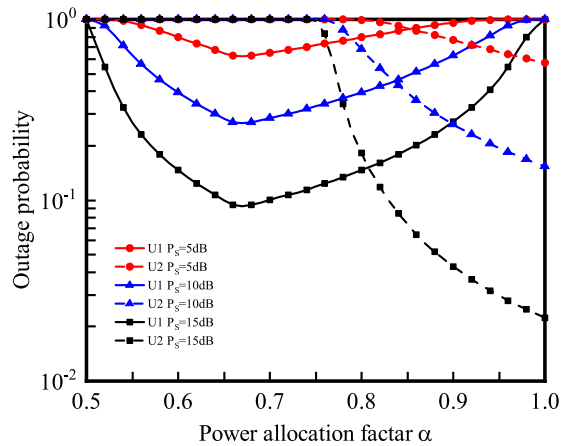


Fig. 5 Outage probability versus α for different values of P_S .

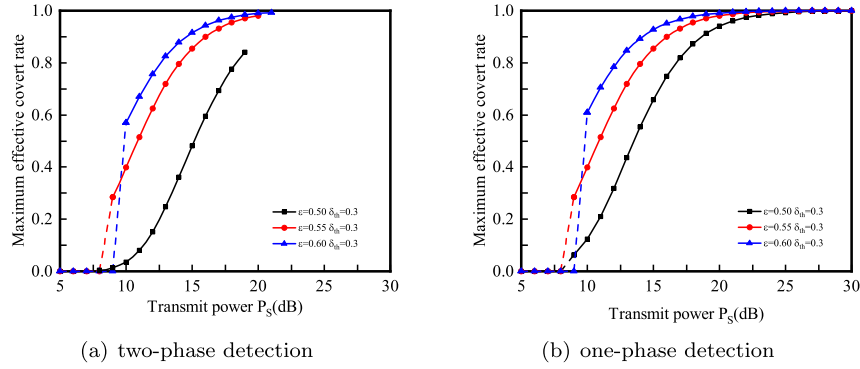


Fig. 6 Maximum effective covert rate versus P_S for different values of ϵ .

In Fig. 5, we plot the OPs versus α for different values of P_S . We set the transmit power $P_r = 0.5P_S$. The OP at U1 declines initially, and then becomes larger as the power allocation factor α grows. There is minimum OP at U1 achieved in $\alpha = (\mu_1 + \mu_1\mu_2)/(\mu_1 + \mu_1 + \mu_1\mu_2)$. The OP of U2 first remains constant and then decreases. This is because U1 needs two phases to transmit information to U2 in HD mode. The transmission power of signal x_2 increases as the allocation factor increases, which makes the probability of outage events decrease.

In Fig. 6, we plot the maximum effective covert rate versus P_S for various choices of ϵ . It can be shown that if P_S increases, the maximum effective covert rate also increases. Furthermore, when the constraint threshold ϵ increases, Willie's detection performance declines and the maximum effective covert rate increases. P_S has the specified regime in Fig. 6(a). This is because at the two-phase detection, Willie's maximum effective covert rate satisfies both the covertness and non-outage requirements. In Fig. 6(b), the maximum effective covert rate only needs to satisfy the covertness constraint of phase I and reliability constraint. Hence, it tends to become a constant when P_S is large enough.

5. Conclusion

In this paper, we investigate the problem of Willie's detection of each phase of information transmission under a cooperative NOMA network. In our study, S transmits covert information to U2 through a direct link and/or with the assistance of U1. Since Willie can detect each phase of covert communication independently, we derive the closed-form expressions for MDEP and OP at U1 and U2 for two phases. Then we analyze the maximum effective covert rate under the covertness and U1's reliability constraints. The results show that two-phase detection can also achieve the covert communication compared to one-phase detection. Our work provides a theoretical bound on the effective covert rate of two-phase detection. The improvement of covert performance for multi-phase detection will be the focus of our future research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. For a given τ^I , according to Eqs. (4) and (5), FAP and MDP are derived as

$$\begin{aligned} P_{FA}^I &= \Pr\{D_1|H_0\} = \Pr\{T_W^I > \tau^I|H_0\} \\ &= \Pr\{P_{SU1}|h_{SW}|^2 + \sigma_W^2 > \tau^I\} \\ &= \Pr\{|h_{SW}|^2 > \frac{\tau^I - \sigma_W^2}{P_{SU1}}\}, \end{aligned} \quad (\text{A.1})$$

and

$$\begin{aligned} P_{MD}^I &= \Pr\{D_0|H_1\} = \Pr\{T_W^I < \tau^I|H_1\} \\ &= \Pr\{P_{SU1}|h_{SW}|^2 + P_{SU2}|h_{SW}|^2 + \sigma_W^2 < \tau^I\} \\ &= \Pr\{|h_{SW}|^2 < \frac{\tau^I - \sigma_W^2}{P_{SU1} + P_{SU2}}\}, \end{aligned} \quad (\text{A.2})$$

respectively. Where the PDF of $|h_{SW}|^2$ is $f_{|h_{SW}|^2}(x) = \frac{1}{z_{SW}} \exp\left(-\frac{x}{z_{SW}}\right)$.

Appendix B. For a given τ^{II} , according to Eqs. (4) and (6), FAP and MDP are derived as

$$\begin{aligned} P_{FA}^{II} &= \Pr\{D_1|H_0\} = \Pr\{T_W^{II} > \tau^{II}|H_0\} \\ &= \Pr\{P_j|h_{SW}|^2 + \sigma_W^2 > \tau^{II}\} \\ &= \begin{cases} 1, & \tau^{II} < \sigma_W^2, \\ \int_{\frac{\tau^{II} - \sigma_W^2}{|h_{SW}|^2}}^{P_j^{\max}} f_{P_j}(x) dx, & \sigma_W^2 \leq \tau^{II} \leq \psi, \\ 0, & \tau^{II} > \psi, \end{cases} \end{aligned} \quad (\text{B.1})$$

and

$$\begin{aligned} P_{MD}^{II} &= \Pr\{D_0|H_1\} = \Pr\{T_W^{II} < \tau^{II}|H_1\} \\ &= \Pr\{P_j|h_{SW}|^2 + P_r|h_{U1W}|^2 + \sigma_W^2 < \tau^{II}\} \\ &= \begin{cases} 0, & \tau^{II} < \sigma_W^2, \\ \int_0^{\frac{\tau^{II} - \sigma_W^2}{P_j}} \int_0^{\frac{\tau^{II} - \sigma_W^2 - P_r y}{|h_{SW}|^2}} f_{P_j}(x) f_{|h_{U1W}|^2}(y) dx dy, & \sigma_W^2 \leq \tau^{II} \leq \psi, \\ \int_0^{P_j^{\max}} \int_0^{\frac{\tau^{II} - \sigma_W^2 - |h_{SW}|^2 y}{P_r}} f_{|h_{U1W}|^2}(x) f_{P_j}(y) dx dy, & \tau^{II} > \psi, \end{cases} \end{aligned} \quad (\text{B.2})$$

respectively.

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