Covert Communication With Truncated Channel Inversion Power Control in D2D Underlaid Cellular Networks

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Device-to-device (D2D) underlaid cellular networks are regarded as an emerging network structure in the 5G systems. We study the covert communication of such networks consisting of a base station BS, a cellular user $Alice$, a D2D pair with a transmitter D_t and a receiver D_r, and a warden $Willie$. To conduct the covert communication, $Alice$ adopts the truncated channel inversion power control (CIPC) to hide itself from $Willie$, where the received signal power at BS is fixed avoiding channel estimation for decoding $Alice$'s signal. Meanwhile, the interference generated by the D2D pair reusing the spectrum of $Alice$ is exploited to confuse $Willie$. To understand the fundamental covert rate performance in the considered network, we first provide a theoretical model for characterizing the detection error probability of $Willie$ as well as the effective covert rate at BS under the truncated CIPC scheme. Based on the main results, we then explore the effective covert rate maximization under the constraint of the detection error probability to identify the optimal truncated CIPC scheme designing and interference management. Finally, extensive numerical results are presented to illustrate the impacts of the truncated CIPC and interference from D_t on the covert performance.

***Index Terms*—Device-to-device, covert communication, physical layer security, power control.**

I. INTRODUCTION

DEVICE-to-device (D2D) underlaid cellular networks where the wireless cellular communication and the D2D communication coexist, have been recognized as the promising network architecture for meeting the ever-increasing wireless data traffic in 5G and beyond cellular systems [1]. The D2D communication allows proximity users to communicate directly by reusing the spectrum resources of the cellular communication without relaying through the base station, which brings many possibilities and challenges for cellular communication in such networks [2].

Due to the broadcast nature of wireless medium, security is of great importance concern for deploying the D2D underlaid cellular networks, which has attracted widespread attention from industry and academia [3]. Recently, physical layer security (PLS) which utilizes the inherent randomness nature of wireless channels and noise has been regarded as a promising technology for securing wireless communication. Secure communication and covert communication are two main works with PLS technology. Secure communication protects the transmitted content from being decoded by adversaries, different from the secure communication, the covert communication is to protect the existence of communication, which can guarantee a high level security. Due to the different purposes of secure communication and covert communication, the existing studies on the secure communication [4]–[7] can not be applied for the covert communication in the D2D underlaid cellular networks.

In the wireless systems, numerous studies have been done on covert communication where the source-destination pair protects the communication from being detected by warden(s). The foundation work in [8] introduced the square root law in the additive white Gaussian noise (AWGN) channels, which shows that in n channel uses the transmit bits is limited by $O(\sqrt{n})$. Afterwards, the square root law was also proved to be held in the bosonic channels with thermal noise [9], the noisy discrete memoryless channels [10], [11], and the binary symmetric channels [12]. However, as $n \to \infty$, the covert bits can be transmitted in a channel use is zero [13]. Therefore, the positive covert rate achievement is brought to focus, i.e., for any $n \to \infty$, $O(n)$ bits can be transmitted in n channel uses. The work in [14] proved that uncertainty about the channel state information (CSI) from source to warden is beneficial to the achievement of the positive covert rate. It was also verified that when warden is uncertain about the background noise around itself also beneficial to the positive covert rate [15]. To achieve the positive covert rate artificial noise generation and cooperative jamming schemes are designed [**?**], [16]–[20]. For example, an uninformed jammer uesd to send jamming signal [**?**], [16], [17], a relay in the two-hop networks used to forward signal and send artificial noise [18], and a full-duplex receiver designed to receive source's signal and emit artificial noise [19], [20]. Although a lot of research about covert communication have been done under the various systems [18], [21]–[23], these results can not be applied to the covert communication under the D2D underlaid cellular networks. Recently, numerous efforts for the covert communication in the D2D underlaid cellular networks has been done. For example, to confuse multiple wardens an antenna array at the base station was designed to send artificial noise in the work [24], thus ensure the covertly transmission between the D2D pair. In the work [25], a covert communication scheme that allows the D2D link to transmit covertly was studied by utilizing power allocation to confuse the warden. The work in [26] explores the joint design of spectrum allocation and power control for the maximization of sum covert rate of D2D transmissions, while the work in [27] investigates the user trust

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degree evaluation and spectrum allocation for such sum covert rate maximization. The work in [28] considers the scenario that the D2D transmitters distributed in a safety area can also serve as relays such that wardens cannot detect the existence of D2D transmissions, and investigates the joint designs of relay selection and transmit power of D2D transmitters to maximize the covert rate of cellular users. While these works mainly focus on the covert transmission on the D2D links, the covert transmission of the cellular communication has not been well studied, which is the prior communication mode in the D2D underlaid cellular networks.

We can see from the analysis above that the existing researches mainly focus on the hidden of the process of transmission rather than the existence of the transmitter. If the warden knows the position of transmitter, he can always destroy the potential transmission leading to the failure of covert communication. To solve the problem of hiding the transmitter, the channel inversion power control (CIPC) schemes are designed at the transmitter to hide itself from warden in the wireless systems [29], [30]. The CIPC scheme can ensure a fixed received power at the receiver avoiding the requirement of CSI for decoding the transmitter's signal, therefore, the transmitter does not need to send pilot signals to the receiver in advance for channel estimation. In the Rayleigh fading wireless networks, the work [29] exploited the full-duplex receiver to simultaneously receive covert signals and send artificial noise to achieve covert communication, the truncated and conventional CIPC schemes were designed at transmitter. Under the schemes the covert performance was examined with respect to the effective covert rate. In the IoT systems, the work [30] explored the CIPC scheme at the transmitter as well as assumed that warden is uncertain about the background noise. Meanwhile, the optimal CIPC scheme maximizing the effective covert rate was examined. Note that the warden is easily suspicious of the transmission once the external jammers are utilized to generate interference. In the D2D underlaid cellular networks, D2D pairs are allowed to reuse the spectrum resource of cellular communications, which will cause interference to the legal receiver and the warden. For the covert communication, the interference from the D2D transmitter to the warden is beneficial. In addition, the interference management can be conducted to ensure the covert performance.

Motivated by the analysis above, in this paper we are going to explore the covert communication of uplink cellular link with the truncated CIPC scheme at the transmitter in the D2D underlaid cellular network. The network consists of a base station, a cellular user, a D2D pair, and a warden. Thus two fundamental issues of the truncated CIPC design and interference management have attracted our attention, which significantly impacts the covert performance. To address these issues, a theoretical model is developed to depict the covert performance of the considered network, and then we explores the jointly designing of the optimal truncated CIPC scheme and interference management to maximize the covert performance with respect to the effective covert rate. To the best of our knowledge, this is work for the first time jointly studies the truncated CIPC and interference management for the achievement of covert communication in the D2D underlaid cellular networks. The interference from the D2D pair can confuse warden, which also significantly affect the covert performance which can be guaranteed by carefully designing the truncated CIPC. Thus, the research is valuable to study the impact of the truncated CIPC and interference management on the covert performance in the D2D underlaid cellular network. The main contributions are summarized as follows.

- In the considered D2D underlaid cellular network, we adopt a truncated CIPC scheme at the transmitter to avoid the exposure of itself while transmitting to the receiver and to ensure a constant signal power at the receiver. In addition, the inherent interference from the D2D pair is exploited to achieve covert communication.
- Under the scheme, we first present the theoretical framework to derive the average minimal detection probability of the warden, transmission outage probability of the cellular covert communication and that of the D2D communication. We then formulate the performance metric effective covert rate for measuring the cellular covert performance.
- Further, the effective covert rate maximization problem is solved to identify the joint design of optimal truncated CIPC at the transmitter and interference management at the D2D pair under the constraint of covertness requirement.
- Finally, extensive numerical results are presented to show the impacts of the truncated CIPC and interference from the D2D pair on the effective covert rate.

The remainder of this paper is organized as follows. The system model is introduced in Section II. Section III presents the truncated channel inversion power control scheme as well as the modeling and optimization of the covert performance. Extensive numerical results and conclusions are given in Section IV and Section V, respectively.

II. SYSTEM MODEL

A. Network Model

As illustrated in Fig. 1, we consider a D2D underlaid cellular network which consists of one base station BS, one cellular user $Alice$, one D2D pair as well as one warden $Willie$ who passively detects the covert transmission between $Alice$ and BS. The transmitter and the receiver of the D2D pair is denoted by D_t and D_r, respectively. D_t and D_r operate in underlay mode reusing the spectrum resources of the transmission between $Alice$ and BS. Thus, there is interference from D_t to BS and that from $Alice$ to D_r. We assume that all wireless channels are time-slotted quasi-static Rayleigh fading channels, where each channel remains constant for one time slot while changing randomly and independently from one time slot to the next. The channel coefficient from node i to node j is denoted as h_{ij}, which is modeled as a complex zero mean Gaussian random variable with variance λ_{ij}. We assume that λ_{ij} is publicly known by all nodes, thus, the corresponding channel gain $|h_{ij}|^2$ is an exponentially distributed random variable with mean λ_{ij}, and the probability density function (pdf) of $|h_{ij}|^2$ is given by $f_{|h_{ij}|^2}(x) = \frac{1}{\lambda_{ij}} \exp(-\frac{x}{\lambda_{ij}})$. Here,

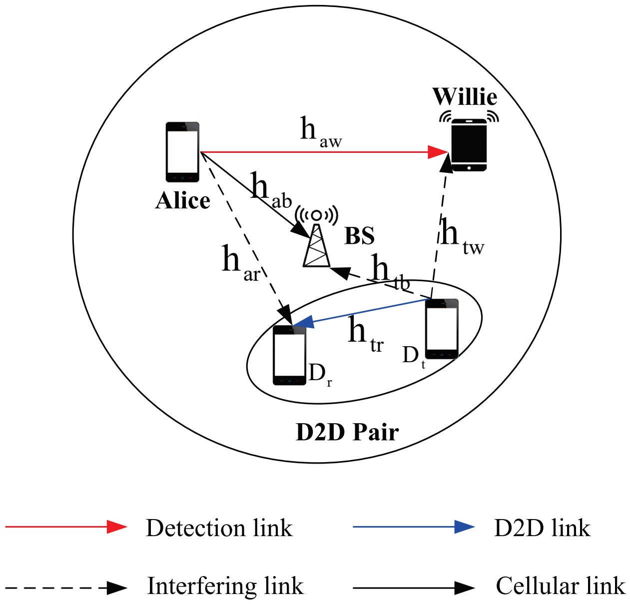

Fig. 1: System Model.

$i \in \{a, t\}$ and $j \in \{b, r, w\}$, a, t, r, b, w denote $Alice$, D_t, D_r, and $Willie$, respectively. In addition, we use n_b, n_r and n_w to denote the additive white Gaussian noise at BS, D_r and $Willie$ with variance σ^2. $Alice$, $Willie$, D_r, and D_t are equipped with a single antenna.

For the covert cellular communication, to hide the transmitter $Alice$, $Alice$ will not broadcast pilots for channel estimating, which results in the lack of h_{aw} at $Willie$. To guarantee the correct decoding at BS without CSI from $Alice$ to BS, $Allice$ adopts a truncated CIPC scheme to guarantee a fixed value of received power at BS [29], [30], i.e.,

$$P_a|h_{ab}|^2 = Q, \tag{1}$$

where P_a is the transmit power at $Alice$ and $P_a \leq P_a^{\max}$. To ensure a fixed value at BS, $Alice$ varies P_a based on h_{ab}. Thus, BS should broadcast pilots to enable $Alice$ to estimate his channel h_{ba} from BS, considering channel reciprocity, $|h_{ab}|^2$ is the same as $|h_{ba}|^2$. Note that $Alice$ may transmit to BS only when the channel gain from $Alice$ to BS is greater than $\frac{Q}{P_a^{\max}}$. We denote the condition as $\mathbb{B}$ and the probability of meeting the condition is $P_{\mathbb{B}}$, which is given by

$$\begin{aligned} P_{\mathbb{B}} &= \mathbb{P}\{|h_{ab}|^2 \geq \frac{Q}{P_a^{\max}}\} \\ &\overset{(a)}{=} \exp(-\frac{Q}{P_a^{\max}\lambda_{ab}}), \end{aligned} \tag{2}$$

where the process (a) is achieved because $|h_{ab}|^2$ is an exponentially distributed random variable with mean λ_{ab}. As such, the transmit power at $Alice$ is given by

$$P_a = \begin{cases} \frac{Q}{|h_{ab}|^2}, & |h_{ab}|^2 \geq \frac{Q}{P_a^{\max}}. \\ 0, & \text{otherwise}. \end{cases} \tag{3}$$

For the D2D communication, D_t reuses the spectrum resources of cellular transmission to communicate with D_r, the transmit power at D_t is denoted by P_t, which is an uniformly distributed random variable in the interval $[0, P_t^{\max}]$, where $P_t^{\max}$ is the maximum transmit power allocated by BS, the pdf of P_t is given by

$$f_{P_t}(x) = \begin{cases} \frac{1}{P_t^{\max}}, & 0 \leq P_t \leq P_t^{\max}. \\ 0, & \text{otherwise}. \end{cases} \tag{4}$$

We assume Willie knows the CSI of his channel from D_t, i.e. h_{tw}.

B. Detection at Willie

From the perspective of Willie, his goal is to decide whether the transmission between $Alice$ and BS exists or not according to his observations. Therefore, binary hypothesis testing is conducted on $Willie$'s observations. The null hypothesis H_0 denotes that $Alice$ does not transmit to BS and the alternative hypothesis H_1 denotes that $Alice$ transmits to BS. We use $y_w(i)$ to denote the ith received signal at Willie, thus we have

$$y_w(i) = \begin{cases} \sqrt{P_t}h_{tw}x_t(i) + n_w(i), & \mathrm{H}_0. \\ \sqrt{P_a}h_{aw}x_a(i) + \sqrt{P_t}h_{tw}x_t(i) + n_w(i), & \mathrm{H}_1. \end{cases} \tag{5}$$

where $x_a(i)$ and $x_t(i)$ are the ith signal transmitted by $Alice$ and D_t, respectively. Each of the ith signals meets that $\mathbb{E}[|x_a(i)|^2] = 1$ and $\mathbb{E}[|x_t(i)|^2] = 1$, where $\mathbb{E}[\cdot]$ is the expectation operator. $i = 1, 2, \ldots, n$ is the index of time slot and n is assumed to be infinity, i.e., $n \to \infty$. To conduct the detection, we assume that the radiometer is employed at Willie, which is the power detector and is considered as the optimal detector [13] which is given by

$$Y_W \underset{D_0}{\overset{D_1}{\gtrless}} \tau, \tag{6}$$

where Y_W is the average received power in a time slot at Willie and is given by $Y_W = \frac{1}{n}\sum_{i=1}^{n}|y_w(i)|^2$, τ is the detection threshold. D_0 and D_1 are the decisions in favor of H_0 and H_1, respectively. Considering $n \to \infty$, we have

$$Y_W = \begin{cases} P_t|h_{tw}|^2 + \sigma^2, & \mathrm{H}_0. \\ P_a|h_{aw}|^2 + P_t|h_{tw}|^2 + \sigma^2, & \mathrm{H}_1. \end{cases} \tag{7}$$

To measure the detection performance, two types of errors are given: false alarm and missed detection. The false alarm is the event that Willie decides D_1 to support H_1 while H_0 is true, we use P_{FA} to denote the probability of false alarm, which is formulated by $P_{FA} = \mathcal{P}\{D_1|\mathrm{H}_0\}$. The missed detection is defined as the event that Willie decides D_0 to support H_0 while H_1 is true, the probability of missed detection is denoted by P_{MD}, which is given by $P_{MD} = \mathcal{P}\{D_0|\mathrm{H}_1\}$. The metric of detection error probability is adopted to model the detection performance at Willie. We use P_e to denote the detection error probability, which is given by

$$P_e = P(H_0)P_{FA} + P(H_1)P_{MD}, \tag{8}$$

where $P(H_1)$ is the probability that $Alice$ transmit covertly to BS, and $P(H_0)$ is the probability that $Alice$ does not transmit Recall that $Alice$ can transmit only when $\mathbb{B}$ is met, We make an assumption of an equal priori probability of $Alice$ transmitting or not when $\mathbb{B}$ is met, thus,

$$P(H_1) = \frac{1}{2}P_{\mathbb{B}}, \tag{9}$$

and

$$P(H_0) = 1 - P(H_1). \tag{10}$$

In practice, it is difficult to know P_e for $Alice$, since the detection threshold τ selected by Willie is unknown. Thus, to achieve the covert transmission, we will examine the optimal τ that minimizes the detection error probability at $Willie$, which is the worst case for $Alice$.

C. Performance Metrics

Considering the uplink cellular transmission and D2D communication, the i-th received signal at BS and D_r are denoted by $y_b(i)$ and $y_w(i)$ and given by

$$y_b(i) = \sqrt{P_a} h_{ab} x_a(i) + \sqrt{P_t} h_{tb} x_t(i) + n_b(i), \tag{11}$$

$$y_r(i) = \sqrt{P_t} h_{tr} x_t(i) + \sqrt{P_a} h_{ar} x_a(i) + n_r(i). \tag{12}$$

Thus, the instantaneous channel capacity C_b of $Alice$ and C_d of D_t are given by

$$\mathrm{C}_b = \log_2(1 + \mathrm{SINR}_b). \tag{13}$$

and

$$\mathrm{C}_d = \log_2(1 + \mathrm{SINR}_d), \tag{14}$$

where SINR_b and SINR_d are the signal-to-interference-plus-noise ratio (SINR) at BS and D_r and given by

$$\mathrm{SINR}_b = \frac{P_a |h_{ab}|^2}{P_t |h_{tb}|^2 + \sigma^2}, \tag{15}$$

and

$$\mathrm{SINR}_d = \frac{P_t |h_{tr}|^2}{P_a |h_{ar}|^2 + \sigma^2}. \tag{16}$$

To explore the performances of covert transmission of $Alice$, we define the metric of **effective covert rate** to model the covert rate without transmission outages of cellular and D2D transmissions under the constraints of a high detection error probability at $Willie$ and tolerance of transmission outage at D_t. We use R_c to denote the effective covert rate and is formulated as

$$R_c = r_c(1 - P_{out}^b) P_{\mathbb{B}}, \tag{17}$$

where r_c is the pre-determined covert rate from $Alice$ to BS, P_{out}^b is the transmission outage probability of the cellular communication from $Alice$ to BS, which is defined as the probability that the instantaneous channel capacity is lower than a pre-determined rate. Thus, we formulate P_{out}^b as

$$P_{out}^b = \mathbb{P}\{C_b < r_c\}. \tag{18}$$

III. COVERT PERFORMANCE MODELING AND OPTIMIZATION UNDER THE TRUNCATED CHANNEL INVERSION POWER CONTROL SCHEME

In the D2D underlaid cellular network, considering the truncated CIPC scheme presented in Section II-A, in this section, we first give the corresponding detection performance at $Willie$ under the scheme. Then, we study the modeling of the effective covert rate under the scheme. Based on the results, we further investigate the optimal truncated CIPC scheme and interference management for maximizing the effective covert rate.

A. Detection Error Probability at Willie

According to the definition of the detection error probability in (8) for characterizing the detection performance at $Willie$, we first give the probability of false alarm and that of missed detection in the following theorem.

Theorem 1. *Consider the D2D underlaid cellular network with the truncated CIPC scheme, the probability of false alarm P_{FA} and the probability of missed detection P_{MD} are determined as*

$$P_{FA} = \begin{cases} 1, & \tau < \sigma^2. \\ 1 - \alpha_1, & \sigma^2 \le \tau \le \eta. \\ 0, & \tau > \eta. \end{cases} \tag{19}$$

and

$$P_{MD} = \begin{cases} 0, & \tau < \sigma^2. \\ \alpha_1 - \alpha_2 e^{\alpha_3} \Big[\mathrm{Ei}(-(\alpha_3 + \alpha_4)) - \mathrm{Ei}(-\alpha_3) \Big], & \sigma^2 \le \tau \le \eta. \\ 1 - \alpha_2 e^{\alpha_3} \Big[\mathrm{Ei}(-(\alpha_3 + \alpha_4)) - \mathrm{Ei}(-(\alpha_3 + \alpha_5)) \Big], & \tau > \eta \end{cases} \tag{20}$$

where $\mathrm{Ei}(x)$ *is the exponential integral function and* $\mathrm{Ei}(x) = -\int_{-x}^{\infty} \frac{e^{-t}}{t} dt$, $\eta = P_t^{\max} |h_{tw}|^2 + \sigma^2$, $\alpha_1 = \frac{\tau - \sigma^2}{P_t^{\max} |h_{tw}|^2}$, $\alpha_2 = \frac{Q \lambda_{aw}}{P_t^{\max} \lambda_{ab} |h_{tw}|^2}$, $\alpha_3 = \frac{Q}{P_a^{\max} \lambda_{ab}}$, $\alpha_4 = \frac{\tau - \sigma^2}{P_a^{\max} \lambda_{aw}}$, $\alpha_5 = \frac{\tau - \eta}{P_a^{\max} \lambda_{aw}}$

Proof. Following the definitions of P_{FA} and P_{MD} in Section II-B, we have

$$\begin{aligned} P_{FA} &= \mathbb{P}\{P_t |h_{tw}|^2 + \sigma^2 > \tau | \mathbb{B}\} + \mathbb{P}\{P_t |h_{tw}|^2 + \sigma^2 > \tau | \mathbb{B}^{'}\} \\ &= \mathbb{P}\{P_t |h_{tw}|^2 + \sigma^2 > \tau\} \\ &= \mathbb{P}\{P_t > \frac{\tau - \sigma^2}{|h_{tw}|^2}\} \\ &= \begin{cases} 1, & \tau < \sigma^2. \\ \int_{\frac{\tau - \sigma^2}{|h_{tw}|^2}}^{P_t^{\max}} f_{P_t}(x) dx, & \sigma^2 \le \tau \le \eta. \\ 0, & \tau > \eta. \end{cases} \end{aligned} \tag{21}$$

and

$$\begin{aligned} P_{MD} &= \mathbb{P}\{P_a |h_{aw}|^2 + P_t |h_{tw}|^2 + \sigma^2 > \tau | \mathbb{B}\} \\ &= \mathbb{P}\{P_a |h_{aw}|^2 + P_t |h_{tw}|^2 + \sigma^2 > \tau\} P_{\mathbb{B}}^{-1} \\ &= \mathbb{P}\{\frac{Q |h_{aw}|^2}{|h_{ab}|^2} + P_t |h_{tw}|^2 + \sigma^2 < \tau\} P_{\mathbb{B}}^{-1} \\ &= \begin{cases} 0, & \tau < \sigma^2. \\ P_{\mathbb{B}}^{-1} \mathbb{P}\{P_t < \frac{\tau - \sigma^2 - \frac{Q |h_{aw}|^2}{|h_{ab}|^2}}{|h_{tw}|^2}\}, & \sigma^2 \le \tau < \eta. \\ P_{\mathbb{B}}^{-1} \mathbb{P}\{\frac{|h_{aw}|^2}{|h_{ab}|^2} < \frac{\tau - \sigma^2 - P_t |h_{tw}|^2}{Q}\}, & \tau \ge \eta. \end{cases} \\ &= \begin{cases} 0, & \tau < \sigma^2. \\ P_{\mathbb{B}}^{-1} \int_{\frac{Q}{P_a^{\max}}}^{\infty} \int_0^{\frac{(\tau - \sigma^2) z}{Q}} \int_0^{\frac{\tau - \sigma^2 - \frac{Q y}{z}}{|h_{tw}|^2}} & \\ f_{P_t}(x) f_{|h_{aw}|^2}(y) f_{|h_{ab}|^2}(z) dx dy dz, & \sigma^2 \le \tau < \eta. \\ P_{\mathbb{B}}^{-1} \int_0^{P_t^{\max}} \int_{\frac{Q}{P_a^{\max}}}^{\infty} \int_0^{\frac{(\tau - \eta) y}{Q}} & \\ f_{|h_{aw}|^2}(x) f_{|h_{ab}|^2}(y) f_{P_t}(z) dx dy dz, & \tau \ge \eta. \end{cases} \end{aligned}$$

Recall that P_t follows uniform distribution in the interval $[0, P_t^{\max}]$ and the pdf of P_t is given in (4). All channel gains are exponential distribution random variables and the pdf is $f_{|h_{ij}|^2}(x) = \frac{1}{\lambda_{ij}} \exp(-\frac{x}{\lambda_{ij}})$. With these pdfs we can solve the above integrations and obtain the results of P_{FA} and P_{MD} in (19) and (20), respectively.

Next, we will explore the optimal detection threshold for minimizing the detection error probability at Willie, which is given in the following theorem.

Theorem 2. *Consider the D2D underlaid cellular network introduced in this paper, we use τ^* to denote the optimal detection threshold selected by $Willie$, which is given by $\tau^* = \eta$. P_e^* is used to denote the corresponding minimal detection error probability at $Willie$ and is determined as*

$$P_e^* = \frac{\exp(-\alpha_3)}{2} - \frac{\alpha_2[\mathrm{Ei}(-(\frac{P_t^{\max}|h_{tw}|^2}{P_a^{\max}\lambda_{aw}} + \alpha_3)) - \mathrm{Ei}(-\alpha_3)]}{2} \tag{22}$$

Proof. According to results of the probability of false alarm P_{FA} and the probability of missed detection P_{MD} given in Theorem 1, the detection error probability P_e at $Willie$ can be determined as

$$\begin{aligned} P_e &= P(H_0)P_{FA} + P(H_1)P_{MD} \\ &= \begin{cases} 1 - \frac{e^{-\alpha_3}}{2}, & \tau < \sigma^2. \\ \frac{\eta-\tau}{P_t^{\max}|h_{tw}|^2} + \frac{(2(\tau-\sigma^2)-P_t^{\max}|h_{tw}|^2)e^{-\alpha_3}}{2P_t^{\max}|h_{tw}|^2} \\ -\frac{\alpha_2[\mathrm{Ei}(-(\alpha_3+\alpha_4))-\mathrm{Ei}(-\alpha_3)]}{2}, & \sigma^2 \le \tau < \eta. \\ \frac{e^{-\alpha_3}}{2} - \frac{\alpha_2[\mathrm{Ei}(-(\alpha_3+\alpha_4))-\mathrm{Ei}(-(\alpha_3+\alpha_5))]}{2}, & \tau \ge \eta. \end{cases} \end{aligned}$$

To find the optimal threshold τ minimizing the detection error probability P_e, the first derivative of P_e in terms of τ is calculated. We can see that for $\tau < \sigma^2$, P_e is a constant unrelated with τ, thus we mainly focus on the derivative of P_e when $\sigma^2 \le \tau < \eta$ and $\tau \ge \eta$.

For $\sigma^2 < \tau < \eta$, we have

$$\begin{aligned} \frac{\partial P_e}{\partial \tau} =& \frac{\exp(-\frac{Q}{P_a^{\max}\lambda_{ab}}) - 1}{P_t^{\max}|h_{tw}|^2} - \frac{Q\lambda_{aw}}{2P_t^{\max}|h_{tw}|^2} \\ &\times \frac{\exp(-\frac{\lambda_{ab}(\tau-\sigma^2)+Q\lambda_{aw}}{P_a^{\max}\lambda_{aw}\lambda_{ab}})}{\lambda_{ab}(\tau-\sigma^2)+Q\lambda_{aw}}. \end{aligned} \tag{23}$$

Recall that $0 < \exp(-\frac{Q}{P_a^{\max}\lambda_{ab}}) \le 1$ for $Q \ge 0$ and the second term of $\frac{\partial P_e}{\partial \tau}$ is positive, thus $\frac{\partial P_e}{\partial \tau} < 0$, which indicates that P_e decreases with the increase of τ, therefore, the minimal detection error probability P_e^* is obtained when $\tau^* = \eta$ and the corresponding P_e^* is given by

$$P_e^* = \frac{\exp(-\alpha_3)}{2} - \frac{\alpha_2[\mathrm{Ei}(-(\frac{P_t^{\max}|h_{tw}|^2}{P_a^{\max}\lambda_{aw}} + \alpha_3)) - \mathrm{Ei}(-\alpha_3)]}{2}. \tag{24}$$

For $\tau \ge \eta$,

$$\frac{\partial P_e}{\partial \tau} = -\frac{Q\lambda_{aw}\left[\frac{\exp(-\frac{x_1}{P_a^{\max}\lambda_{aw}})}{x_1} - \frac{\exp(-\frac{x_2}{P_a^{\max}\lambda_{aw}})}{x_2}\right]}{2P_t^{\max}|h_{tw}|^2\lambda_{ab}}, \tag{25}$$

where $x_1 = \frac{(\tau-\sigma^2)\lambda_{ab}+Q\lambda_{aw}}{\lambda_{ab}}$ and $x_2 = \frac{(\tau-\eta)\lambda_{ab}+Q\lambda_{aw}}{\lambda_{ab}}$. To determine the sign of (25), we need to determine the sign of the term of $\frac{\exp(-\frac{x_1}{P_a^{\max}\lambda_{aw}})}{x_1} - \frac{\exp(-\frac{x_2}{P_a^{\max}\lambda_{aw}})}{x_2}$. Let $g(x) = \frac{\exp(-\frac{x}{P_a^{\max}\lambda_{aw}})}{x}$ and $\frac{\partial g(x)}{\partial x} = -\frac{(\frac{x}{P_a^{\max}\lambda_{aw}}+1)\exp(-\frac{x}{P_a^{\max}\lambda_{aw}})}{x^2} \le 0$ for $x > 0$. Note that $x_1 > x_2$, thus $g(x_1) - g(x_2) < 0$. We can determine that $\frac{\partial P_e}{\partial \tau} > 0$, which indicates that P_e increases with τ. Thus, when $\tau = \eta$ we can obtain the P_e^* in (24).

Next, we compare the P_e when $\tau < \sigma^2$ with P_e^* to determine the smaller one. Let $A = P_e - P_e^* = \frac{\alpha_2[\mathrm{Ei}(-(\frac{P_t^{\max}|h_{tw}|^2}{P_a^{\max}\lambda_{aw}}+\alpha_3))-\mathrm{Ei}(-\alpha_3)]}{2}$. Note that $\frac{P_t^{\max}|h_{tw}|^2}{P_a^{\max}\lambda_{aw}}+\alpha_3 > \alpha_3$ and $\frac{\partial \mathrm{Ei}(x)}{\partial x} < 0$, thus $A > 0$, which indicates that $P_e > P_e^*$. To this end, we complete the proof.

B. Average Minimal Detection Error Probability

From the perspective of $Alice$ who is unknown about the CSI $|h_{tw}|^2$ of the channel from D_t to $Willie$. Thus the average minimal detection error probability should be given to measure the covertness. We use $\overline{P}_e^*$ to denote the average minimal detection error probability, which is the expected value of $\overline{P}_e^*$ with respect to $|h_{tw}|^2$. Therefore, we have

$$\begin{aligned} \overline{P}_e^* =& \int_0^\infty P_e^* f_{|h_{tw}|^2}(x)dx \\ =& \int_0^\infty \left\{ \frac{\exp(-\frac{Q}{P_a^{\max}\lambda_{ab}})}{2} - \frac{Q\lambda_{aw}}{2P_t^{\max}\lambda_{ab}x} \right. \\ & \left. \times [\mathrm{Ei}(-(\frac{P_t^{\max}\lambda_{ab}x + Q\lambda_{aw}}{P_a^{\max}\lambda_{aw}\lambda_{ab}})) - \mathrm{Ei}(-\frac{Q}{P_a^{\max}\lambda_{ab}})] \right\} \\ & \times \frac{1}{\lambda_{tw}} \exp(-\frac{x}{\lambda_{tw}})dx \\ =& \frac{\exp(-\frac{Q}{P_a^{\max}\lambda_{ab}})}{2} - \frac{Q\lambda_{aw}\left[\Phi(x) - \mathrm{Ei}(-\frac{Q}{P_a^{\max}\lambda_{ab}})\Psi(x)\right]}{2P_t^{\max}\lambda_{tw}\lambda_{ab}}, \end{aligned} \tag{26}$$

where $\Phi(x) = \int_0^\infty \frac{\exp(-\frac{x}{\lambda_{tw}})}{x}\mathrm{Ei}(-(\frac{P_t^{\max}\lambda_{ab}x+Q\lambda_{aw}}{P_a^{\max}\lambda_{aw}\lambda_{ab}}))dx$ and $\Psi(x) = \int_0^\infty \frac{\exp(-\frac{x}{\lambda_{tw}})}{x}dx$, which can be solved by the numerical analysis methods. In fact, to achieve covert communication, $Alice$ should satisfy the covertness requirement, i.e., a high detection error probability at $Willie$. According to [30], $P_e \ge \min\{P(H_0), P(H_1)\}(P_{FA} + P_{MD}) \ge \min\{P(H_0), P(H_1)\} - \varepsilon$. Thus, for an arbitrarily small $\varepsilon \ge 0$, $Alice$ can achieve covert communication as $\overline{P}_e^* \ge \min\{P(H_0), P(H_1)\} - \varepsilon$.

C. Effective Covert Rate Modeling

To depict the effective covert rate of the considered D2D underlaid cellular network, we need to first derive the transmission outage probability of the cellular link according to the definition of the effective covert rate in (17). We give the transmission outage probability of cellular link in the following theorem.

Theorem 3. *With the truncated CIPC scheme in the considered D2D underlaid cellular network in our work, the transmission outage probability P_{out}^b from Alice to BS is given by*

$$P_{out}^b = \begin{cases} 1, & Q < (2^{r_c} - 1)\sigma^2. \\ \exp(-\beta) + \beta\mathrm{Ei}(-\beta), & Q \ge (2^{r_c} - 1)\sigma^2. \end{cases} \tag{27}$$

where $\beta = \frac{Q-(2^{r_c}-1)\sigma^2}{(2^{r_c}-1)\lambda_{tb}P_t^{\max}}$.

Proof. We first derive the transmission outage probability P_{out}^{b} from $Alice$ to BS, which is formulated in (18). We have

$$\begin{aligned} P_{out}^{b} &= \mathbb{P}\{C_b < r_c\} \\ &= \mathbb{P}\{\text{SINR}_b < 2^{r_c} - 1\} \\ &= \mathbb{P}\{\frac{Q}{P_t|h_{tb}|^2 + \sigma^2} < 2^{r_c} - 1\} \\ &= \mathbb{P}\{|h_{tb}|^2 > \frac{Q - \sigma^2(2^{r_c} - 1)}{P_t(2^{r_c} - 1)}\} \end{aligned} \tag{28}$$

Note that if $Q - \sigma^2(2^{r_c} - 1) < 0$, i.e. $Q < \sigma^2(2^{r_c} - 1)$, $P_{out}^{b} = 1$, otherwise, (28) can be rewritten as

$$P_{out}^{b} = \int_{0}^{P_t^{\max}} \int_{\frac{Q-\sigma^2(2^{r_c}-1)}{y(2^{r_c}-1)}}^{\infty} f_{|h_{tb}|^2}(x) f_{P_t}(y) dxdy. \tag{29}$$

Solving the integral above we can obtain the P_{out}^{b} in (27).

By substituting (27) and (2) into (17), we can obtain the expression of effective covert rate of the D2D underlaid cellular network.

D. Covert Performance Optimization

In this section, our purpose is to explore the maximization of the effective covert rate by jointly designing the truncated CIPC scheme and power control at D_t. Following the definition of the effective covert rate in (17), the maximization problem can be formulated as

$$\max_{Q, P_t^{\max}} \quad R_c, \tag{30a}$$

$$\text{s.t.} \quad \overline{P}_e^{*} \geq \min\{P(H_0), P(H_1)\} - \varepsilon, \tag{30b}$$

$$P_{out}^{d} \leq \delta, \tag{30c}$$

$$0 \leq P_t^{\max} \leq \Omega, \tag{30d}$$

where (30b) is the constraint of covertness requirement, Ω is the maximum transmission power that can be allocated to D_t by BS, (30c) presents the tolerance of the transmission outage between D_t and D_r, P_{out}^{d} is used to denote the transmission outage probability from D_t to D_r, δ is the threshold of the transmission outage probability at D_t. According to the definition of the transmission outage probability P_{out}^{b}, P_{out}^{d} can be formulated as

$$\begin{aligned} P_{out}^{d} &= \mathbb{P}\{C_d < r_d\} \\ &= \mathbb{P}\{\text{SINR}_d < 2^{r_d} - 1\} \\ &= \mathbb{P}\{\frac{P_t|h_{tr}|^2}{P_a|h_{ar}|^2 + \sigma^2} < 2^{r_d} - 1\} \\ &= \mathbb{P}\{\frac{P_t|h_{tr}|^2}{\frac{Q|h_{ar}|^2}{|h_{ab}|^2} + \sigma^2} < 2^{r_d} - 1\} \\ &= \mathbb{P}\{|h_{tr}|^2 < \frac{2^{r_d} - 1}{P_t}(\frac{Q|h_{ar}|^2}{|h_{ab}|^2} + \sigma^2)\} \\ &= \int_{0}^{P_t^{\max}} \int_{\frac{Q}{P_a^{\max}}}^{\infty} \int_{0}^{\infty} \int_{0}^{\frac{2^{r_d}-1}{P_t}(\frac{Qy}{z}+\sigma^2)} f_{|h_{tr}|^2}(x) \\ &\quad \times f_{|h_{ar}|^2}(y) f_{|h_{ab}|^2}(z) f_{P_t}(P_t) dxdyxzdP_t \end{aligned} \tag{31}$$

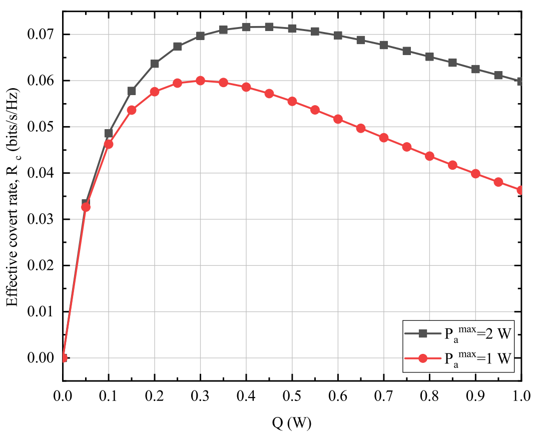

Fig. 2: The impact of Q on the effective covert rate R_c with different $P_a^{\max}$.

where r_d is the pre-determined rate from D_t to D_r. Solving (31), we can obtain the transmission outage probability P_{out}^{d} of D2D communication.

From the expressions of P_{out}^{b} and P_{out}^{d}, we can see that the expression of R_c is complicated. Thus, the closed-form solutions $(Q^*, P_t^{\max *})$ for $(Q, P_t^{\max})$ is usually difficult to obtain, so a two-dimensional search over $(Q, P_t^{\max})$ can be used to find the Q^* and $P_t^{\max *}$. We use R_c^* to denote the maximum value of the effective covert rate R_c, which can be obtained by substituting Q^* and $P_t^{\max *}$ into R_c.

IV. NUMERICAL RESULTS

In this section, we provide extensive numerical results to illustrate how the truncated CIPC and interference impact the effective covert rate of $Alice$. We set some parameters used in this paper as $\lambda_{i,j} = 1$, $\sigma = 0.01$, $r_c = 0.1$ bits/s/Hz, $r_d = 0.5$ bits/s/Hz, and $\Omega = 5$ W where $i \in \{a, t\}$ and $j \in \{b, r, w\}$, unless otherwise specified.

To explore the impact of the truncated CIPC scheme on the effective covert rate R_c, we summarize in Fig. 2 how the R_c varies with Q for a setting of $\varepsilon = 0.15$, $P_a^{\max} = \{1, 2\}$ W and $P_t^{\max} = 5$ W. It can be seen from Fig. 2 that the effective covert rate R_c first increases and then decreases with the increase of Q. This is due to the following reasons. First, as Q increases, the transmit power P_a at $Alice$ also increases, thus, the probability of transmission from $Alice$ to BS without outage increases, which dominates the value of R_c and thus leads to the increase of R_c. As Q continues to increase, the probability $P_{\mathbb{B}}$ of meeting the condition $|h_{ab}|^2 \geq \frac{Q}{P_a^{\max}}$ decreases, which dominates the R_c, thus the effective covert rate R_c decreases. We can also find that there is an optimal value of Q to maximize the effective covert rate.

To explore the impact of the maximum transmit power $P_t^{\max}$ at D_t on the effective covert rate R_c, we summarize in Fig. 3 how the R_c varies with $P_t^{\max}$ for a setting of $\varepsilon = 0.15$, $P_a^{\max} = \{1, 2\}$ W and $Q = 0.1$ W. We can observe that the effective covert rate R_c first is zero and then decreases from

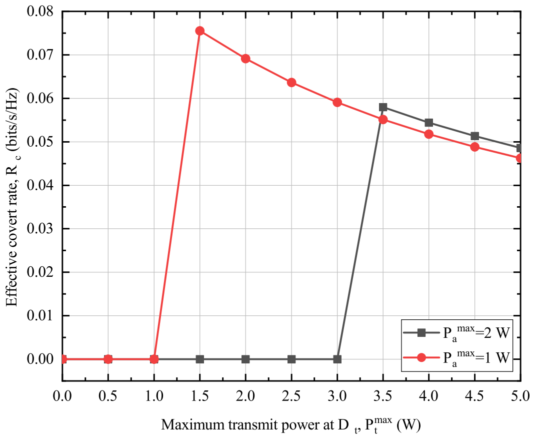

Fig. 3: The impact of the maximum transmit power at D_t on the effective covert rate R_c with different $P_a^{\max}$.

a maximum value. The reasons behind the phenomena can be explained as follows. For a given maximum transmit power $P_a^{\max}$ of $Alice$, as $P_t^{\max}$ is relatively small, the covertness requirement in (30b) under the setting of parameters can not be satisfied, i.e. $\overline{P}_e^* < \min\{P(H_0), P(H_1)\} - \varepsilon$. Thus, R_c first is zero. As $P_t^{\max}$ continues to increase, the interference from D_t to BS increases, thus the transmission outage probability from $Alice$ to BS increases according to (27), which leads to the decrease of R_c according to (17). We can also see that a smaller $P_a^{\max}$ requires a smaller $P_t^{\max}$ to maximize the effective covert rate R_c. This is because that a smaller transmit power of $Alice$ requires a smaller interference power to meet the covertness requirement.

V. CONCLUSION

This paper studied the truncated CIPC at the transmitter $Alice$ and the transmit power at the D2D pair for the covert cellular communication in the D2D underlaid cellular networks. We first derive the optimal detection threshold for minimizing the detection error probability at $Willie$, as well as the average minimal detection error probability. Then we present the theoretical model to depict the effective covert rate, on the basis of the main results we further solve the effective covert rate maximization problem to identify the optimal truncated CIPC scheme at $Alice$ and the maximum transmit power at D_r. We can conclude from our numerical results that increasing the maximum transmit power at D_t may not benefit for maximizing the effective covert rate and there is an optimal Q maximizing the effective covert rate. Besides, the maximum effective covert rate can be achieved by carefully designing the truncated CIPC at $Alice$ and the maximum transmit power at D_t. We consider a relatively simple scenario with one cellular user, one D2D pair, and one warden in this paper. To better study issues of the CIPC at cellular users and power control at underlaid D2D pairs for covert communication in the D2D underlaid cellular networks, multiple cellular users, multiple D2D pairs and multiple wardens will be considered in our future work.

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