Capacity Enhanced Cooperative D2D Systems over Rayleigh Fading Channels with NOMA

Wei Duan, Jinjuan Ju, Qiang Sun, Yancheng Ji, Zhiliang Wang,
Jeaho Choi, and Guoan Zhang†

Abstract

This paper considers the cooperative device-to-device (D2D) systems with non-orthogonal multiple access (NOMA). We assume that the base station (BS) can communicate simultaneously with all users to satisfy the full information transmission. In order to characterize the impact of the weak channel and different decoding schemes, two kinds of decoding strategies are proposed: single signal decoding scheme and MRC decoding scheme, respectively. For the single signal decoding scheme, the users immediately decode the received signals after receptions from the BS. Meanwhile, for the MRC decoding scheme, instead of decoding, the users will keep the receptions in reserve until the corresponding phase comes and the users jointly decode the received signals by employing maximum ratio combining (MRC). Considering Rayleigh fading channels, the ergodic sum-rate (SR), outage probability and outage capacity of the proposed D2D-NOMA system are analyzed. Moreover, approximate expressions for the ergodic SR are also provided with a negligible performance loss. Numerical results demonstrate that the ergodic SR and outage probability of the proposed D2D-NOMA scheme overwhelm that of the conventional NOMA schemes. Furthermore, it is also revealed that the system performance including the ergodic SR and outage probability are limited by the poor channel condition for both the single signal decoding scheme and conventional NOMA schemes.

Index Terms: Non-orthogonal multiple access (NOMA), device-to-device (D2D), ergodic sum-rate, decode-and-forward (DF), outage probability, outage capacity.

W. Duan, J. Ju, Q. Sun, Y. Ji, Z. Wang and G. Zhang are with School of Electronics and Information, Nantong University, Nantong 226019, China. (e-mail: \{sinder, sunqiang, jiyancheng, wangzl, gzhang\}@ntu.edu.cn)

J. Choi is Division of Electronics Engineering, Chonbuk National University, Korea. (e-mail: wave@jbnu.ac.kr)

J. Ju is also with School of Electronics and Information, Nantong University, Nantong 226019, China. (e-mail: Janice-jjj@163.com)

†Corresponding email: gzhang@ntu.edu.cn.
I. INTRODUCTION

For the next generation networks, with the massive connectivity of cellular internet-of-things (IoT) [1], non-orthogonal multiple access (NOMA) has been envisioned as a promising technique to realize the spectral efficient massive access [2], [3]. Unlike conventional orthogonal multiple access (OMA) schemes such as frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA), etc., NOMA allows multiple users to simultaneously transmit signals in a superposition way by using the same orthogonal resources (i.e., time/frequency/code) but different power levels [4]. The key idea of NOMA is to explore the power domain for realizing multiple access, where the users with strong channels are normally limited by the bandwidth, in the meanwhile that the users with weak channels are limited by the noise. In summary, the concept of NOMA is to superpose multiple users over different power levels at the transmitter, and employ the successive interference cancellation (SIC) to detect the signals at the receiver. More specifically, an overview of the NOMA researches and future trends has been studied in [5], which shows that massive connectivity can be realistically achieved with NOMA and the delay can be also reduced since the users are no longer forced to wait until an orthogonal resource block becomes available. In [6], the authors comprehensively surveyed the recent progress of NOMA in 5G systems, including the state-of-the-art capacity analysis, power allocation strategies, user fairness, and user-pairing schemes in NOMA. Furthermore, an overview of the resource allocation algorithms for downlink NOMA in a categorized fashion is studied in [7], which provides the basis for further research directions on the resource allocation for NOMA systems, such as the joint optimization of power allocation (PA), lower complexity resource allocation, and security-aware resource allocation.

In the recent researches, for the excellent compatibility of the NOMA with other communication technologies, NOMA has been integrated in various communication systems. Since massive multiple-input multiple-output (MIMO) [8]–[10] makes a clean break with current practice through the use of a very large number of service antennas, in [11], the authors proposed a massive-MIMO-NOMA transmission scheme. Particularly, in [12]–[14], the authors studied the secrecy issue of NOMA for single- and multiple-antenna scenarios, where the security performance of the NOMA networks can be significantly improved compared with the convention OMA one. In [15], the resource allocation for the downlink MIMO-based NOMA (MIMO-NOMA) system is studied, in which, the proposed system achieves near optimal sum-rate
(SR) performance with a high-complexity beamforming scheme by considering both perfect and imperfect channel state information (CSI). Since radio-frequency (RF) signals have the ability to carry both information and energy, simultaneous wireless information and power transfer (SWIPT) has been attracted increasing attention in the communication research community \[16\]. Motivated by the advantages of NOMA and SWIPT, the application of SWIPT to NOMA networks are investigated in \[17\], \[18\], where the user with a strong channel condition serves as an energy-harvesting (EH) relay to complete the power splitting scheme. In addition, the antenna and relay selection problems for NOMA systems have been studied in \[19\], \[20\], which demonstrate that the proposed selection schemes yield a significant performance gain over the OMA. More specifically, the works \[21\], \[22\] introduced NOMA into short packet communication to achieve low latency and a much higher effective throughput, as well as reduce the latency in short-packet communications for achieving the same effective throughput compared with the OMA. It is worth noting that, the fairness is also an important issue for NOMA \[23\], since there is a tradeoff between the total throughput and user fairness. Moreover, in \[24\], since cooperative NOMA systems inherit advantages of the NOMA protocol and cooperative relaying, the cooperative NOMA systems in MIMO channels are considered, which outperforms the conventional NOMA scheme in terms of the achievable rate. Specifically, the imperfect CSI scheme with NOMA is also studied in \[25\], where the robust scheme is developed based on the worst-case performance optimization framework.

Since the relaying transmission significantly increases the system capacity, the cooperative relaying networks (CRNs) have garnered considerable interest. Recently, the CRN-NOMA systems have been proposed in the literatures \[26\]–\[34\]. The authors in \[27\] investigated a CRN over Rician fading channels by deriving the exact analytical expressions of the achievable rates. It is noted that in \[28\], the outage performance of CRN-NOMA with an amplify-and-forward (AF) relay is studied, which reveals the proposed CRN-NOMA achieves the same diversity order and a superior coding gain compared with the cooperative OMA scheme. Considering an orthogonal frequency division multiplexing (OFDM) AF relaying system allocated the spectrum and power resources, the resource allocation problem for a single-cell CRN-NOMA is studied in \[29\], which results in a maximum average SR. In particular, adopting maximal ratio combining (MRC), NOMA for multiple-antenna relaying networks are designed in \[30\] which shows the correctness of the theoretical analysis and the superiority of NOMA. Meanwhile, a coordinated direct and relay transmission (CDRT) with the decode-and-forward (DF) protocol in NOMA
system is investigated in [31], in which, it is also showed that the main challenges of the non-orthogonal CDRT can be solved by using the inherent property of NOMA. It is worth noting that, the achievable ergodic rate is restricted by the weak channel for its lower channel gain. To solve this problem, the authors in [32] designed a novel MRC receiver which provides an excellent performance gain in terms of the ergodic SR and outage probability. Unfortunately, the MRC in [32] requires the lower power signals to be decoded first that does not strictly follow the NOMA decoding principle. With these observations, [33] proposed a two-stage power allocation scheme, where a novel type of the construction for the superposition coded signals at the relay is designed to avoid the problem described above. Moreover, a device-to-device (D2D) aided NOMA is proposed in [34], in which, the spectral efficiency is significantly improved for both the D2D aided cooperative communication and D2D communication systems.

Actually, in [34], the signals forwarded by the relay node do not include the full information (i.e., the signal $x_1$ is not forwarded during the second phase), in the meanwhile that there is no direct link between the base station (BS) and user 3 (UE3). On the other hand, it is possible to see that, with the similar transmission and decoding strategies, straightforwardly including one direct link between the BS and UE3 to satisfy the full information transmitting requirements, the performance of the inspired systems will be worse than that the one in [34] due to the poor channel limitation (the path loss from the BS to users is normally worse than that of the one from the relay to users). In this paper, we will first characterize the impact of the weak channel and different decoding schemes, and then provide the mentality to study the D2D-NOMA systems, meanwhile the applicable in the future cooperative NOMA networks. These motivate us to investigate a capacity enhanced transmission scheme for the proposed D2D-NOMA systems, which considering the superposition coded signals are transmitted from both of the BS and relay. More details of implementations and essential contributions of this paper are summarized as follows:

- Considering all the users are within the transmission scope of the BS, to further improve the spectrum efficiency, the direct links between the BS and users are necessary to be included. For the proposed D2D-NOMA system, unlike existing works, a more practical D2D scenario is proposed and investigated, wherein the BS can communicate simultaneously with all the users to satisfy the full information transmitting requirements. In particular, both the BS and relay are allowed to transmit superposition coded signals.
- Without loss of the generality, to characterize the impact of the weak channel condition
and different decoding schemes, two decoding strategies are proposed which are termed as single signal decoding scheme and MRC decoding scheme. For the single signal decoding scheme, all the users, i.e., the BS and relay, will immediately decode the received signals after receptions from the BS. Unlike the single signal decoding scheme, for the MRC decoding scheme, instead of decoding, the users will keep the receptions in reserve until the corresponding phase comes.

- Asymptotic closed-form expressions for the ergodic SR, outage probability and outage capacity of the proposed D2D-NOMA systems are derived with a negligible performance loss for high transmit SNR scenarios, respectively. The correctness of the analytical results is corroborated by simulations. Moreover, we also discuss the ergodic SR judgement of these two decoding schemes through the asymptotic closed-form expressions.

- By means of the numerical results, both analytically and numerically, we compare the proposed D2D-NOMA schemes with the one in [34] in terms of the ergodic SR and outage probability. It is demonstrated that, the proposed MRC decoding scheme outperforms that of the one in [34] and single signal decoding scheme significantly. In addition, it is also shown that the system performance will be limited by the poor channel condition for the single signal decoding scheme and conventional NOMA scheme, but not for the proposed MRC decoding scheme.

The remainder of this paper is organised as follows. In Section II, the system model for the proposed D2D-NOMA system is introduced. In Section III, the analytical expressions of the achievable ergodic SR for the proposed two decoding strategies are derived. Then the outage probability and outage capacity for D2D-NOMA are investigated in Section IV. Analytical results and numerical simulations are presented in Section V. Finally, Section V concludes this paper.

Notations: $\mathcal{C}N(\cdot)$ represents a complex Gaussian distribution. $\text{Ei}(\cdot)$, $\text{Ec}$ and $E[\cdot]$ denote the exponential integral function, Euler constant and expectation, respectively. $\Pr\{A|B\}$ denotes the conditional probability of the event $A$ on event $B$. $|\cdot|^2$ stands for the norm square of a scalar.

II. SYSTEM MODEL AND PROPOSED SCHEME

By employing decode-and-forward (DF) schemes, a simple cooperative D2D relaying system consisting of one BS, one relay (UE1) and two users (UE2 and UE3) is considered as shown in Fig. 1, in which all nodes operate in a half-duplex mode. It is also assumed that all the nodes in the system are equipped with a single antenna, meanwhile that all receiving nodes acquire
the perfect CSI. The independent Rayleigh fading channel coefficients from the BS to users $i \in \{1, 2, 3\}$, and from the relay to UE2 and UE3 are denoted as $h_{BU_i}$, $h_{RU_2}$ and $h_{RU_3}$, where the average powers are given as $\alpha_{BU_i}$, $\alpha_{RU_1}$ and $\alpha_{RU_2}$, respectively. Without loss of generality, it is also assumed that $\alpha_{BU_i} < \min\{\alpha_{RU_1}, \alpha_{RU_2}\}$, since that the path loss from the BS to users is normal worse than that of the one from the relay to users.

In our proposed scheme, two-phase transmission is considered. With the observation of the NOMA principle, the power allocation factor $a_i$, for $i \in \{1, 2\}$, follows the conditions of $a_1 > a_2$ and $a_1 + a_2 = 1$, which are related to the quality of the channel coefficients. During the first phase, a superposed signal

$$y_{U_i} = \sqrt{a_1 P_t} x_1 + \sqrt{a_2 P_t} x_2$$

(1)

is transmitted from the BS to user $i$, where $x_i$ denotes the broadcasted symbol at the BS and $P_t$ means the total transmit power. Therefore, the received signal at the user $i$ can be given as

$$y_{U_i} = h_{SU_i} (\sqrt{a_1 P_t} x_1 + \sqrt{a_2 P_t} x_2) + n_{U_i},$$

(2)

where $n_{U_i} \sim \mathcal{CN}(0, \sigma^2)$ stands for the additive white Gaussian noise (AWGN) with zero mean and variance $\sigma^2_{U_i}$.

In order to successfully and simultaneously decode the symbols $x_1$ and $x_2$ at UE1, the SIC technique is utilized. Following this manner, the received SNRs for $x_1$ and $x_2$ at UE1 can be
respectively obtained as
\[ \gamma_{U_1}^{(x_1)} = \frac{|h_{SU_1}|^2 a_1 \rho}{|h_{SU_1}|^2 a_2 \rho + 1}, \quad \gamma_{U_1}^{(x_2)} = |h_{SU_1}|^2 a_2 \rho, \tag{3} \]
with \( \rho = \frac{P_t}{\sigma_k^2} \) as the transmit SNR.

During the second phase, for UE1, to improve the spectral efficiency as well as offload the traffic, our proposed capacity enhanced D2D-NOMA systems allow the relay to forward its own signal to the UE2 and UE3. With this observation, the relay node forwards a new superposition coded to the destination:
\[ \sqrt{b_1} x_2 + \sqrt{b_2} x_r \tag{4} \]
where \( b_i \), for \( i \in \{1, 2\} \), is the new power allocation coefficient with \( b_1 + b_2 = 1 \). It is worth noting that, since the signal \( x_2 \) is with lower transmit power during the first phase, which leads to a worse spectral efficiency at the UE2 and UE3. Therefore, during the second phase, the signal \( x_2 \) is reasonable to be retransmitted to solve this problem. Correspondingly, the received signals at the UE2 and UE3 can be expressed as
\[ r_{U_2} = h_{RU_2} \left( \sqrt{a_1 P_t} x_2 + \sqrt{a_2 P_t} x_r \right) + n_{U_2}^{(2)}, \]
\[ r_{U_3} = h_{RU_3} \left( \sqrt{a_1 P_t} x_2 + \sqrt{a_2 P_t} x_r \right) + n_{U_3}^{(2)}, \tag{5} \]
where \( n_{U_2}^{(2)} \) and \( n_{U_3}^{(2)} \) are the AWGN with zero mean and variance \( \sigma_{U_2}^2 \) and \( \sigma_{U_3}^2 \), respectively.

Without loss of generality, in this paper, two kinds of decoding strategies will be studied: one is similar to [34], the other is the MRC one, which will be introduced in the following subsections.

A. Single Signal Decoding Scheme

During the first phase, the UE2 and UE3 immediately decode the receptions, i.e., \( x_1 \), with the corresponding received SNR as
\[ \gamma_{U_1}^{(S,x_1)} = \frac{a_1 |h_{SU_1}|^2 \rho}{a_2 |h_{SU_1}|^2 \rho + 1}. \tag{6} \]
At the second phase, the UE2 and UE3 will respectively decode the received signals \( x_2 \) and \( x_r \). By this way, the received SNRs for \( x_2 \) and \( x_r \) are given as

\[
\gamma_{U_1}^{(S,x_2)} = \frac{b_1 |h_{RU_i}|^2 \rho}{b_2 |h_{RU_i}|^2 \rho + 1},
\]

(7)

and

\[
\gamma_{U_1}^{(S,x_r)} = b_2 |h_{RU_i}|^2 \rho.
\]

(8)

In this manner, the achievable SR can be obtained from

\[
C_{sum}^{(S)} = \frac{1}{2} \log_2 \left( 1 + \min \left\{ \gamma_{U_1}^{(S,x_1)}, \gamma_{U_2}^{(S,x_1)}, \gamma_{U_3}^{(S,x_1)} \right\} \right) + \frac{1}{2} \log_2 \left( 1 + \min \left\{ \gamma_{U_1}^{(S,x_2)}, \gamma_{U_2}^{(S,x_2)}, \gamma_{U_3}^{(S,x_2)} \right\} \right)
\]

\[
+ \frac{1}{2} \log_2 \left( 1 + \min \left\{ \gamma_{U_2}^{(S,x_r)}, \gamma_{U_3}^{(S,x_r)} \right\} \right),
\]

(9)

where \( \frac{1}{2} \) results from the two-phase transmission.

**B. MRC Decoding Scheme**

In this scheme, realizing that the performance of the achievable rate is limited by a poor channel, the UE2 and UE3 will not immediately decode the receptions but instead conserve them until the second phase comes. To jointly decode \( x_1 \) and \( x_2 \) by utilizing MRC at the UE2 and UE3, the corresponding effective SNRs for \( x_1, x_2 \) and \( x_r \) are respectively given as

\[
\gamma_{U_1}^{(M,x)} = \frac{a_1 |h_{SU_i}|^2 \rho}{a_2 |h_{SU_i}|^2 \rho + 1},
\]

(10)

and

\[
\gamma_{U_1}^{(M,x_2)} = \frac{b_1 |h_{RU_i}|^2 \rho}{b_2 |h_{RU_i}|^2 \rho + 1} + a_2 |h_{SU_i}|^2 \rho,
\]

(11)

and

\[
\gamma_{U_1}^{(M,x_r)} = b_2 |h_{RU_i}|^2 \rho.
\]

(12)
for $l \in \{2, 3\}$. Therefore, in this scheme, the achievable SR for the proposed capacity enhanced D2D-NOMA system can be obtained from:

$$C^{(M)}_{\text{sum}} = \frac{1}{2} \log_2 \left( 1 + \min \left\{ \gamma_{U_1}^{(x_1)} + \frac{a_1 \beta_{SU_1} \rho}{a_2 \beta_{SU_1} \rho + 1}, \frac{a_1 \beta_{SU_2} \rho}{a_2 \beta_{SU_2} \rho + 1}, \frac{a_1 \beta_{SU_3} \rho}{a_2 \beta_{SU_3} \rho + 1} \right\} \right) + \frac{1}{2} \log_2 \left( 1 + \min \left\{ \gamma_{U_2}^{(x_2)} + \frac{a_1 \beta_{SU_1} \rho}{a_2 \beta_{SU_1} \rho + 1}, \frac{a_1 \beta_{SU_2} \rho}{a_2 \beta_{SU_2} \rho + 1}, \frac{a_1 \beta_{SU_3} \rho}{a_2 \beta_{SU_3} \rho + 1} \right\} \right) + \frac{1}{2} \log_2 \left( 1 + \min \left\{ \gamma_{U_3}^{(x_r)} + \frac{a_1 \beta_{SU_1} \rho}{a_2 \beta_{SU_1} \rho + 1}, \frac{a_1 \beta_{SU_2} \rho}{a_2 \beta_{SU_2} \rho + 1}, \frac{a_1 \beta_{SU_3} \rho}{a_2 \beta_{SU_3} \rho + 1} \right\} \right). \quad (13)$$

### III. Ergodic Rate Analysis for the Proposed Two Decoding Strategies

In this section, we focus on the performance analysis of the proposed capacity enhanced cooperative D2D-NOMA system for both of two decoding strategies, which includes the achievable ergodic SR, outage probability and outage capacity over the Rayleigh fading channel.

#### A. Single Signal Decoding Scheme

Letting $\beta_{SU_i} \triangleq |h_{SU_i}|^2$, and $\beta_{RU_l} \triangleq |h_{RU_l}|^2$, we have

$$S_1 = \min \left\{ \frac{a_1 \beta_{SU_1} \rho}{a_2 \beta_{SU_1} \rho + 1}, \frac{a_1 \beta_{SU_2} \rho}{a_2 \beta_{SU_2} \rho + 1}, \frac{a_1 \beta_{SU_3} \rho}{a_2 \beta_{SU_3} \rho + 1} \right\}. \quad (14)$$

Based on (14), the complementary cumulative distribution function (CCDF) of $S_1$ can be obtained as

$$F_{S_1}(s_1) = \Pr \left\{ \frac{a_1 \beta_{SU_1} \rho}{a_2 \beta_{SU_1} \rho + 1} > s_1, \frac{a_1 \beta_{SU_2} \rho}{a_2 \beta_{SU_2} \rho + 1} > s_1, \frac{a_1 \beta_{SU_3} \rho}{a_2 \beta_{SU_3} \rho + 1} > s_1 \right\}. \quad (15)$$

Note that the CCDF of $\beta_\delta = e^{-\frac{\delta}{a_\delta}}$, for $\delta \in \{SU_i, RU_l\}$. When $s_1 < \frac{a_1}{a_2}$, (15) can be equivalently represented as

$$F_{S_1}(s_1) = F_{SU_1} \left( \frac{s_1}{a_1 \rho - a_2 \rho x} \right) F_{SU_2} \left( \frac{s_1}{a_1 \rho - a_2 \rho x} \right) F_{SU_3} \left( \frac{s_1}{a_1 \rho - a_2 \rho x} \right) = e^{-\frac{s_1}{a_1 \rho - a_2 \rho x} \left( \frac{1}{\alpha_{SU_1} + 1}, \frac{1}{\alpha_{SU_2} + 1}, \frac{1}{\alpha_{SU_3} + 1} \right)}. \quad (16)$$

For the case $s_1 > \frac{a_1}{a_2}$, $F_{S_1}(s_1) = 0$ always holds due to

$$\frac{\beta_{SU_1} a_1 \rho}{\beta_{SU_1} a_2 \rho + 1} < \frac{a_1}{a_2}. \quad (17)$$
Taking derivative of (16), the PDF of $S_1$ is given as
\[ f_{S_1}(s_1) = \frac{s_1}{a_1 \rho - a_2 \rho s_1} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right) e^{-\frac{s_1}{a_1 \rho - a_2 \rho s_1} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right)}. \] (18)

Using the equality
\[ \int_0^\infty \log_2 (1 + x) f_X(x) dx = \frac{1}{2 \ln 2} \int_0^\infty \frac{1 - F(x)}{1 + x} dx, \] (19)

and considering the high SNR case, from (16), the achievable ergodic rate for $x_1$ can be obtained as follows:
\[
C_{S_1}(x_1) = \int_0^{\frac{a_1}{a_2}} \frac{1}{2} \log_2 \left( 1 + s_1 \right) dF_{S_1}(s_1) + \frac{1}{2} \log_2 \left( 1 + \frac{a_1}{a_2} \right) \left( 1 - F_{S_1} \left( \frac{a_1}{a_2} \right) \right)
\]
\[
= \frac{1}{2} \log_2 \left( 1 + \frac{a_1}{a_2} \right) - \frac{1}{2 \ln 2} \int_0^{\frac{a_1}{a_2}} \frac{1}{1 + s_1} \left( 1 - e^{-\frac{s_1}{a_1 \rho - a_2 \rho s_1} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right)} \right) ds_1
\]
\[
= \frac{1}{2 \ln 2} \int_0^{\frac{a_1}{a_2}} e^{-\frac{s_1}{a_1 \rho - a_2 \rho s_1} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right)} ds_1
\]
\[
= -\frac{1}{2 \ln 2} \left( e^{-\frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}}} \left[ \text{Ei} \left( -\frac{1}{\rho} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right) \right) \right] - e^{\frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}}} \left[ \text{Ei} \left( -\frac{1}{\rho} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right) \right) \right] \right), \tag{20}
\]

where the third term in (20) is simplified by using
\[ \int_0^u e^{-\mu x} dx = e^\beta \left[ \text{Ei} \left( -\mu u - \mu \beta \right) - \text{Ei} \left( -\mu \beta \right) \right] \tag{21} \]

[35, Eq. (3.352.1)].

For $S_2$, the corresponding CCDF can be obtained from
\[
\overline{F}_{S_2}(s_2) = \Pr \left\{ a_2 \beta_{SU_1} \rho > s_2, b_1 \beta_{RU_2} \rho + 1 > s_2, b_1 \beta_{RU_3} \rho + 1 > s_2 \right\}
\]
\[
= \overline{F}_{SU_1} \left( \frac{s_2}{a_2 \rho} \right) \overline{F}_{RU_2} \left( \frac{s_2}{b_1 \rho - b_2 \rho s_2} \right) \overline{F}_{RU_3} \left( \frac{s_2}{b_1 \rho - b_2 \rho s_2} \right)
\]
\[
= e^{-\frac{s_2}{a_1 \rho - a_2 \rho s_2} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right)} \overline{F}_{SU_1} \left( \frac{s_2}{a_1 \rho - a_2 \rho s_2} \right). \tag{22}
\]
Similar to [13], considering a high transmit SNR case, which leads to

\[
\frac{b_1 |h_{RU}|^2}{b_2 |h_{RU}|^2} \rho + 1 \sim \frac{b_1}{b_2},
\]

(23)

the effective capacity of \( x_2 \) can be approximately obtained from

\[
C_{S_2}^{(x_2)} \sim \frac{1}{2\ln 2} \left( \text{Ei} \left( -\frac{1}{a_2 \rho \alpha_{SU_1}} \left( 1 + \frac{b_1}{b_2} \right) \right) - \text{Ei} \left( -\frac{1}{a_2 \rho \alpha_{SU_1}} \right) \right)
\]

(24)

Correspondingly, for \( S_3 \), the corresponding CCDF is given as

\[
\overline{F}_{S_3}(s_3) = \Pr \{ b_2 \beta_{RU_2} \rho > s_3, b_2 \beta_{RU_3} \rho > s_3 \} = \overline{F}_{RU_2} \left( \frac{s_3}{b_2 \rho} \right) \overline{F}_{RU_3} \left( \frac{s_3}{b_2 \rho} \right) = e^{-\frac{s_3}{b_2 \rho} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right)}
\]

(25)

with the effective rate as

\[
C_{S_3}^{(x_3)} = \frac{e^{\frac{1}{a_2 \rho \alpha_{SU_1}} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right)}}{2\ln 2} \text{Ei} \left( -\frac{1}{b_2 \rho} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right) \right)
\]

(26)

Synthesizing (20), (24) and (26), the achievable SR for the single signal decoding scheme can be expressed as

\[
C_{S}^{(\text{sum})} = -\frac{1}{2\ln 2} \left( e^{\frac{1}{a_2 \rho} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right)} \left[ \text{Ei} \left( -\frac{1}{\rho} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right) \right) \right] \\
- e^{\frac{1}{a_2 \rho} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right)} \left[ \text{Ei} \left( -\frac{1}{a_2 \rho} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right) \right) \right] \\
+ \frac{e^{\frac{1}{a_2 \rho} \alpha_{SU_1}}}{2\ln 2} \left( \text{Ei} \left( -\frac{1}{a_2 b_2 \rho \alpha_{SU_1}} \right) \right) - \text{Ei} \left( -\frac{1}{a_2 \rho \alpha_{SU_1}} \right) \\
+ \frac{e^{\frac{1}{a_2 \rho} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right)}}{2\ln 2} \text{Ei} \left( -\frac{1}{b_2 \rho} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right) \right).
\]

(27)

By further applying the approximations \( \text{Ei}(-x) \sim Ec + \ln x \) and \( e^x \sim 1 + x \), for small \( x \), after
some algebra, (27) can be finally rewritten as
\[
C^{(sum)}_S \sim \frac{1}{2\ln2} \left( \frac{A}{a_2} - a_1 Ec - a_1 \ln A + \ln a_2 + \left( 1 + \frac{1}{a_2 \rho \alpha_{SU_1}} \right) \ln b_2 + (1 + B) (Ec + \ln B) \right),
\]
where \( A = \frac{1}{\rho} \left( \frac{1}{a_{SU_1}} + \frac{1}{a_{SU_2}} + \frac{1}{a_{SU_3}} \right) \) and \( B = \frac{1}{b_2 \rho} \left( \frac{1}{a_{RU_2}} + \frac{1}{a_{RU_3}} \right). \)

**B. MRC Decoding Scheme**

Since that the final expressions of the ergodic rate for \( \mathcal{M}_1 \) and \( \mathcal{M}_3 \) are equivalent to the ones of \( \mathcal{S}_1 \) and \( \mathcal{S}_3 \), respectively. In this subsection, we will focus on the closed-form expression of \( \mathcal{M}_2 \):
\[
\mathcal{M}_2 = \min \left\{ a_2 \beta_{SU_1} \rho, \frac{b_1 \beta_{RU_2} \rho}{b_2 \beta_{RU_2} \rho + 1} + a_2 \beta_{SU_2} \rho, \frac{b_1 \beta_{RU_3} \rho}{b_2 \beta_{RU_3} \rho + 1} + a_2 \beta_{SU_3} \rho \right\}
\]
with the corresponding CCDF as
\[
\overline{F}_{M_2}(m) = \text{Pr} \left\{ a_2 \beta_{SU_1} \rho > m, \frac{b_1 \beta_{RU_2} \rho}{b_2 \beta_{RU_2} \rho + 1} + a_2 \beta_{SU_2} \rho > m, \frac{b_1 \beta_{RU_3} \rho}{b_2 \beta_{RU_3} \rho + 1} + a_2 \beta_{SU_3} \rho > m \right\}
\]
\[
= \overline{F}_{SU_1} \left( \frac{m}{a_2 \rho} \right) \overline{F}_{SU_2} \left( \frac{m - \frac{b_1 \beta_{RU_2} \rho}{b_2 \beta_{RU_2} \rho + 1}}{a_2 \rho} \right) \overline{F}_{SU_3} \left( \frac{m - \frac{b_1 \beta_{RU_3} \rho}{b_2 \beta_{RU_3} \rho + 1}}{a_2 \rho} \right).
\]

For \( \mathcal{P}_1 \), we have the exact expression as following:
\[
\mathcal{P}_1 = \left\{ \begin{array}{l}
\text{Pr} \left\{ \frac{b_1 \beta_{RU_2} \rho}{b_2 \beta_{RU_2} \rho + 1} < m_2 \right\} \text{Pr} \left\{ a_2 \beta_{SU_2} \rho > m_2 - \frac{b_1 \beta_{RU_2} \rho}{b_2 \beta_{RU_2} \rho + 1} \right\} + \text{Pr} \left\{ \frac{b_1 \beta_{RU_2} \rho}{b_2 \beta_{RU_2} \rho + 1} > m_2 \right\}, m_2 < \rho_2 \\
\text{Pr} \left\{ a_2 \beta_{SU_2} \rho > m_2 - \frac{b_1 \beta_{RU_2} \rho}{b_2 \beta_{RU_2} \rho + 1} \right\}, \ m_2 > \rho_2
\end{array} \right\}
\]

For \( m_2 > \rho_2 \), we have
\[
\mathcal{P}_1 = \frac{1}{\beta_{RU_2}} e^{-\frac{m_2}{\beta_{SU_2}}} \int_0^\infty e^{-\frac{1}{\beta_{SU_2}} \left( \frac{b_1 u}{b_2 \rho + 1} \right) - \frac{u}{\beta_{RU_2}}} \, du.
\]

In the meanwhile that, for \( m_2 < \rho_2 \), the effective CCDF for \( \mathcal{M}_2 \) can be obtained from
\[
\mathcal{P}_1 = e^{-\frac{1}{\beta_{RU_2}} \left( \frac{m_2}{\beta_{SU_2}} \right)} + \frac{1}{\beta_{RU_2}} \left( 1 - e^{-\frac{1}{\beta_{RU_2}} \left( \frac{m_2}{\beta_{SU_2}} \right)} \right) e^{-\frac{m_2}{\beta_{SU_2}}} \int_0^\infty e^{-\frac{1}{\beta_{SU_2}} \left( \frac{b_1 u}{b_2 \rho + 1} \right) - \frac{u}{\beta_{RU_2}}} \, du.
\]
Clearly, (33) is quite involved to derive the exact ergodic achievable rate. Therefore, we turn to examine it in an approximate way, i.e., \( b_1 \beta_{RU_2}^{\rho} + 1 \sim b_1 \), for a high transmit SNR. By this way, the CCDF for \( \mathcal{M}_2 \) can be finally obtained as

\[
\mathcal{F}_{\mathcal{M}_2}(m_2) = e^{\frac{-m_2}{a_2^2}} \left( \frac{1}{\beta_{SU_1}} + \frac{1}{\beta_{SU_2}} + \frac{1}{\beta_{SU_3}} \right) + \frac{b_1}{b_2} \left( \frac{1}{\beta_{RU_2}} + \frac{1}{\beta_{RU_3}} \right),
\]

with the corresponding ergodic achievable rate as

\[
C_{\mathcal{M}_2}^{(x_2)} = \frac{1}{2\ln 2} \int_0^\infty e^{-\frac{m_2}{a_2^2}} \left( \frac{1}{\beta_{SU_1}} + \frac{1}{\beta_{SU_2}} + \frac{1}{\beta_{SU_3}} \right) \left( 1 + m_2 \right) \, dm_2
\]

\[
= -e^{\frac{1}{a_2^2}} \left( \frac{1}{\beta_{SU_1}} + \frac{1}{\beta_{SU_2}} + \frac{1}{\beta_{SU_3}} \right) \frac{1}{2\ln 2} \text{Ei}\left( -\frac{1}{a_2^2} \left( \frac{1}{\beta_{SU_1}} + \frac{1}{\beta_{SU_2}} + \frac{1}{\beta_{SU_3}} \right) \right),
\]

where the equation (19) is used. By substituting (20), (26), and (35) back into (13), the achievable SR for the proposed capacity enhanced D2D-NOMA system can be expressed as

\[
C_{\text{sum}}^{(M)} = -e^{\frac{1}{a_2^2}} \left( \frac{1}{\beta_{SU_1}} + \frac{1}{\beta_{SU_2}} + \frac{1}{\beta_{SU_3}} \right) \frac{1}{2\ln 2} \text{Ei}\left( -\frac{1}{a_2} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right) \right)
\]

\[
- \frac{1}{2\ln 2} \left( \frac{1}{e^\rho} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right) \right) \left[ \text{Ei}\left( -\frac{1}{\rho} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right) \right) \right]
\]

\[
- e^{\frac{1}{a_2^2}} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right) \frac{1}{2\ln 2} \text{Ei}\left( -\frac{1}{b_2} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right) \right) - \frac{1}{2\ln 2} \left( \frac{1}{e^\rho} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right) \right) \left[ \text{Ei}\left( -\frac{1}{\rho} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right) \right) \right].
\]

Similarly, employing the approximations \( \text{Ei}(-x) \sim Ec + \ln x \) and \( e^x \sim 1 + x \), for small \( x \), (36) can be approximately rewritten into

\[
C_{S}^{(\text{sum})} \sim \frac{1}{2\ln 2} \left( \frac{A}{a_2} \left( -\left(a_1 + 1\right) Ec - a_1 \ln A + \ln \frac{a_2^2}{A} \right) + \ln a_2 + B \left( Ec + \ln B \right) + \ln \frac{a_2B}{A} \right).
\]

Discussion: It is clear, for these two proposed decoding strategies, the difference of the sum-rate is provided by \( S_2 \) and \( M_2 \), which are the corresponding received SNR for \( x_2 \). More specifically, for a high transmit SNR case, the first term in (22) and (29) will be greater than the last two terms, since that the distance between the BS and relay is normal smaller than the one between the BS and users. With this observation, comparing the last two terms in (22) and (29), it is
easy to see that, the difference \( a_2 \beta_{SU_2} \rho \) and \( a_2 \beta_{SU_3} \rho \) will result in a significant performance improvement for the proposed MRC decoding scheme. In the following section, the numerical results will be used to further confirm the correctness of our analysis.

IV. OUTAGE PROBABILITY AND OUTAGE CAPACITY ANALYSIS

A. Outage Probability Analysis

In this subsection, we will derive the outage probability into asymptotic expressions for the proposed D2D-NOMA system with two decoding schemes. Assuming \( R_{x_1}^T, R_{x_2}^T \) and \( R_{x_r}^T \) denoted as the predefined target rate thresholds of the symbols \( x_1, x_2 \) and \( x_3 \), respectively, the outage event occurs when \( R_{x_1}, R_{x_2} \) and \( R_{x_r} \) are smaller than that of the \( R_{x_1}^T, R_{x_2}^T \) and \( R_{x_r}^T \), where \( R_{x_g}^T \) denotes the achievable rate for the date \( x_g \), for \( g \in \{1, 2, r\} \).

The exact outage probability for the MRC decoding scheme can be written as:

\[
P_S = 1 - \Pr \left[ R_{x_1} > R_{x_1}^T, R_{x_2} > R_{x_2}^T, R_{x_r} > R_{x_r}^T \right]
\]

\[
= 1 - \Pr \left\{ \frac{M_1}{\kappa_1} > 2^{R_{x_1}^T} - 1 \right\} \cap \left\{ \frac{M_2}{\kappa_2} > 2^{R_{x_2}^T} - 1 \right\} \cap \left\{ \frac{M_3}{\kappa_r} > 2^{R_{x_r}^T} - 1 \right\} . \tag{38}
\]

Further assuming \( W_1 = 2^{R_{x_1}^T} - 1 \), \( W_2 = 2^{R_{x_2}^T} - 1 \) and \( W_r = 2^{R_{x_r}^T} - 1 \) respectively, the final closed-form expressions of \( K_1 \), \( K_2 \) and \( K_r \) can be obtained as:

\[
K_1 = \Pr \left\{ \min \left( \frac{a_1 \beta_{SU_1} \rho}{a_2 \beta_{SU_1} \rho + 1}, \frac{a_1 \beta_{SU_1} \rho}{a_2 \beta_{SU_2} \rho + 1}, \frac{a_1 \beta_{SU_1} \rho}{a_2 \beta_{SU_3} \rho + 1} \right) > W_1 \right\}
\]

\[
= \Pr \left\{ \frac{a_1 \beta_{SU_1} \rho}{a_2 \beta_{SU_1} \rho + 1} > W_1 \right\} \Pr \left\{ \frac{a_1 \beta_{SU_2} \rho}{a_2 \beta_{SU_2} \rho + 1} > W_1 \right\} \Pr \left\{ \frac{a_1 \beta_{SU_3} \rho}{a_2 \beta_{SU_3} \rho + 1} > W_1 \right\}
\]

\[
= \begin{cases} 
\frac{\ln W_1}{a_2 \beta_{SU_2} \rho + 1} & \text{for } W_1 < \frac{a_1}{a_2}, \\
0 & \text{for } W_1 > \frac{a_1}{a_2}, 
\end{cases} \tag{39}
\]
\[ K_2 = \Pr \left\{ \mathcal{M}_2 > 2^{R_2^2} - 1 \right\} \]
\[ = \Pr \left\{ \min \left\{ a_2 \beta_{SU_1} \rho, \frac{b_1 \beta_{RU_2} \rho}{b_2 \beta_{RU_2} \rho + 1} + a_2 \beta_{SU_2} \rho, \frac{b_1 \beta_{RU_3} \rho}{b_2 \beta_{RU_3} \rho + 1} + a_2 \beta_{SU_3} \rho \right\} > \mathcal{W}_2 \right\} \]
\[ = \Pr \{ a_2 \beta_{SU_1} \rho > \mathcal{M}_2 \} \Pr \left\{ \frac{b_1 \beta_{RU_2} \rho}{b_2 \beta_{RU_2} \rho + 1} + a_2 \beta_{SU_2} \rho > \mathcal{M}_2 \right\} \Pr \left\{ \frac{b_1 \beta_{RU_3} \rho}{b_2 \beta_{RU_3} \rho + 1} + a_2 \beta_{SU_3} \rho > \mathcal{M}_2 \right\} \]
\[ = \begin{cases} 
 0 & \text{for } \mathcal{W}_2 > \frac{b_1}{b_2}, \\
e^{-\frac{W_2}{a_2}(\frac{1}{\beta_{SU_1}} + \frac{1}{\beta_{SU_2}} + \frac{1}{\beta_{SU_3}}) + \frac{b_1}{b_2}(\frac{1}{\beta_{RU_2}} + \frac{1}{\beta_{RU_3}})}, & \text{for } \mathcal{W}_2 < \frac{b_1}{b_2}, 
\end{cases} \quad (40) \]

and

\[ K_r = \Pr \{ (b_2 \beta_{RU_2} \rho, b_2 \beta_{RU_3} \rho) > \mathcal{W}_r \} \]
\[ = \Pr \{ b_2 \beta_{RU_2} \rho > \mathcal{W}_r \} \Pr \{ b_2 \beta_{RU_3} \rho > \mathcal{W}_r \} \]
\[ = e^{-\frac{W_r}{b_2 \rho}(\frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}})}. \quad (41) \]

With the conditions \( \{ \mathcal{W}_1, \mathcal{W}_2 \} < \min \left\{ \frac{a_1}{a_2}, \frac{b_1}{b_2} \right\} \), substituting (39), (40) and (41) back into (38), we have the outage probability in a closed-form expression as

\[ P_M \sim 1 - e^{\frac{W_1}{a_1 \rho - a_2 \rho W_1} \left( \frac{1}{\alpha_{SU_1}} + \frac{1}{\alpha_{SU_2}} + \frac{1}{\alpha_{SU_3}} \right) - \frac{W_2}{b_2 \rho} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right) - \frac{W_2}{b_2 \rho} \left( \frac{1}{\beta_{SU_1}} + \frac{1}{\beta_{SU_2}} + \frac{1}{\beta_{SU_3}} \right) - \frac{W_2}{b_2 \rho} \left( \frac{1}{\beta_{RU_2}} + \frac{1}{\beta_{RU_3}} \right)}. \quad (42) \]

### B. Outage Capacity Analysis

In this subsection, the outage capacity analysis of our proposed D2D-NOMA system is analyzed. Since it is quit involved to obtain the exact outage capacity for our proposed scheme, in this paper, we turn to find an approximate way to derive the outage capacity, i.e., consider the high transmit SNR case.

Employing the approximation \( e^x \sim 1 + x \) for small \( x \) and letting \( P_M = \varepsilon_M \), (42) can be approximately rewritten into:

\[ \varepsilon_M \sim \frac{W_r}{b_2 \rho} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right) + \frac{W_2}{a_2 \rho} - \frac{b_1}{b_2} \left( \frac{1}{\beta_{SU_1}} + \frac{1}{\beta_{SU_2}} + \frac{1}{\beta_{SU_3}} \right) \cdot \frac{W_2}{a_2 \rho} \left( \frac{1}{\beta_{SU_1}} + \frac{1}{\beta_{SU_2}} + \frac{1}{\beta_{SU_3}} \right). \quad (43) \]

It is worth mentioning that, in a high transmit SNR case, for the condition \( \mathcal{W}_1 < \frac{a_1}{a_2} \), \( K_1 \triangleq 1 \) always holds. Therefore, to satisfy the QoS condition, setting the target thresholds as \( \mathcal{W}_1 =
\( W_2 = W_r = W_S = W_M \), (43) can be finally reexpressed as

\[
W_M = \left( \frac{1}{b_2 \rho} \left( \frac{1}{\alpha_{RU_2}} + \frac{1}{\alpha_{RU_3}} \right) + \frac{1}{a_2 \rho} \left( \frac{1}{\beta_{SU_1}} + \frac{1}{\beta_{SU_2}} + \frac{1}{\beta_{SU_3}} \right) \right)^{-1} \\
\times \left( \varepsilon_M + \frac{b_1}{a_2 b_2 \rho} \left( \frac{1}{\beta_{SU_1}} + \frac{1}{\beta_{SU_2}} + \frac{1}{\beta_{SU_3}} \right) \right),
\]

(44)

with the outage capacity:

\[
C_{out}^M = \frac{1}{2} \log_2 (1 + W_M).
\]

(45)

V. NUMERICAL RESULT

In this section, the performance of our proposed D2D-NOMA schemes in terms of the ergodic SR, outage probability and outage capacity are evaluated by using computer simulations and comparing to the benchmarks. All the numerical results are averaged over 100,000 channel realizations. In the following results, “Simulation” and “Analysis” are used to denote the simulation and analytical results, respectively. In the meanwhile, the “Recent D2D work”, “Enhance-D2D Single”, and “Enhance-D2D MRC” denote the convention NOMA scheme in [34], single signal decoding scheme and MRC decoding scheme, respectively.

Figs. 2 and 3 illustrate how the transmit SNR at the BS affects the ergodic SR performance of our proposed single signal decoding scheme, MRC decoding scheme and the conventional D2D-NOMA scheme in [34]. In Fig. 2, we fixed \( \alpha_{SU_1} = 5, \alpha_{SU_2} = 1, \alpha_{SU_3} = 1, \alpha_{RU_2} = 2, \alpha_{RU_3} = 10 \), for two power allocation setting groups as \( \{a_1 = 0.9, b_1 = 0.6\} \) and \( \{a_1 = 0.6, b_1 = 0.9\} \). In the meanwhile, we set \( \alpha_{SU_1} = 5, \alpha_{SU_2} = \{1, 2\}, \alpha_{SU_3} = \{2, 1\}, \alpha_{RU_2} = \{3, 10\}, \alpha_{RU_3} = \{10, 3\} \) with \( \{a_1 = 0.9, b_1 = 0.6\} \) for Fig. 3, respectively. As can be observed from both Figs. 2 and 3, with a increasing transmit SNR, the ergodic SR increases for all the schemes. Specifically, the proposed MRC decoding scheme overwhelms the single signal decoding scheme and conventional D2D-NOMA one, and it is worth pointing out that the analytical results match the simulation results well for both of the proposed two schemes especially at the high SNR region, which validate our theoretical analysis in Section III. Remarkably, the ergodic SR of the proposed single signal decoding scheme is worse than that of the convention D2D-NOMA one. It is reasonable, because the additional channel \( h_{SU_3} \) between the BS and UE3 is normal a week channel, which limits the corresponding received SNR for \( x_2 \). Clearly, the proposed MRC decoding scheme effectively refrain from this negative influence. Moreover, it is also shown that, with a greater
Fig. 2. The ergodic SRs achieved by our proposed \textit{Single Decoding scheme}, \textit{MRC Decoding scheme}, and the \textit{Recent D2D scheme} with fixed $\alpha_{SU_1} = 5$, $\alpha_{SU_2} = 1$, $\alpha_{SU_3} = 1$, $\alpha_{RU_2} = 2$, $\alpha_{RU_3} = 10$, and $a_1 = \{0.6, 0.9\}$, $b_1 = \{0.9, 0.6\}$ versus the transmission SNR.

Fig. 3. The ergodic SRs achieved by our proposed \textit{Single Decoding scheme}, \textit{MRC Decoding scheme}, and the \textit{Recent D2D scheme} with fixed $\alpha_{SU_1} = 5$, $\alpha_{SU_2} = \{1, 2\}$, $\alpha_{SU_3} = \{2, 1\}$, $\alpha_{RU_2} = \{3, 10\}$, $\alpha_{RU_3} = \{3, 10\}$, and $a_1 = 0.9$, $b_1 = 0.6$ versus the transmit SNR.
Fig. 4. The outage probability for our proposed Single Decoding scheme, MRC Decoding scheme, and the Recent D2D scheme with fixed $\alpha_{SU_1} = 5$, $\alpha_{SU_1} = 1$, $\alpha_{SU_3} = 2$, $\alpha_{RU_2} = 1$, $\alpha_{RU_3} = 10$, and $a_1 = 0.9$, $b_1 = 0.6$ with the target rate as 0.4 and 0.45 versus the transmit SNR.

power allocation factor $a_1$, and channels coefficients $\alpha_{SU_2}$, $\alpha_{RU_2}$, $\alpha_{RU_3}$, the ergodic SR for all the schemes are also improved.

Fig. 4 demonstrates the performance of the outage probability for the proposed schemes and conventional one in both simulation and analytical results with QoS thresholds as $\mathcal{W}_1 = \mathcal{W}_2 = \mathcal{W}_3 = \{0.4, 0.45\}$, where the power allocation factors are set as $a_1 = 0.9$, and $b_1 = 0.6$, while that $\alpha_{SU_1} = 5$, $\alpha_{SU_1} = 1$, $\alpha_{SU_3} = 2$, $\alpha_{RU_2} = 1$, $\alpha_{RU_3} = 10$. In Fig. 4, it can be seen that the probabilities decrease with a increasing transmit SNR. Particularly, the increase of QoS thresholds improves the above outage probabilities dramatically. The asymptotic simulations are also provided to confirm the close agreement between the simulation and analytical results. Moreover, the proposed MRC decoding scheme outperforms the other two schemes significantly, since that our proposed MRC decoding scheme provides a greater corresponding received SNR. In addition, it is also observed that the outage probability are similar for the single signal decoding scheme and convention D2D-NOMA one.

In Fig. 5, we present the outage capacity with respect to the transmit SNR and $\varepsilon$, where $\varepsilon$ is set to be $\{0.1, 0.2, 0.6\}$ with fixed $\alpha_{SU_1} = 20$, $\alpha_{SU_1} = 1$, $\alpha_{SU_3} = 10$, $\alpha_{RU_2} = 25$, $\alpha_{RU_3} = 30$, 

and the power allocation factors as $a_1 = 0.9$, $b_1 = \{0.6, 0.9\}$, respectively. It is clear, the outage sum capacity decreases with a increasing value of $\varepsilon$. More specifically, it is noted that for any given power allocation factor $b_1$, the outage sum capacity is better for a lower $b_1$ case.

Fig. 6 plots the impact of the power allocation factors $a_1$ as well as $b_1$ on the performance of the ergodic SR for the single signal decoding scheme and MRC decoding scheme, respectively. For both figures, we fixed $\alpha_{SU_1} = 5$, $\alpha_{SU_2} = 1$, $\alpha_{SU_3} = 1$, $\alpha_{RU_2} = 10$, $\alpha_{RU_3} = 10$, and $a_1 = 0.9$, $b_1 = \{0.6, 0.9\}$, $\varepsilon_M = \{0.1, 0.2, 0.6\}$ with respect to the transmit SNR.

Figs. 7-8 present the ergodic SR performance of our proposed single signal decoding scheme and MRC decoding scheme versus power allocation factors $a_1$ and $b_1$, where the channel coeffi-
Fig. 6. The ergodic SRs achieved by our proposed Single Decoding scheme and MRC Decoding scheme with fixed $\alpha_{SU_1} = 5$, $\alpha_{SU_2} = 1$, $\alpha_{SU_3} = 1$, $\alpha_{RU_2} = 10$, $\alpha_{RU_3} = 10$ and $\rho = \{15, 20, 25\}$ dB versus the power allocation factors $a_1$ and $b_1$.

Fig. 7. The ergodic SRs achieved by our proposed Single Decoding scheme with respect to the power allocation factors $a_1$ and $b_1$, for (a): $\rho = 15$ dB, (b): $\rho = 20$ dB, (c): $\rho = 25$ dB, (d): $\rho = 30$ dB.
VI. CONCLUSIONS

In this paper, a cooperative D2D-NOMA system has been studied with two decoding strategies named the single signal decoding scheme and MRC decoding scheme, respectively. The asymptotic closed-form expressions for the ergodic SR, outage probability and outage capacity for the proposed D2D-NOMA system were provided. Specifically, numerical results have been presented to corroborate the theoretical analysis, and results have demonstrated that the MRC decoding scheme yield significant performance gains over the single signal decoding scheme and conventional D2D-NOMA one. Moreover, all the results showed that the system performance are limited by the weak channel condition for both the single signal decoding scheme and conventional NOMA scheme but not for the MRC decoding scheme. It remains future work to

Fig. 8. The ergodic SRs achieved by our proposed MRC Decoding scheme with respect to the power allocation factors $a_1$ and $b_1$, for (a): $\rho = 15$ dB, (b): $\rho = 20$ dB, (c): $\rho = 25$ dB, (d): $\rho = 30$ dB.
investigate the practical power allocation method for the BS and users to further improve the system performance.

**List of Abbreviation**
Cooperative relay networks (CRN), non-orthogonal multiple access (NOMA), orthogonal multiple access (OMA), successive interference cancellation (SIC), maximum ratio combining (MRC), sum-rate (SR), power allocation (PA), frequency-division multiple access (FDMA), time-division multiple access (TDMA), channel state information (CSI), simultaneous wireless information and power transfer (SWIPT), amplify-and-forward (AF), orthogonal frequency division multiplexing (OFDM), coordinated direct and relay transmission (CDRT), decode-and-forward (DF), additive white Gaussian noise (AWGN), base station (BS), internet of things (IoT), multiple-input multiple-output (MIMO).

**Availability of data and materials**
The authors declare that all the data and materials in this manuscript are available.

**Competing interests**
The authors declare that they have no competing interests.

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**Authors’ contributions**
W. Duan, J. Ju and G. Zhang conceived and designed the study. W. Duan, Y. Ji, and Q. Sun performed the simulations. W. Duan and Z. Wang wrote the paper. J. Ju, G. Zhang, Z. Wang, Y. Ji and Q. Sun reviewed and edited the manuscript. All authors read and approved the manuscript.

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