Performance Analysis of D2D-enabled Non-orthogonal Multiple Access in Cooperative Relaying System

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ABSTRACT

Recently, device-to-device (D2D) enabled non-orthogonal multiple access (NOMA) is emerged as a new paradigm to improve spectrum efficiency. However, existing researches are confined to two-hop relaying scenarios, which restricts the coverage of the wireless networks. In this paper, we propose a novel multi-hop relaying scheme where both D2D transmitter and receiver are used as relays. Further, the cell-edge user employs maximal ratio combing (MRC) to enhance the quality of the received signal, of which the analysis becomes more complicated. Exact new closed-form expressions are provided for the cumulative distribution functions (CDFs) of the received signal-to-interference-plus-noise-ratio (SINR) at all users. Analysis on outage probability and ergodic capacity is presented and validated by simulations. It is demonstrated that the proposed scheme significantly outperforms typical two-hop relaying schemes.

CCS CONCEPTS

• **Networks** → **Mobile networks**.

KEYWORDS

Non-orthogonal Multiple Access, D2D communication, Cooperative communication

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1 INTRODUCTION

Multiple access techniques are main tasks in wireless communication system. The rapid growth of emerging wireless applications imposes higher requirements on fifth generation (5G) and beyond networks. Non-orthogonal multiple access (NOMA) has been deemed as a potential multiple access technique for 5G since it can improve spectral efficiency, provide massive connectivity, balance user fairness and reduce latency [7][3].

Different from conventional orthogonal multiple access (OMA) technologies (e.g., frequency/time/code division multiple access), NOMA allows multiple users to transmit at the same radio resource but with different power levels [16]. Specifically, at the transmitter side, the signals of multiple users are superimposed at the base station (BS), which follows a power allocation principle that a user with better channel quality is assigned with less power. Then at the receiver side, successive interference cancellation (SIC) is performed at each user. Since the complexity of SIC receiver is proportional to the number of users on the same subcarrier, thus, the number of NOMA users is usually restricted to two in practice. Consequently, the user with better channel quality (e.g., the near user) first decodes the signal of the user with weaker channel quality (e.g., the far user) and subtracts it, and then decodes its own signal. Meanwhile, the far user directly decodes its own signal by viewing the signal of the near user as noise [15]. Therefore, the near user has the prior information of the signal of the far user. That is the idea behind cooperative NOMA (CNOMA) where users with better channel qualities serve as relays for those with weaker channel qualities [4].

NOMA has been widely combined with other advanced technologies and the performance are investigated in the existing literature. In [8], a selection strategy is proposed which switches between OMA and NOMA, and the outage probability is derived for all users. In [18], the ergodic rates of NOMA are studied with both half-duplex and full-duplex techniques. In [5], the multiple-input multi-output (MIMO) is applied to NOMA system and analytical results are developed to facilitate the performance evaluation of the proposed system. In [12], NOMA is considered in heterogeneous networks (HetNets) where MOMA is adopted in small cells. The analytical expressions for the spectral efficiency is derived to evaluate the performance of the proposed framework. In [13], NOMA is introduced into cloud radio access networks and the achievable rates are presented in closed-form.

CNOMA has also been extensively studied in terms of performance analysis and resource allocation. In [4], the outage performance of the weakest user is improved and maximum diversity gain is achieved for all users. In [9], the error performance of CNOMA is investigated with statistical channel state information (CSI). In [11], the outage performance and capacity are analyzed with different relay selection. In [17], an optimal relay selection scheme is proposed. In [1], the asymptotic outage probability are derived for the users for the proposed novel CNOMA scheme. However,

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a cooperation is hard to achieve when a user is far away from its NOMA companion.

In this paper, we propose a novel multi-hop relaying scheme for D2D integrated CNOMA system. Different from the above researches, we introduce the DR as an additional relay and use MRC at the receiver of the cell-edge user to earn more diversity gain. We derive the closed-form expressions for the cumulative distribution function (CDF) of the signal-to-interference-plus-noise-ratio (SINR) at all users. Accordingly, we present the analytical expressions of the ergodic capacity and outage probability of the proposed scheme. Simulation results are provided to verify the accuracy of our analytical derivations. It is shown that our proposed scheme outperforms conventional two-hop relaying schemes, especially when the cell-edge user locates far away from the BS.

The remainder of the paper is organized as follows. Section II introduces some state of the art related work. Section III describes the system model, based on which we propose our multi-hop relaying scheme and compare it with the conventional scheme. The outage probability and the ergodic capacity are presented in Section IV and V, respectively. In Section VI, the simulation results are presented to validate our analysis. Finally, Section VII concludes this paper.

2 RELATED WORK

Device-to-device (D2D) communication, which allows D2D users to reuse the radio resources of cellular users, is another promising technology in 5G. On the one hand, cellular users suffer interference when D2D users reuse the same resources (e.g., the underlay mode). On the other hand, cellular users sacrifice its own resources when D2D users occupy dedicated resources (e.g., the overlay mode). Therefore, a cooperative relaying mode is proposed where D2D users act as relays for cellular users in exchange for their own opportunity of transmission [2]. However, the aforementioned work only consider the OMA scenario.

Integrating D2D communication into CNOMA system can further increase the spectral efficiency, which is called as D2D-aided CNOMA (DCNOMA) [10, 19]. Particularly, to encourage D2D users to participate in the cooperation, a D2D user adopts NOMA to simultaneously transmit the signal of a far user and that of its own. In [4], maximal ratio combining (MRC) technology has shown its advantage in improving the system performance. In [19], the MRC is applied to improve the quality of received signal, and the outage probability of the cell-edge user is given but not in the closed-form. In [10], the cell-edge user's signal is split into two symbols for transmission and the ergodic sum capacity is investigated without MRC. However, existing researches only consider the D2D transmitter (DT) as the relay for a cellular user (CU), which neglects the prior information of the D2D receiver (DR).

3 SYSTEM MODEL

In this section, we elaborate our system model in detail. As shown in Fig. 1, we consider a downlink cooperative relaying system with one BS and two CUs, namely CU_1 and CU_2. Furthermore, a D2D pair is considered where a DT communicates directly with the DR. It is assumed that each node is equipped with a single antenna. In addition, all nodes operate in the half-duplex mode using decode-and-forward (DF) strategy.

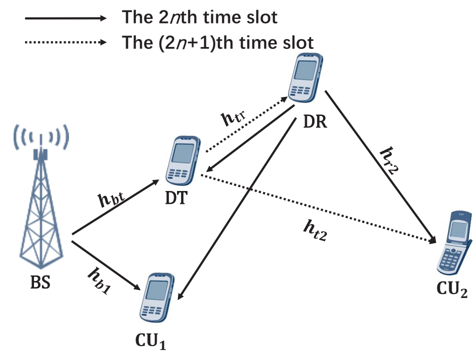

Figure 1: System model of the proposed scheme.

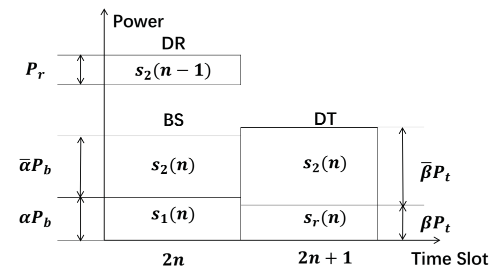

Figure 2: Transmission scheme of the proposed scheme in time and power domain.

Furthermore, it is assumed that the direct link from the BS to CU_2 is absent due to large path loss, where CU_2 requires assistance from its nearby D2D users for transmission. On the other hand, CU_1 locates at the nearby of the BS and can directly communicate with the BS.

For the notation simplicity, the BS, CU_1, CU_2, DT and DR are denoted by subscript b, 1, 2, t and r, respectively. Then, the channel coefficients between node i and node j can be denoted as h_{ij}, where $i \in \{b, t, r\}$ and $j \in \{t, r, 1, 2\}$. For instance, the channel coefficients between the BS and CU_1 is denoted as h_{b1}.

All channels are assumed to experience independent and identically block Rayleigh fading, i.e., the channel is constant for a block of transmission. The channel power gain of $|h_{ij}|^2$ is assumed to be exponentially distributed random variable with parameter Ω_{ij}, i.e., $h_{ij} \sim CN(0, \Omega_{ij})$.

Without loss of generality, we consider a scenario where a D2D pair is located between the near user and the far user. Since D2D communication occurs at two users in proximity, it is reasonable to assume that $|h_{b1}|^2 > |h_{bt}|^2$ and $|h_{tr}|^2 > |h_{t2}|^2$.

We assume perfect CSI is available on all nodes. Further, the signal of the BS intended for CU_1 and CU_2 are denoted as s_1 and s_2 , respectively, and the signal of DT intended for DR is denoted as s_r. All signals are normalized with $\mathbb{E}[s_1] = \mathbb{E}[s_2] = \mathbb{E}[s_r] = 0$ and $\mathbb{E}[|s_1|^2] = \mathbb{E}[|s_2|^2] = \mathbb{E}[|s_r|^2] = 1$.

3.1 The Proposed Multi-hop Relaying

As shown in Fig. 2, the complete process of our proposed scheme are achieved in two phases, i.e., the even time slot and the odd time slot.

In the $2n$th time slot, the BS superimposes the signal of CU_1 and CU_2, i.e., $s_1(n)$ and $s_2(n)$, and forms a composite signal $\sqrt{\alpha P_b}s_1(n)+\sqrt{\bar{\alpha} P_b}s_2(n)$, where P_b is the transmit power of the BS, and α and $\bar{\alpha}$ are the power allocation coefficients with $\alpha+\bar{\alpha}=1$. According to the power allocation principle as aforementioned, it requires that $\alpha \in [0, \frac{1}{2}]$. The BS then broadcasts the composite signal.

At the same time, DR acts as a relay and transmits $\sqrt{P_r}s_2(n-1)$ to CU_2, where P_r is the transmit power of DR and $s_2(n-1)$ is the signal it has received at the previous time slot. It can be learned from Fig. 1 that CU_1 and DT receive $\sqrt{P_r}s_2(n-1)$ as well. However, since CU_1 and DT already decode $s_2(n-1)$ in the $2(n-1)$th time slot, they can cancel $s_2(n-1)$ in the $2n$th time slot and are not interfered.

Therefore, the received signals at CU_1, DT and CU_2 in this slot can respectively be given by

$$r_1(2n) = h_{b1}(\sqrt{\alpha P_b}s_1(n) + \sqrt{\bar{\alpha} P_b}s_2(n)) + n_1(2n), \tag{1}$$

$$r_t(2n) = h_{bt}(\sqrt{\alpha P_b}s_1(n) + \sqrt{\bar{\alpha} P_b}s_2(n)) + n_t(2n), \tag{2}$$

$$r_2(2n) = h_{r2}\sqrt{P_r}s_2(n-1) + n_2(2n), \tag{3}$$

where $n_j \sim CN(0,\sigma^2)$ is the additive white Gaussian noise (AWGN) at the corresponding receiver.

In the $(2n+1)$th time slot, it is supposed DT can successfully decode $s_2(n)$. Then it can act as another relay and transmits a composite signal $\sqrt{\bar{\beta} P_t}s_2(n) + \sqrt{\beta P_t}s_r(n)$ to DR and CU_2, where P_t denotes the transmit power of DT. Similarly, β is the power allocation coefficient with $\beta+\bar{\beta}=1$ and $\beta \in [0,\frac{1}{2}]$. The received signal at the two receivers DR and CU_2 can be given by

$$r_r(2n+1) = h_{tr}(\sqrt{\bar{\beta} P_t}s_2(n) + \sqrt{\beta P_t}s_r(n)) + n_r(2n+1), \tag{4}$$

$$r_2(2n+1) = h_{t2}(\sqrt{\bar{\beta} P_t}s_2(n) + \sqrt{\beta P_t}s_r(n)) + n_2(2n+1). \tag{5}$$

Then the received signals in the next two time slots are derived by substituting n in (1)-(5) with $(n+1)$.

Based on the NOMA power allocation protocol, SIC is performed at CU_1 in the even time slot. Therefore, CU_1 first decodes the data of CU_2, and the SINR for CU_1 to decode $s_2(n)$ can be expressed as

$$\gamma_{2\to1} = \frac{g_{b1}\bar{\alpha}\rho_b}{g_{b1}\alpha\rho_b + 1}, \tag{6}$$

where we assume $\rho_i = \frac{P_i}{\sigma^2}$ and $g_{ij} = |h_{ij}|^2$ for notify simplicity.

If $s_2(n)$ can be perfectly decoded, CU_1 subtracts $h_{b1}s_2(n)$ from $r_{b1}(2n)$ and decodes its own signal. The SINR for CU_1 to decode $s_1(n)$ is given by

$$\gamma_{1\to1} = g_{b1}\alpha\rho_b. \tag{7}$$

Meanwhile, DT directly decodes $s_2(n)$ by regarding $s_1(n)$ as noise, the SINR for DT to decode $s_2(n)$ is given by

$$\gamma_{2\to t} = \frac{g_{bt}\bar{\alpha}\rho_b}{g_{bt}\alpha\rho_b + 1}. \tag{8}$$

After implementing MRC, CU_2 combines $r_{t2}(2n+1)$ and $r_{r2}(2n+2)$ to decode its own signal. The SINR for CU_2 to decode $s_2(n)$ is given by

$$\gamma_{2\to2} = g_{r2}\rho_r + \frac{g_{t2}\bar{\beta}\rho_t}{g_{t2}\beta\rho_t + 1}. \tag{9}$$

In the odd time slot, DR performs SIC and first decodes $s_2(n)$. If $s_2(n)$ can be perfectly decoded, DR then decodes its own signal $s_r(n)$. The SINR for DR to decode $s_2(n)$ and $s_r(n)$ are respectively given by

$$\gamma_{2\to r} = \frac{g_{tr}\bar{\beta}\rho_t}{g_{tr}\beta\rho_t + 1}, \tag{10}$$

$$\gamma_{r\to r} = g_{tr}\beta\rho_t. \tag{11}$$

Based on the DF protocol, the end-to-end rate is dominated by the weakest link. Furthermore, CU_1, DT and DR must successfully decode the cell-edge user's signal before decoding their own signals. Therefore, the achievable rates at CU_1, CU_2 and DR of the system are given by

$$R^1 = \frac{1}{2}\log_2(1+\gamma_{1\to1}), \tag{12}$$

$$R^2 = \frac{1}{2}\log_2(1+\min\{\gamma_{2\to1},\gamma_{2\to t},\gamma_{2\to r},\gamma_{2\to2}\}), \tag{13}$$

$$R^d = \frac{1}{2}\log_2(1+\gamma_{r\to r}). \tag{14}$$

The factor $\frac{1}{2}$ is due to the fact that CU_1 and CU_2 decode their own signal only in even time slots and DR decodes its own signal only in odd time slots.

3.2 The Conventional Two-hop Relaying

In a two-hop relaying scheme, the BS transmits a composite signal of s_1 and s_2 in the even time slot and DT superimposed s_r on s_2 in the odd time slot. Therefore, the achievable rates are given by

$$R^1_{con} = \frac{1}{2}\log_2(1+\gamma_{1\to1}), \tag{15}$$

$$R^2_{con} = \frac{1}{2}\log_2(1+\min\{\gamma_{2\to1},\gamma_{2\to t},\gamma_{2\to r},\frac{g_{t2}\bar{\beta}\rho_t}{g_{t2}\beta\rho_t+1}\}), \tag{16}$$

$$R^d_{con} = \frac{1}{2}\log_2(1+\gamma_{r\to r}). \tag{17}$$

4 OUTAGE PROBABILITY

In this section, we investigate the outage behaviors for each user. The outage probability is defined as the probability that achievable rate is below than a target rate.

Using R_1^{th}, R_2^{th} and R_d^{th} to denote the target rate of CU_1, CU_2 and DR, respectively. Then, the thresholds of SINR at these receivers can be denoted as $\gamma_1^{\text{th}} = 2^{2R_1^{\text{th}}-1}$, $\gamma_2^{\text{th}} = 2^{2R_2^{\text{th}}-1}$ and $\gamma_d^{\text{th}} = 2^{2R_d^{\text{th}}-1}$.

The probability density function (PDF) of g_{ij} can be expressed as

$$f_{g_{ij}}(x) = \Omega_{ij}e^{-\Omega_{ij}x}. \tag{18}$$

Then the complementary CDF (CCDF) is given by

$$\bar{F}_{g_{ij}}(x) = \Pr\{\mathrm{g_{ij}} > \mathrm{x}\} = \mathrm{e}^{-\Omega_{\mathrm{ij}}\mathrm{x}}. \tag{19}$$

The outage events at CU_1 can be described as: CU_1 fails to decode s_1. Therefore, the outage probability of CU_1 can be expressed as

$$\begin{aligned} O_1 &= 1 - \Pr(\gamma_{2\to 1} > \gamma_2^{\text{th}}) \cdot \Pr(\gamma_{1\to 1} > \gamma_1^{\text{th}}) \\ &= F_{\gamma_{2\to 1}}(\gamma_2^{\text{th}}) + F_{\gamma_{1\to 1}}(\gamma_1^{\text{th}}) - F_{\gamma_{2\to 1}}(\gamma_2^{\text{th}}) F_{\gamma_{1\to 1}}(\gamma_1^{\text{th}}). \end{aligned} \tag{20}$$

Based on equation (19), the CDFs of $\gamma_{2\to 1}$ and $\gamma_{1\to 1}$ can be expressed as

$$F_{\gamma_{2\to 1}}(\gamma_2^{\text{th}}) = \begin{cases} 1 - e^{-\frac{\gamma_2^{\text{th}}}{(\bar{\alpha} - \alpha\gamma_2^{\text{th}})\rho_b \Omega_{b1}}}, \gamma_2^{\text{th}} < \frac{\bar{\alpha}}{\alpha} \\ 1, \text{otherwise} \end{cases} \tag{21}$$

$$F_{\gamma_{1\to 1}}(\gamma_1^{\text{th}}) = 1 - e^{-\frac{\gamma_1^{\text{th}}}{\alpha\rho_b\Omega_{b1}}}. \tag{22}$$

Inserting (21) and (22) into (20), the closed-form expression for O_1 can be obtained as

$$O_1 = \begin{cases} 1 - e^{-\frac{\gamma_2^{\text{th}}}{(\bar{\alpha} - \alpha\gamma_2^{\text{th}})\rho_b \Omega_{b1}} - \frac{\gamma_1^{\text{th}}}{\alpha\rho_b\Omega_{b1}}}, \gamma_2^{\text{th}} < \frac{\bar{\alpha}}{\alpha} \\ 1, \text{otherwise} \end{cases} \tag{23}$$

As for the outage probability of CU_2, it is reasonable to assume that if DR fails to decode s_2, CU_2 will be allowed to detect s_2 from $r_{t2}(2n+1)$ alone. The SINR of CU_2 in this case can be given by

$$\gamma_{2\to 2}^{*} = \frac{g_{t2}\bar{\beta}\rho_t}{g_{t2}\beta\rho_t + 1}. \tag{24}$$

Therefore, the outage events at CU_2 can be described as: 1) DT cannot decode s_2. 2) DT can successfully decode s_2, however, either DR cannot decode s_2 and CU_2 cannot decode s_2 from r_{t2}, or DR successfully decodes s_2 but cannot decode s_2 using MRC. Then, the outage probability of CU_2 can be expressed as

$$\begin{aligned} O_2 &= \Pr(\gamma_{2\to t} < \gamma_2^{\text{th}}) + \Pr(\gamma_{2\to t} > \gamma_2^{\text{th}})[\Pr(\gamma_{2\to r} < \gamma_2^{\text{th}}) \\ &\quad \cdot \Pr(\gamma_{2\to 2}^{*} < \gamma_2^{\text{th}}) + \Pr(\gamma_{2\to r} > \gamma_2^{\text{th}})\Pr(\gamma_{2\to 2} < \gamma_2^{\text{th}})] \\ &= F_{\gamma_{2\to t}}(\gamma_2^{\text{th}}) + (1 - F_{\gamma_{2\to t}}(\gamma_2^{\text{th}}))[F_{\gamma_{2\to r}}(\gamma_2^{\text{th}}) \\ &\quad \cdot F_{\gamma_{2\to 2}^{*}}(\gamma_2^{\text{th}}) + (1 - F_{\gamma_{2\to r}}(\gamma_2^{\text{th}}))F_{\gamma_{2\to 2}}(\gamma_2^{\text{th}})]. \end{aligned} \tag{25}$$

Similarly, the CDFs of $\gamma_{2\to t}$, $\gamma_{2\to r}$ and $\gamma_{2\to 2}^{*}$ can be expressed as

$$F_{\gamma_{2\to t}}(\gamma_2^{\text{th}}) = \begin{cases} 1 - e^{-\frac{\gamma_2^{\text{th}}}{(\bar{\alpha} - \alpha\gamma_2^{\text{th}})\rho_b \Omega_{bt}}}, \gamma_2^{\text{th}} < \frac{\bar{\alpha}}{\alpha} \\ 0, \text{otherwise.} \end{cases} \tag{26}$$

$$F_{\gamma_{2\to r}}(\gamma_2^{\text{th}}) = \begin{cases} 1 - e^{-\frac{\gamma_2^{\text{th}}}{(\bar{\beta} - \beta\gamma_2^{\text{th}})\rho_t \Omega_{tr}}}, \gamma_2^{\text{th}} < \frac{\bar{\beta}}{\beta} \\ 0, \text{otherwise.} \end{cases} \tag{27}$$

$$F_{\gamma_{2\to 2}^{*}}(\gamma_2^{\text{th}}) = \begin{cases} 1 - e^{-\frac{\gamma_2^{\text{th}}}{(\bar{\beta} - \beta\gamma_2^{\text{th}})\rho_t \Omega_{t2}}}, \gamma_2^{\text{th}} < \frac{\bar{\beta}}{\beta} \\ 0, \text{otherwise.} \end{cases} \tag{28}$$

After algebraic manipulations, the CDF of $\gamma_{2\to 2}$ can be rewritten as

$$\begin{aligned} F_{\gamma_{2\to 2}}(\gamma_2^{\text{th}}) &= \Pr(g_{r2}\rho_r + \frac{g_{t2}\bar{\beta}\rho_t}{g_{t2}\beta\rho_t + 1} < \gamma_2^{\text{th}}) \\ &= \Pr\{g_{t2}(g_{r2} - \frac{\gamma_2^{\text{th}} - \frac{\bar{\beta}}{\beta}}{\rho_r}) < \frac{\frac{\gamma_2^{\text{th}}}{\rho_r} - g_{r2}}{\beta\rho_t}\}. \end{aligned} \tag{29}$$

On one hand, if $\gamma_2^{\text{th}} < \frac{\bar{\beta}}{\beta}$, then $F_{\gamma_{2\to 2}}(\gamma_2^{\text{th}})$ can be further extended as

$$\begin{aligned} &F_{\gamma_{2\to 2}}(\gamma_2^{\text{th}}) \\ &= \Pr\{g_{t2} < \frac{\frac{\gamma_2^{\text{th}}}{\rho_r} - g_{r2}}{\beta\rho_t(g_{r2} - \frac{\gamma_2^{\text{th}} - \frac{\bar{\beta}}{\beta}}{\rho_r})}\} \cdot \Pr\{g_{r2} < \frac{\gamma_2^{\text{th}}}{\rho_r}\} \\ &= \int_0^{\frac{\gamma_2^{\text{th}}}{\rho_r}} f_{g_{r2}}(x) \int_0^{\frac{(\frac{\gamma_2^{\text{th}}}{\rho_r} - x)}{\beta\rho_t(x - \frac{\gamma_2^{\text{th}} - \frac{\bar{\beta}}{\beta}}{\rho_r})}} f_{g_{t2}}(y)dydx \\ &= \int_0^{\frac{\gamma_2^{\text{th}}}{\rho_r}} f_{g_{r2}}(x)[1 - \exp(-\frac{(\frac{\gamma_2^{\text{th}}}{\rho_r} - x)}{\beta\rho_t(x - \frac{\gamma_2^{\text{th}} - \frac{\bar{\beta}}{\beta}}{\rho_r})})]dx \\ &\overset{(a)}{=} F_{g_{r2}}(\frac{\gamma_2^{\text{th}}}{\rho_r}) - \frac{e^{-\frac{\gamma_2^{\text{th}} - \frac{\bar{\beta}}{\beta}}{\rho_r\Omega_{r2}} + \frac{1}{\beta\rho_t\Omega_{t2}}}}{\Omega_{r2}} \\ &\quad \cdot \underbrace{\int_{\frac{\frac{\bar{\beta}}{\beta} - \gamma_2^{\text{th}}}{\rho_r}}^{\frac{\bar{\beta}}{\beta\rho_r}} e^{-\frac{v}{\Omega_{r2}} - \frac{\bar{\beta}}{\beta\rho_r\beta\rho_t\Omega_{t2}v}} dv}_{A}. \end{aligned} \tag{30}$$

where step (a) is based on the substitution $v = x - \frac{\gamma_2^{\text{th}} - \frac{\bar{\beta}}{\beta}}{\rho_r}$. To resolve term A, we propose a lemma whose proof is given in Appendix A.

Lemma 1. *The integration $\int_0^b \exp(-\frac{p}{u} - qu)du$ can be calculated as $g(b, p, q) = \sum_{n=0}^{\infty} \frac{(-q)^n p^{n+1}}{n!}\Gamma(-(n+1), \frac{p}{b})$, where $\Gamma(a, x) = \int_x^{\infty} e^{-t}t^{a-1}dt$ is the incomplete gamma function which is defined as [14, Eq.(6.5.3)].*

Therefore, term A can be expressed as

$$\begin{aligned} A =& g(\frac{\bar{\beta}}{\beta\rho_r}, \frac{\bar{\beta}}{\beta\rho_r\beta\rho_t\Omega_{t2}}, \frac{1}{\Omega_{r2}}) \\ &- g(\frac{\frac{\bar{\beta}}{\beta} - \gamma_2^{\text{th}}}{\rho_r}, \frac{\bar{\beta}}{\beta\rho_r\beta\rho_t\Omega_{t2}}, \frac{1}{\Omega_{r2}}). \end{aligned} \tag{31}$$

On the other hand, if $\gamma_2^{\text{th}} > \frac{\bar{\beta}}{\beta}$, then $F_{\gamma_{2\to 2}}(\gamma_2^{\text{th}})$ can be extended as

$$\begin{aligned} &F_{\gamma_{2\to 2}}(\gamma_2^{\text{th}}) \\ &= \Pr\{g_{r2} < \frac{\gamma_2^{\text{th}} - \frac{\bar{\beta}}{\beta}}{\rho_r}\} + \Pr\{g_{t2} < \frac{\frac{\gamma_2^{\text{th}}}{\rho_r} - g_{r2}}{\beta\rho_t(g_{r2} - \frac{\gamma_2^{\text{th}} - \frac{\bar{\beta}}{\beta}}{\rho_r})}\} \\ &\cdot \Pr\{\frac{\gamma_2^{\text{th}} - \frac{\bar{\beta}}{\beta}}{\rho_r} < g_{r2} < \frac{\gamma_2^{\text{th}}}{\rho_r}\} \end{aligned}$$

$$
\begin{aligned}
&= \int_0^{\frac{\gamma_2^{\mathrm{th}} - \frac{\bar{\beta}}{\beta}}{\rho r}} f_{g_{r2}}(x)dx \\
&+ \int_{\frac{\gamma_2^{\mathrm{th}} - \frac{\bar{\beta}}{\beta}}{\rho r}}^{\frac{\gamma_2^{\mathrm{th}}}{\rho r}} f_{g_{r2}}(x) \int_0^{\frac{(\frac{\gamma_2^{\mathrm{th}}}{\rho r} - x)}{\beta \rho_t (x - \frac{\gamma_2^{\mathrm{th}} - \frac{\bar{\beta}}{\beta}}{\rho r})}} f_{g_{t2}}(y)dydx \\
&= F_{g_{r2}}(\frac{\gamma_2^{\mathrm{th}}}{\rho_r}) - \frac{e^{-\frac{\gamma_2^{\mathrm{th}} - \frac{\bar{\beta}}{\beta}}{\rho r \Omega_{r2}} + \frac{1}{\beta \rho_t \Omega_{t2}}}}{\Omega_{r2}} g(\frac{\bar{\beta}}{\beta \rho_r}, \frac{\bar{\beta}}{\beta \rho_r \beta \rho_t \Omega_{t2}}, \frac{1}{\Omega_{r2}}). \quad (32)
\end{aligned}
$$

Finally, the closed-form expression can be obtained as (40) on top of the next page. By substituting (26), (27), (28), (40) into (25) and after mathematical manipulations, the outage probability of CU_2 is given in closed-form as (41), where the closed-form expression of $\Psi(\gamma_2^{\mathrm{th}})$ is derived as

$$
\begin{aligned}
&\Psi(\gamma_2^{\mathrm{th}}) \\
&= e^{-\frac{\gamma_2^{\mathrm{th}}}{\rho r \Omega_{r2}}} (1 - e^{\frac{\bar{\beta}}{\beta \rho r \Omega_{r2}} + \frac{1}{\beta \rho_t \Omega_{t2}}} \cdot \sum_{n=0}^{\infty} \frac{(\frac{\bar{\beta}}{\beta \rho_r \Omega_{r2}} \frac{1}{\beta \rho_t \Omega_{t2}})^{n+1}}{n!} \\
&[\Gamma(-(n+1), \frac{1}{\beta \rho_t \Omega_{t2}}) - \Gamma(-(n+1), \frac{\bar{\beta}}{(\bar{\beta} - \beta \gamma_2^{\mathrm{th}}) \beta \rho_t \Omega_{t2}})]), \quad (33)
\end{aligned}
$$

The complementary outage events at DR can be described as: DT can successfully decode s_2 and DR can successfully decode s_2 and s_r. Therefore, the outage probability of DR can be expressed as

$$
\begin{aligned}
O_r &= 1 - \Pr(\gamma_{2\to t} > \gamma_2^{\mathrm{th}}) \Pr(\gamma_{2\to r} > \gamma_2^{\mathrm{th}}) \Pr(\gamma_{r\to r} > \gamma_d^{\mathrm{th}}) \\
&= 1 - [1 - F_{\gamma_{2\to t}}(\gamma_2^{\mathrm{th}})][1 - F_{\gamma_{2\to r}}(\gamma_2^{\mathrm{th}})][1 - F_{\gamma_{r\to r}}(\gamma_d^{\mathrm{th}})]. \quad (34)
\end{aligned}
$$

Accordingly, the CDFs of $\gamma_{r\to r}$ can be expressed as

$$
F_{\gamma_{r\to r}}(\gamma_d^{\mathrm{th}}) = 1 - e^{-\frac{\gamma_d^{\mathrm{th}}}{\beta \rho_t \Omega_{tr}}}. \quad (35)
$$

After substituting (26), (27) and (35) into (34), the outage probability of DR is given in closed-form as (42) on top of this page.

5 ERGODIC CAPACITY

In this section, we provide the capacity analysis of each signal s_i for the proposed scheme.

According to (12) and (14), the ergodic rates of s_1 and s_r are respectively represented as

$$
\begin{aligned}
C_1 &= \int_0^{\infty} \frac{1}{2} \log_2(1 + \gamma_{1\to 1}) f_{F_{\gamma_{1\to 1}}}(x)dx \\
&= \frac{1}{2 \ln 2} \int_0^{\infty} \frac{1 - F_{\gamma_{1\to 1}}(x)}{1+x} dx \\
&\overset{(a)}{=} -\frac{1}{2 \ln 2} e^{\frac{1}{\Omega_{b1} \alpha \rho_b}} \mathrm{Ei}(-\frac{1}{\Omega_{b1} \alpha \rho_b}), \quad (36)
\end{aligned}
$$

$$
\begin{aligned}
C_r &= \frac{1}{2 \ln 2} \int_0^{\infty} \frac{1 - F_{F_{\gamma_{r\to r}}}(x)}{1+x} dx \\
&= -\frac{1}{2 \ln 2} e^{\frac{1}{\Omega_{tr} \beta \rho_t}} \mathrm{Ei}(-\frac{1}{\Omega_{tr} \beta \rho_t}), \quad (37)
\end{aligned}
$$

where step (a) is based on [6, Eq. (3.352.4)].

We denote $\gamma_2 = \min\{\gamma_{2\to 1}, \gamma_{2\to t}, \gamma_{2\to r}, \gamma_{2\to 2}\}$ for notation simplicity, and based on (13), the ergodic rate of s_2 is represented as

$$
C_2 = \frac{1}{2 \ln 2} \int_0^{\infty} \frac{1 - F_{\gamma_2}(x)}{1+x} dx. \quad (38)
$$

Accordingly, the CCDF of γ_2 can be expressed as

$$
\bar{F}_{\gamma_2}(x) = \bar{F}_{\gamma_{2\to 1}}(x) \bar{F}_{\gamma_{2\to t}}(x) \bar{F}_{\gamma_{2\to r}}(x) \bar{F}_{\gamma_{2\to 2}}(x). \quad (39)
$$

Since, in general, it is impossible to obtain a closed-form solution to the integration for (38), we use numerical integration to verify the correctness of our analysis.

6 NUMERICAL RESULTS

In this section, we compare our proposed scheme with conventional two-hop relaying schemes. The analytical results derived from the above expressions are validated by simulation results. Some common parameters are adopted in Figs. 2 and 3, e.g., $\Omega_{b1} = \Omega_{tr} = 2$ and the transmit SNRs are set as $\rho_r = \rho_t = \frac{1}{2}\rho_b$.

Since the outage probability of CU_1 and D2D user are the same in the two comparing schemes, we investigate the outage probability of CU_2 versus the transmit SNR of the BS ρ_b in Fig. 3. Moreover, we consider three topologies: (1) $\Omega_{bt} = 1$, $\Omega_{t2} = \Omega_{r2} = 0.1$, (2) $\Omega_{bt} = \Omega_{t2} = \Omega_{r2} = 0.1$ and (3) $\Omega_{bt} = 0.1$, $\Omega_{t2} = \Omega_{r2} = 1$. The data rate requirements are set as $R_1^{\mathrm{th}} = R_2^{\mathrm{th}} = R_d^{\mathrm{th}} = 1$ bps/Hz. Fixed power allocation are considered with $\alpha = \beta = 0.1$ [10]. It can be seen that the multi-hop relying scheme outperforms the two-hop relaying scheme for all the three topologies. Moreover, the performance gap is especially remarkable for topology 1. This is because the effect of diversity gain becomes more evident when CU_2 locates farther away from the BS. Thus, the multi-hop relaying scheme can enlarge the network coverage. Furthermore, our analytical results match perfectly with simulation results.

In Fig. 4, the ergodic sum capacity versus the power allocation coefficients are investigated with different transmit SNR ρ_b. Topology 1 is adopted and the transmit SNR is set as $\rho_b = 15$ dB. In the top sub-figure, the impact of α is presented assuming $\beta = 0.1$, whereas in the bottom one, the impact of β is presented assuming $\alpha = 0.1$. It is observed that the multi-hop relaying scheme outperforms the two-hop relaying scheme in all combinations of power allocation coefficients. Further, the performance gain between the two comparing schemes becomes smaller when the power allocation tends to be equally allocated. Therefore, proper power allocation is needed for the proposed scheme to earn a better performance.

7 CONCLUSION

In this paper, we propose a novel cooperative scheme for D2D integrated CNOMA system. By taking both DT and DR as relays, the cell-edge user applies MRC to improve the quality of the received signal. Closed-form expressions of the outage probability and ergodic sum capacity of the proposed solution are derived. Simulation results indicate that the proposed scheme can achieve lower outage probability and higher sum capacity compared with existing two-hop relaying schemes. To further enhance the performance, optimum resource allocation policies will be investigated in our future work.

$$F_{\gamma_{2\to 2}}(\gamma_2^{\mathrm{th}}) = \begin{cases} 1 - e^{-\frac{\gamma_2^{\mathrm{th}}}{\rho_r \Omega_{r2}}} - \frac{e^{-\frac{\gamma_2^{\mathrm{th}} - \frac{\bar{\beta}}{\beta}}{\rho_r \Omega_{r2}} + \frac{1}{\beta \rho_t \Omega_{t2}}}}{\Omega_{r2}} \cdot [g(\frac{\bar{\beta}}{\beta \rho_r}, \frac{\bar{\beta}}{\beta \rho_r \beta \rho_t \Omega_{t2}}, \frac{1}{\Omega_{r2}}) - g(\frac{\frac{\bar{\beta}}{\beta} - \gamma_2^{\mathrm{th}}}{\rho_r}, \frac{\bar{\beta}}{\beta \rho_r \beta \rho_t \Omega_{t2}}, \frac{1}{\Omega_{r2}})], \gamma_2^{\mathrm{th}} < \frac{\bar{\beta}}{\beta} \\ 1 - e^{-\frac{\gamma_2^{\mathrm{th}}}{\rho_r \Omega_{r2}}} - \frac{e^{-\frac{\gamma_2^{\mathrm{th}} - \frac{\bar{\beta}}{\beta}}{\rho_r \Omega_{r2}} + \frac{1}{\beta \rho_t \Omega_{t2}}}}{\Omega_{r2}} g(\frac{\bar{\beta}}{\beta \rho_r}, \frac{\bar{\beta}}{\beta \rho_r \beta \rho_t \Omega_{t2}}, \frac{1}{\Omega_{r2}}), \gamma_2^{\mathrm{th}} > \frac{\bar{\beta}}{\beta} \end{cases} \tag{40}$$

$$O_2 = \begin{cases} 1 + e^{-\frac{\gamma_2^{\mathrm{th}}}{(\bar{\alpha} - \alpha \gamma_2^{\mathrm{th}}) \rho_b \Omega_{bt}}} (-e^{-\frac{\gamma_2^{\mathrm{th}}}{(\bar{\beta} - \beta \gamma_2^{\mathrm{th}}) \rho_t \Omega_{t2}}} - e^{-\frac{\gamma_2^{\mathrm{th}}}{(\bar{\beta} - \beta \gamma_2^{\mathrm{th}}) \rho_t \Omega_{tr}}} \Psi(\gamma_2^{\mathrm{th}}) + e^{-\frac{\gamma_2^{\mathrm{th}}}{(\bar{\beta} - \beta \gamma_2^{\mathrm{th}}) \rho_t \Omega_{tr}}} e^{-\frac{\gamma_2^{\mathrm{th}}}{(\bar{\beta} - \beta \gamma_2^{\mathrm{th}}) \rho_t \Omega_{t2}}}), \gamma_2^{\mathrm{th}} < \min\{\frac{\bar{\alpha}}{\alpha}, \frac{\bar{\beta}}{\beta}\} \\ 1, \text{otherwise} \end{cases} \tag{41}$$

$$O_r = \begin{cases} 1 - e^{-\frac{\gamma_2^{\mathrm{th}}}{(\bar{\alpha} - \alpha \gamma_2^{\mathrm{th}}) \rho_b \Omega_{bt}} - \frac{\gamma_2^{\mathrm{th}}}{(\bar{\beta} - \beta \gamma_2^{\mathrm{th}}) \rho_t \Omega_{tr}} - \frac{\gamma_d^{\mathrm{th}}}{\beta \rho_t \Omega_{tr}}}, \gamma_2^{\mathrm{th}} < \min\{\frac{\bar{\alpha}}{\alpha}, \frac{\bar{\beta}}{\beta}\} \\ 1, \text{otherwise} \end{cases} \tag{42}$$

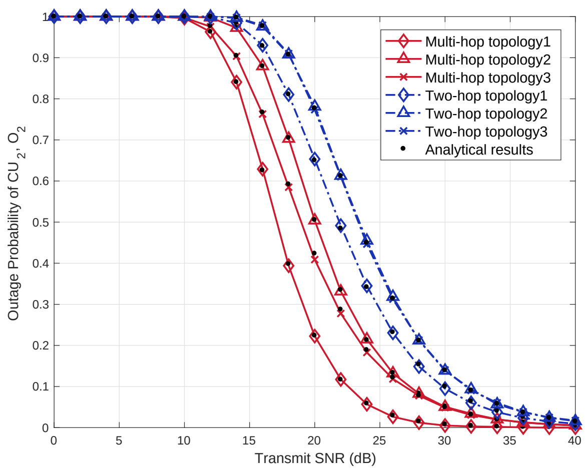

Figure 3: Outage probability analysis.

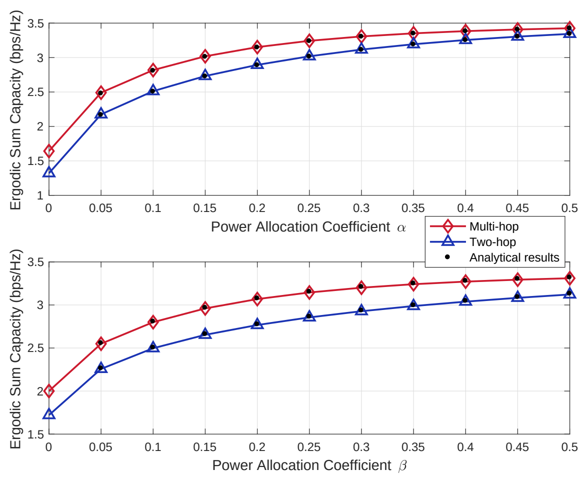

Figure 4: Ergodic capacity analysis.

A PROOF OF LEMMA 1

Using the series expassion [14, Eq. (1.211.1)] , the integration can be expanded as

$$\begin{aligned} \int_0^a \exp(-\frac{p}{u} - qu)du &= \sum_{n=0}^{\infty} \frac{(-q)^n}{n!} \int_0^a u^n e^{-\frac{p}{u}} du \\ &\overset{(a)}{=} \sum_{n=0}^{\infty} \frac{(-q)^n}{n!} \int_{\frac{p}{a}}^{\infty} p^{n+1} t^{-(n+2)} e^{-t} dt \\ &\overset{(b)}{=} \sum_{n=0}^{\infty} \frac{(-q)^n p^{n+1}}{n!} \Gamma(-(n+1), \frac{p}{a}) \end{aligned}$$

where (a) is based on the variable change $t = \frac{p}{u}$ and (b) is according to [14, Eq.(6.5.3)].

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