Full-Duplex Device-to-Device Aided Cooperative Non-Orthogonal Multiple Access

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***Abstract*—This paper presents a full-duplex device-to-device (D2D) aided cooperative non-orthogonal multiple access (NOMA) scheme to improve the outage performance of the NOMA-weak user in a NOMA user pair, where the NOMA-weak user is helped by the NOMA-strong user with the capability of full-duplex D2D communications. The expressions for the outage probability are derived to characterize the performance of the proposed scheme. The results show that the proposed cooperative NOMA scheme can achieve superior outage performance compared to the conventional NOMA and orthogonal multiple access (OMA). In order to further improve the outage performance, an adaptive multiple access (AMA) scheme is also studied, which dynamically switches between the proposed cooperative NOMA, conventional NOMA, and OMA schemes, according to the level of residual self-interference and the quality of links. The results show that the AMA scheme can achieve the best outage performance.**

***Index Terms*—Cooperative non-orthogonal multiple access, full-duplex, device-to-device communications, 5G systems.**

I. Introduction

NON-orthogonal multiple access (NOMA) has recently attracted significant attention both in academia and industry as a promising candidate technology in the fifth-generation (5G) wireless networks [1], [2] and has already been introduced to 4G long term evolution-advanced (LTE-Advanced) systems as multiuser superposition transmission (MUST) [3] to improve the downlink performance, due to its higher spectrum efficiency than traditional orthogonal multiple access (OMA). In order to further improve the performance of NOMA, recently cooperative NOMA (C-NOMA) schemes have attracted some attentions. In [4], the authors proposed a half-duplex user-aided N-timeslot cooperative NOMA scheme and the results show that the proposed cooperative NOMA scheme could improve the outage probability, due to the achievement of the maximum diversity gain. In [5], a novel cooperative simultaneous wireless information and power transfer (SWIPT) NOMA protocol was proposed, in which the NOMA-strong users that were close to the source act as energy harvesting relays to help the NOMA-weak users. In [6], the application of NOMA to the coordinated multiple points (CoMP) systems was studied. In [7], a cooperative beamforming NOMA scheme was proposed, which employed intra-beam superposition coding of a multiuser signal at the transmitter and the spatial filtering of inter-beam interference followed by the intra-beam successive interference cancellation (SIC) at the terminal receiver. In addition, the performance of NOMA for relaying networks was also investigated [8], [9].

Device-to-device (D2D) communications enable the direct communications between users [10] and D2D users can also play as relays to cooperate data transmission, which can improve the system performance by sharing with the bandwidth used by cellular base stations (BSs). With the help of full-duplex radio [11], full-duplex D2D communications can further improve the system performance in heterogeneous networks [12].

In order to further improve the outage performance of the NOMA-weak user[1] in a user pair and reduce cooperative delay, in this paper, we focus on full-duplex D2D-aided cooperative NOMA, in which the user pair is predefined and configured and the NOMA-strong user has the capability of full-duplex D2D communications. With the help of full-duplex operation, the NOMA-strong user can receive data from the BS and forward the data to the NOMA-weak user over the same carrier frequency, simultaneously. Compared to the existed works, the contributions of this paper are summarized as follows.

- We present a full-duplex D2D-aided cooperative NOMA scheme to improve the transmission reliability of the NOMA-weak user, in which the NOMA-weak user is cooperated by the NOMA-strong user with the capability of full-duplex D2D communications.
- We analyze the outage performance and derive the expressions for the proposed full-duplex D2D-aided cooperative NOMA scheme.
- We also investigate the impact of the full-duplex mode and cooperation on the outage performance, and further study an adaptive multiple access (AMA) scheme to

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[1]Note that for the two users that are served in NOMA, the user with a higher signal-to-interference-plus-noise ratio (SINR) is considered as the NOMA-strong user, while the user with a lower SINR is considered as the NOMA-weak user.

improve the outage performance, which enables the BS to dynamically choose a proper multiple access mode among the proposed cooperative NOMA, conventional NOMA, and OMA schemes, according to the level of residual self-interference[2] and the quality of channels.

II. System Model

Fig. 1 illustrates the system model of full-duplex D2D-aided cooperative NOMA, which consists of one BS, one NOMA-strong user having the capability of the full-duplex D2D communications, UE1, and one NOMA-weak user, UE2. The BS transmits a superposed signal $x = \sqrt{P_{3,1}}x_1 + \sqrt{P_{3,2}}x_2$ to a pre-defined NOMA user pair, based on statistical channel state information (CSI), where $E[|x_i|^2] = 1, i = 1, 2$, $P_{3,1} = \alpha P_3$, and $P_{3,2} = (1-\alpha)P_3$. It holds that $P_{3,1} = \alpha P_3$ and $P_{3,2} = (1-\alpha)P_3$, where P_3 is the total transmit power at the BS; $\alpha \in (0,\ 1)$ is the power allocation factor. In general, in order to ensure the performance of NOMA systems, the NOMA-strong user is allocated less power than the NOMA-weak user. Consequently the power allocation factor α can be further limited to (0, 0.5). The NOMA-strong user forwards x_2 to the NOMA-weak user with transmit power P_1. The optimal order for decoding in downlink is the increasing order of channel gain normalized by noise and interference power. Similar to [4], full-duplex D2D-aided cooperative NOMA still consists of direct transmission and cooperative phases. Due to the NOMA-strong user working in the full-duplex mode, the direct transmission phase and cooperative phase can be performed simultaneously. In the direct transmission phase, UE1 first decodes and cancels UE2's signal by SIC before decoding its own data. In the cooperative phase, UE1 forwards the decoded data x_2 to UE2, then UE2 combines and decodes the signals from the BS and UE1. Since the NOMA-strong user, UE1, works in the full-duplex mode, it suffers from residual self-interference, which is caused by co-channel transmission and imperfect interference cancellation.

The involved channels are BS→UE1, BS→UE2, UE1→UE1, and UE1→UE2, whose channel coefficients are denoted as h_1, h_2, $h_{1,1}$, and h_3[3], respectively. Channels BS→UE1, BS→UE2, and UE1→UE2 are subjected to Rayleigh fading, while the residual self-interference channel UE1→UE1 is assumed to be free of fading.

III. Performance Analysis

A. Full-Duplex D2D-Aided Cooperative NOMA

In the k-th time slot, $k = 1, 2, 3, \ldots$, the BS transmits a superposed signal with different powers to two users and is [1]

$$x[k] = \sqrt{P_{3,1}}x_1[k] + \sqrt{P_{3,2}}x_2[k]. \tag{1}$$

[2]Self-interference refers to the signals that are transmitted by a full-duplex node and looped back to the receiver simultaneously. Through multi-stage self-interference cancellation technologies, including antenna cancellation, radio frequency (RF) and digital interference cancellation [11], those strong loop signals can be suppressed to a low level. However, loop back signals still remain in the receiver due to imperfect interference cancellation, and are considered as interference, when decoding the desired data.

[3]Note that in this paper, we focus on the improvement of the performance by virtue of cooperation in NOMA systems. We assume that sophisticated channel estimation algorithms have been used with sufficient training information to obtain perfect CSI.

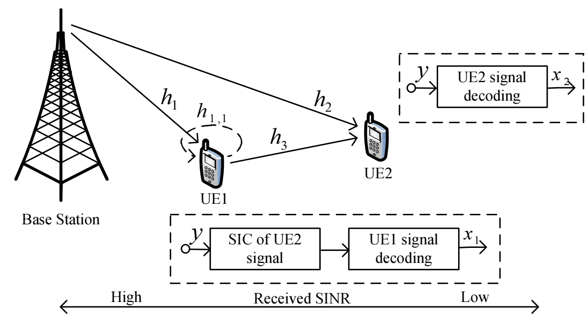


Fig. 1. System model of full-duplex D2D-aided cooperative NOMA

The NOMA-strong user, UE1, receives downlink signal from the based station and residual self-interference due to its co-channel transmission, thus, its received signal is represented as

$$y_1[k] = h_1[k](\sqrt{P_{3,1}}x_1[k]+\sqrt{P_{3,2}}x_2[k])+h_{1,1}[k]\sqrt{P_1}s[k]+n_1[k], \tag{2}$$

where $s(k)$ is the transmit signal to UE2 and $E[|s(k)|^2] = 1$; $n_i \sim \mathcal{CN}(0,\ \sigma_i^2)$ is the additive white Gaussian noise (AWGN) at UE$i, i = 1, 2$. The NOMA-strong user, UE1, first decodes UE2's data, x_2, then cancels it from the received signal and detects its own data. Therefore, the received SINR that UE1 detects UE2's data, x_2, is given by

$$\gamma_{1,2} = \frac{|h_1|^2 P_{3,2}}{|h_1|^2 P_{3,1} + |h_{1,1}|^2 P_1 + \sigma_1^2} = \frac{(1-\alpha)|h_1|^2 P_3}{\alpha |h_1|^2 P_3 + |h_{1,1}|^2 P_1 + \sigma_1^2}. \tag{3}$$

The received SINR at UE1 to detect its own information is

$$\gamma_{1,1} = \frac{|h_1|^2 P_{3,1}}{|h_{1,1}|^2 P_1 + \sigma_1^2} = \frac{\alpha |h_1|^2 P_3}{|h_{1,1}|^2 P_1 + \sigma_1^2}. \tag{4}$$

The NOMA-strong user, UE1, decodes and forwards the data, x_2, to the NOMA-weak user, UE2, thus a processing delay, τ, is introduced, which is assumed to be one without loss of generality. The NOMA-weak user, UE2, receives both downlink signal from the BS and signal forwarded by UE1, which is expressed as

$$\begin{aligned} y_2[k] =& h_2[k](\sqrt{P_{3,1}}x_1[k] + \sqrt{P_{3,2}}x_2[k]) \\ &+ h_3[k]\sqrt{P_1}x_2[k-\tau] + n_2[k], \end{aligned} \tag{5}$$

where P_1 is the transmit power of UE1. We assume that the two signals from the BS and UE1 are fully resolvable at UE2, so that they can be appropriately co-phased and merged by maximal ratio combining (MRC). Therefore, the received SINR at UE2 to detect information from the BS is expressed as

$$\gamma_{2,2} = \frac{|h_2|^2 P_{3,2}}{|h_2|^2 P_{3,1} + \sigma_2^2} = \frac{(1-\alpha)|h_2|^2 P_3}{\alpha |h_2|^2 P_3 + \sigma_2^2}. \tag{6}$$

The received SINR at UE2 to detect information forwarded from UE1 is written as

$$\gamma_{2,1} = \frac{|h_3|^2 P_1}{\sigma_2^2}. \tag{7}$$

Therefore, the overall SINR received at UE2 after MRC is

$$\gamma_{2,MRC} = \gamma_{2,2} + \gamma_{2,1} = \frac{(1-\alpha)|h_2|^2 P_3}{\alpha |h_2|^2 P_3 + \sigma_2^2} + \frac{|h_3|^2 P_1}{\sigma_2^2}. \tag{8}$$

Outage probability is an important metric to characterize the systems, which is defined as the probability that the data rate supported by the instantaneous channel conditions is below a target rate, R_{th}. We first define the following outage events: $E_{i,j}^{m} = \{\gamma_{i,j}^{m} < \gamma_{T1}\}, i,j = 1,2$ and $m = 1,2,3$, which means that the outage occurs when the i-th user detects the signal of the j-th user or the i-th user detects the signal forwarded by the j-th user under the m-th multiple access scheme, where $m = 1,2,3$ donate the proposed cooperative NOMA, conventional NOMA and OMA schemes, respectively. In addition, we also define the outage event as $E_{2,MRC}^{1} = \{\gamma_{2,MRC}^{1} < \gamma_{T1}\} = \{\gamma_{2,2}^{1} + \gamma_{2,1}^{1} < \gamma_{T1}\}$. $\bar{E}_{i,j}^{m}$ is the complementary set of $E_{i,j}^{m}$.

As defined in [5], the outage event of the NOMA-weak user is $\{E_2^1 : (\bar{E}_{1,2}^1 \cap E_{2,MRC}^1) \cup (E_{1,2}^1 \cap E_{2,2}^1)\}$. As a result, the outage probability of the NOMA-weak user is

$$\begin{aligned} P_{out,2}^{CNOMA} =& Pr(E_2^1) = Pr(\bar{E}_{1,2}^1 \cap E_{2,MRC}^1) + Pr(E_{1,2}^1 \cap E_{2,2}^1) \\ =& (1 - Pr(E_{1,2}^1)) Pr(E_{2,MRC}^1) + Pr(E_{1,2}^1) Pr(E_{2,2}^1). \end{aligned} \tag{9}$$

Note that $\gamma_{T1} = 2^{R_T} - 1$ is the threshold to detect the signals of UE1 and UE2 in full-duplex D2D-aided cooperative NOMA, while $\gamma_{T2} = 2^{2R_T} - 1$ is for OMA because two time slots are allocated to the two users.

In order to assist the derivation, we define random variables (RVs) $X = |h_1|^2 P_3/\sigma_1^2$, $Y = |h_2|^2 P_3/\sigma_2^2$, $W = |h_3|^2 P_1/\sigma_2^2$, and constant $A = \bar{\gamma}_{SI} = |h_{1,1}|^2 P_1/\sigma_1^2$. Considering Rayleigh fading, it holds that $X \sim Exp(1/\bar{\gamma}_1)$, $Y \sim Exp(1/\bar{\gamma}_2)$, and $W \sim Exp(1/\bar{\gamma}_3)$, where $\bar{\gamma}_1 = \epsilon\{|h_1|^2\} P_3/\sigma_1^2$, $\bar{\gamma}_2 = \epsilon\{|h_2|^2\} P_3/\sigma_2^2$, $\bar{\gamma}_3 = \epsilon\{|h_3|^2\} P_1/\sigma_2^2$, and $\epsilon\{\cdot\}$ denotes expectation.

In downlink NOMA, the maximum SINR to detect the NOMA-weak user is limited, which can be obtained by the lim operation and is $\lim_{X\to\infty} \frac{(1-\alpha)X}{\alpha X + A + 1} = \frac{1-\alpha}{\alpha}$. For the outage event, $E_{1,2}^1$, when $\gamma_{T1} \geq \frac{1-\alpha}{\alpha}$, the probability of the event, $E_{1,2}^1$, is $Pr(E_{1,2}^1) = 1$; when $0 < \gamma_{T1} < \frac{1-\alpha}{\alpha}$, we have

$$\begin{aligned} Pr(E_{1,2}^1) =& Pr\left(\frac{(1-\alpha)X}{\alpha X + A + 1} < \gamma_{T1}\right) \\ =& \int_0^{\frac{\gamma_{T1}(A+1)}{(1-\alpha-\alpha\gamma_{T1})}} \frac{1}{\bar{\gamma}_1} e^{-\frac{x}{\bar{\gamma}_1}} dx = 1 - e^{-\frac{\gamma_{T1}(\bar{\gamma}_{SI}+1)}{(1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_1}}. \end{aligned} \tag{10}$$

Therefore, the probability of the event, $E_{1,2}^1$, can be written as

$$Pr(E_{1,2}^1) = \begin{cases} 1, & \gamma_{T1} \geq \frac{1-\alpha}{\alpha}, \\ 1 - e^{-\frac{\gamma_{T1}(A+1)}{(1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_1}}, & 0 < \gamma_{T1} < \frac{1-\alpha}{\alpha}. \end{cases} \tag{11}$$

Similar to derive the probability of the event, $E_{1,2}^1$, the probability of the event, $E_{2,2}^1$, can be solved, through replacing $A+1$ with 1 in (11) and can be expressed as

$$\begin{aligned} Pr(E_{2,2}^1) =& Pr\left(\frac{(1-\alpha)Y}{\alpha Y + 1} < \gamma_{T1}\right) \\ =& \begin{cases} 1, & \gamma_{T1} \geq \frac{1-\alpha}{\alpha}, \\ 1 - e^{-\frac{\gamma_{T1}}{(1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_2}}, & 0 < \gamma_{T1} < \frac{1-\alpha}{\alpha}. \end{cases} \end{aligned} \tag{12}$$

Let $V = \gamma_{2,2} = \frac{(1-\alpha)Y}{\alpha Y + 1}$, then $Z = \gamma_{2,MRC} = V + W$. The probability of outage event, $E_{2,MRC}^1$, can be expressed as $Pr\{E_{2,MRC}^1\} = Pr\{V + W < \gamma_{T1}\}$. When $0 < \gamma_{T1} < \frac{1-\alpha}{\alpha}$, the integral domain is $D = \{(v,\ w) \mid 0 < v < \gamma_{T1},\ 0 < w < \gamma_{T1} - v\}$. When $\gamma_{T1} \geq \frac{1-\alpha}{\alpha}$, the integral domain is $D = \{(v,\ w) \mid 0 < v < \frac{1-\alpha}{\alpha},\ 0 < w < \gamma_{T1} - v\}$. As a result, the probability can be solved as

$$\begin{aligned} Pr\{E_{2,MRC}^1\} =& \iint_{v+w \leq \gamma_{T1}} f_V(v) f_W(w) dv dw \\ =& \begin{cases} 1 - e^{-\frac{\gamma_{T1}}{\bar{\gamma}_3}} \left(1 - e^{-\frac{1-\alpha}{\alpha\bar{\gamma}_3}} - \frac{1-\alpha}{\alpha\bar{\gamma}_3} e^{\frac{\bar{\gamma}_2(1-\alpha)+\bar{\gamma}_3}{\alpha\bar{\gamma}_2\bar{\gamma}_3}} I\left(\frac{1-\alpha}{\alpha\bar{\gamma}_3}, \frac{1}{\alpha\bar{\gamma}_2}, 0\right)\right), \\ \qquad \gamma_{T1} \geq \frac{1-\alpha}{\alpha}, \\ 1 - e^{-\frac{\gamma_{T1}}{\bar{\gamma}_3}} \left(1 - \frac{1-\alpha}{\alpha\bar{\gamma}_3} e^{\frac{\bar{\gamma}_2(1-\alpha)+\bar{\gamma}_3}{\alpha\bar{\gamma}_2\bar{\gamma}_3}} I\left(\frac{1-\alpha}{\alpha\bar{\gamma}_3}, \frac{1}{\alpha\bar{\gamma}_2}, 1 - \frac{\alpha\gamma_{T1}}{1-\alpha}\right)\right), \\ \qquad 0 < \gamma_{T1} < \frac{1-\alpha}{\alpha}, \end{cases} \end{aligned} \tag{13}$$

where $I(a,b,p) = \int_1^p e^{-(at+\frac{b}{t})} dt$.

Substituting (11), (12), and (13) into (9) and after simplification, the outage probability of the NOMA-weak user can be expressed as

$$P_{out,2}^{CNOMA} = \begin{cases} 1, & \gamma_{T1} \geq \frac{1-\alpha}{\alpha}, \\ 1 + e^{-\frac{\gamma_{T1}(\bar{\gamma}_1 + (\bar{\gamma}_{SI}+1)\bar{\gamma}_2)}{(1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_1\bar{\gamma}_2}} - e^{-\frac{\gamma_{T1}}{(1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_2}} \\ -e^{-\frac{\gamma_{T1}((1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_1 + (\bar{\gamma}_{SI}+1)\bar{\gamma}_3)}{(1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_1\bar{\gamma}_3}} \Big(1 - \frac{1-\alpha}{\alpha\bar{\gamma}_3} e^{\frac{\bar{\gamma}_2(1-\alpha)+\bar{\gamma}_3}{\alpha\bar{\gamma}_2\bar{\gamma}_3}} \\ \times I\left(\frac{1-\alpha}{\alpha\bar{\gamma}_3}, \frac{1}{\alpha\bar{\gamma}_2}, \frac{1-\alpha-\alpha\gamma_{T1}}{1-\alpha}\right)\Big), & 0 < \gamma_{T1} < \frac{1-\alpha}{\alpha}. \end{cases} \tag{14}$$

Note that when $\bar{\gamma}_{SI} = 0$ and removing terms related with forwarding link $\bar{\gamma}_3$, full-duplex D2D-aided cooperative NOMA degrades to the conventional NOMA. Thus, the outage probability of the NOMA-weak user in the conventional NOMA is equal to the probability of the event, $E_{2,2}^1$. According to (12), the outage probability of the NOMA-weak user in the conventional NOMA can be written as

$$P_{out,2}^{NOMA} = \begin{cases} 1, & \gamma_{T1} \geq \frac{1-\alpha}{\alpha}, \\ 1 - e^{-\frac{\gamma_{T1}}{(1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_2}}, & 0 < \gamma_{T1} < \frac{1-\alpha}{\alpha}. \end{cases} \tag{15}$$

For OMA, the instantaneous SINR received at the NOMA-weak user is expressed as

$$\gamma_{2,OMA} = \frac{|h_2|^2 P_3}{\sigma_2^2}. \tag{16}$$

Thus, the outage probability of the NOMA-weak user can be solved as

$$P_{out,2}^{OMA} = Pr\{E_{2,2}^3\} = \int_0^{\gamma_{T2}} \frac{1}{\bar{\gamma}_2} e^{-\frac{y}{\bar{\gamma}_2}} dy = 1 - e^{-\frac{\gamma_{T2}}{\bar{\gamma}_2}}. \tag{17}$$

B. Adaptive Multiple Access Scheme

According to (14), (15), and (17), there is a tradeoff among the proposed cooperative NOMA, conventional NOMA, and OMA schemes in terms of outage performance. In order to further improve the outage performance, we study an AMA scheme, which dynamically switches to a proper multiple access scheme by the quality of channels. The resulting outage probability of the NOMA-weak user is given by

$$P_{out,2}^{AMA} = Pr(E_2^{CNOMA} \cap E_2^{NOMA} \cap E_2^{OMA}). \tag{18}$$

Based on $E_{2,2}^{NOMA}=E_{2,2}^{CNOMA}=E_{2,2}$, (18) can be further simplified as

$$\begin{aligned}P_{out,2}^{AMA} =&Pr(E_{2,2}^{OMA}\cap E_{2,2}^{NOMA}\cap((\bar{E}_{1,2}^{CNOMA}\cap E_{2,MRC}^{CNOMA})\\&\cup(E_{1,2}^{CNOMA}\cap E_{2,2}^{CNOMA})))\\=&Pr(\bar{E}_{1,2}^{CNOMA})Pr(E_{2,2}^{OMA}\cap E_{2,MRC}^{CNOMA})\\&+Pr(E_{1,2}^{CNOMA})Pr(E_{2,2}^{OMA}\cap E_{2,2}).\end{aligned} \tag{19}$$

For the probability, $Pr(E_{1,2}^{CNOMA})Pr(E_{2,2}^{OMA}\cap E_{2,2})$, the integral domain of the event, $E_{2,2}$, is $\{y<\frac{\gamma_{T1}}{1-\alpha-\alpha\gamma_{T1}}\}$, while the integral domain of the event, $E_{2,2}^{OMA}$, is $\{y<\gamma_{T2}\}$. When $\gamma_{T1}\geq\frac{1-\alpha}{\alpha}$, the probability of the event, $E_{2,2}$, is equal to one, thus $Pr(E_{2,2}^{OMA}\cap E_{2,2})=Pr(E_{2,2}^{OMA})$. Furthermore, if $\gamma_{T2}>\frac{\gamma_{T1}}{1-\alpha-\alpha\gamma_{T1}}$ under the condition $\gamma_{T1}<\frac{1-\alpha}{\alpha}$, the probability of the event, $E_{2,2}^{OMA}\cap E_{2,2}$, is, $Pr(E_{2,2}^{OMA}\cap E_{2,2})=Pr(E_{2,2})$, otherwise its probability is, $Pr(E_{2,2}^{OMA}\cap E_{2,2})=Pr(E_{2,2}^{OMA})$. To sum up, we have

$$\begin{aligned}&Pr(E_{2,2}^{OMA}\cap E_{2,2})\\&=\begin{cases}Pr(E_{2,2}), & \gamma_{T1}<\frac{1-\alpha}{\alpha}\ and\ \gamma_{T2}>\frac{\gamma_{T1}}{1-\alpha-\alpha\gamma_{T1}},\\ Pr(E_{2,2}^{OMA}), & others.\end{cases}\end{aligned} \tag{20}$$

Next, we derive the probability of event, $\{E_{2,2}^{OMA}\cap E_{2,MRC}^{CNOMA}\}$. When $\gamma_{T1}\geq\frac{1-\alpha}{\alpha}$, its integral domain is $D1=\{(x,\ y)\mid 0<x<\gamma_{T2},\ 0<y<\frac{(\alpha\gamma_{T1}+\alpha-1)x+\gamma_{T1}}{\alpha x+1}\}$. When $\gamma_{T1}<\frac{1-\alpha}{\alpha}$ and $\gamma_{T2}\leq\frac{\gamma_{T1}}{1-\alpha-\alpha\gamma_{T1}}$, the integral has the same integral domain $D1$. When $\gamma_{T1}<\frac{1-\alpha}{\alpha}$ and $\gamma_{T2}>\frac{\gamma_{T1}}{1-\alpha-\alpha\gamma_{T1}}$, its integral domains are $D2=\{(x,\ y)\mid 0<x<\frac{\gamma_{T1}}{1-\alpha-\alpha\gamma_{T1}},\ 0<y<\frac{(\alpha\gamma_{T1}+\alpha-1)x+\gamma_{T1}}{\alpha x+1}\}$. After solving the integral, the probability can be written as

$$\begin{aligned}&Pr(E_{2,2}^{OMA}\cap E_{2,MRC}^{CNOMA})\\&=\begin{cases}1-e^{-\gamma_{T2}/\bar{\gamma}_2}-\frac{1}{\alpha\bar{\gamma}_2}e^{\frac{\bar{\gamma}_3-\bar{\gamma}_2(\alpha\gamma_{T1}+\alpha-1)}{\alpha\bar{\gamma}_2\bar{\gamma}_3}}I(\frac{1}{\alpha\bar{\gamma}_2},\frac{1-\alpha}{\alpha\bar{\gamma}_3},\alpha\gamma_{T2}+1),\\ \qquad\{\gamma_{T1}\geq\frac{1-\alpha}{\alpha}\}or\{\gamma_{T1}<\frac{1-\alpha}{\alpha},\gamma_{T2}\leq\frac{\gamma_{T1}}{1-\alpha-\alpha\gamma_{T1}}\},\\ 1-e^{-\frac{\gamma_{T1}}{(1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_2}}-\frac{1}{\alpha\bar{\gamma}_2}e^{\frac{\bar{\gamma}_3-\bar{\gamma}_2(\alpha\gamma_{T1}+\alpha-1)}{\alpha\bar{\gamma}_2\bar{\gamma}_3}}\\ \times I(\frac{1}{\alpha\bar{\gamma}_2},\frac{1-\alpha}{\alpha\bar{\gamma}_3},\frac{1-\alpha}{1-\alpha-\alpha\gamma_{T1}}),\ \{\gamma_{T1}<\frac{1-\alpha}{\alpha},\gamma_{T2}>\frac{\gamma_{T1}}{1-\alpha-\alpha\gamma_{T1}}\}.\end{cases}\end{aligned} \tag{21}$$

Substituting (11), (12), (17), (20), and (21) into (19), we obtain the outage probability of the NOMA-weak user in the adaptive multiple access scheme as in (22), shown at the top of the next page.

IV. Numerical Results

The numerical results for the outage probability of full-duplex D2D-aided cooperative NOMA scheme are presented, together with Monte Carlo simulations. All parameters referred to Monte Carlo simulations are summarized in Table I, including power allocation factor, α, outage threshold, R_{th}, average SINR threshold for user pairing[4], average SNR of cooperative channel, $\bar{\gamma}_3$, and residual self-interference. In Monte Carlo simulations, we first predefine a user pair (UE1, UE2) and fix a set of parameters: Power allocation factor, α, outage threshold, R_{th}, average SINR threshold for user pairing, average SNR of cooperative channel, $\bar{\gamma}_3$, and residual self-interference, then generate random numbers for channels $BS\rightarrow UE1$, $BS\rightarrow UE2$, and $UE1\rightarrow UE2$ with Rayleigh fading, next decide and collect statistics on the outage event, followed by calculating the statistical results. Through changing the parameters and repeating the above steps, the simulation results shown in Fig. 2 and Fig. 3 can be obtained.

TABLE I
Monte Carlo simulation parameters

Parameter	Value
Power allocation factor α	0.2, 0.4
Outage threshold R_{th}	0.5b/s/Hz, 1.0b/s/Hz
Average SINR threshold for user pairing	3dB, 6dB
Average SNR of cooperative channel $\bar{\gamma}_3$	1dB, 12dB
Residual self-interference	0dB, 3dB, 12dB

Fig. 2 depicts the outage probabilities of the AMA, full-duplex D2D-aided cooperative NOMA, conventional NOMA, and OMA schemes with power allocation factors, $\alpha=0.2$ and 0.4, $\bar{\gamma}_3=12$dB, and the SNR threshold for user pairing 6dB, under the threshold for outage, $R_{th}=0.5$b/s/Hz. The results show that the proposed full-duplex D2D-aided cooperative NOMA scheme can dramatically improve the outage performance of the NOMA-weak user with proper power allocation, when residual self-interference is below a certain level. With the increasing of residual self-interference and power allocated for the NOMA-strong user, the gain from the cooperation is gradually decreased. With more power allocated for the NOMA-strong user, the outage performance of NOMA is also gradually decreased. The results also show that the performance curve of the AMA scheme is almost overlapped with that of full-duplex D2D-aided cooperative NOMA. This is because the AMA scheme chooses the best multiple access scheme among cooperative NOMA, conventional NOMA, and OMA schemes dynamically, while the cooperative NOMA is absolutely dominant among these three scheme, under the parameters $\bar{\gamma}_3=12$ dB and the SNR threshold for user pairing 6 dB. Consequently, the AMA scheme nearly degrades to the cooperative NOMA.

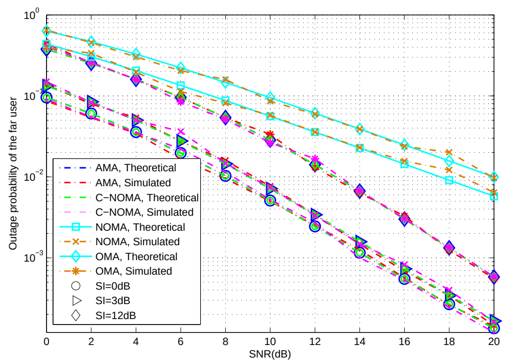
Fig. 3 illustrates the outage probabilities of the AMA, full-duplex D2D-aided cooperative NOMA, conventional NOMA, and OMA schemes with power allocation factor, $\alpha=0.4$, $\bar{\gamma}_3=1$dB, and the SNR threshold for user pairing 3dB, under the threshold for outage, $R_{th}=1.0$b/s/Hz. The results show that the AMA scheme can achieve superior outage performance to other multiple access schemes. Furthermore, Fig. 2 and Fig. 3 also reveal that the AMA scheme can achieve the best outage performance and an obvious gain, when there is no dominant multiple scheme. Conversely, it can still achieve the similar outage performance as the dominant multiple scheme, but no further gain.

V. Conclusions

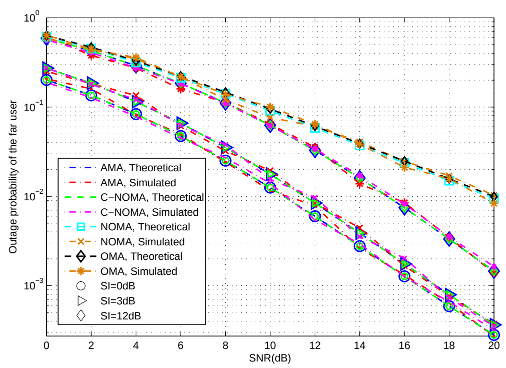
A full-duplex D2D-aided cooperative NOMA scheme is presented to improve the outage performance of the NOMA-weak

[4]The average SINR threshold for user pairing refers to the minimum SINR difference between the channels $BS\rightarrow UE1$ and $BS\rightarrow UE2$, which is used to decide whether those two user can form a user pair in downlink NOMA systems. If the SINR difference between the channels $BS\rightarrow UE1$ and $BS\rightarrow UE2$ is above this threshold, UE1 and UE2 can form a user pair.

$$P_{out,2}^{AMA} = \begin{cases} 1 - e^{-\gamma_{T2}/\bar{\gamma}_2}, \ \gamma_{T1} \geq \frac{1-\alpha}{\alpha}, \\ 1 - e^{-\frac{\gamma_{T1}}{(1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_2}} - \frac{1}{\alpha\bar{\gamma}_2} e^{-\frac{\gamma_{T1}(\bar{\gamma}_{SI}+1)}{(1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_1}} e^{\frac{\bar{\gamma}_3 - \bar{\gamma}_2(\alpha\gamma_{T1}+\alpha-1)}{\alpha\bar{\gamma}_2\bar{\gamma}_3}} I(\frac{1}{\alpha\bar{\gamma}_2}, \frac{1-\alpha}{\alpha\bar{\gamma}_3}, \frac{1-\alpha}{1-\alpha-\alpha\gamma_{T1}}), \ \gamma_{T1} < \frac{1-\alpha}{\alpha} \ and \ \gamma_{T2} > \frac{\gamma_{T1}}{1-\alpha-\alpha\gamma_{T1}}, \\ 1 - e^{-\frac{\gamma_{T2}}{\bar{\gamma}_2}} - \frac{1}{\alpha\bar{\gamma}_2} e^{-\frac{\gamma_{T1}(\bar{\gamma}_{SI}+1)}{(1-\alpha-\alpha\gamma_{T1})\bar{\gamma}_1}} e^{\frac{\bar{\gamma}_3 - \bar{\gamma}_2(\alpha\gamma_{T1}+\alpha-1)}{\alpha\bar{\gamma}_2\bar{\gamma}_3}} I(\frac{1}{\alpha\bar{\gamma}_2}, \frac{1-\alpha}{\alpha\bar{\gamma}_3}, \alpha\gamma_{T2}+1), \quad \gamma_{T1} < \frac{1-\alpha}{\alpha} \ and \ \gamma_{T2} \leq \frac{\gamma_{T1}}{1-\alpha-\alpha\gamma_{T1}}. \end{cases} \tag{22}$$



(a)



(b)

Fig. 2. Outage probability of the AMA, full-duplex D2D-aided cooperative NOMA, conventional NOMA, and OMA schemes under $\bar{\gamma}_3$ = 12dB and R_{th} = 0.5b/s/Hz. (a) $\alpha = 0.2$. (b) $\alpha = 0.4$

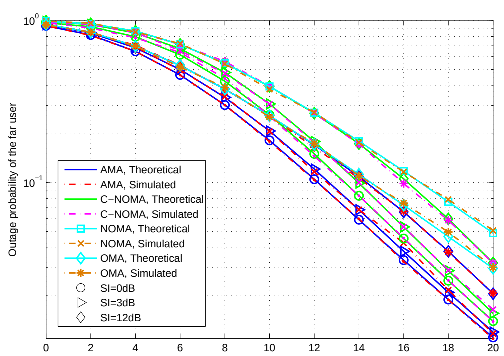


Fig. 3. Outage probability of the AMA, full-duplex D2D-aided cooperative NOMA, NOMA, and OMA schemes with $\alpha = 0.4$ and $\bar{\gamma}_3$ = 1dB under R_{th} = 1.0b/s/Hz

user in downlink NOMA systems. Expressions for the outage probability are derived, in order to evaluate the performance of the proposed cooperative NOMA. Numerical results and simulations are developed to demonstrate the performance gain of the cooperative NOMA scheme. In order to further improve outage performance, an AMA scheme is also studied, which dynamically switched to a proper multiple access scheme based on the level of residual self-interference and the quality of channels. The analytic and numerical results show that the AMA scheme can achieve the best outage performance and obtain an obvious gain, when there is no multiple access scheme with absolute advantage.

REFERENCES

[1] Y. Saito, A. Benjebbour, Y. Kishiyama, and T. Nakamura, "System level performance evaluation of downlink non-orthogonal multiple access (NOMA)," in *Proc. IEEE 24th Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2013, pp. 611-615.

[2] Z. Ma, Z. Zhang, Z. Ding, P. Fan and H. Li, "Key techniques for 5G wireless communications: Network architecture, physical layer, and MAC layer perspectives," *Sci. China Info. Sci.*, vol. 58, pp. 1-20, April 2015.

[3] *Study on Downlink Multiuser Superposition Transmission (MUST) for LTE*, 3GPP TR 36.859, Dec. 2015.

[4] Z. Ding, M. Peng, and H. V. Poor, "Cooperative non-orthogonal multiple access in 5G systems," *IEEE Commun. Lett.*, vol. 19, no. 8, pp. 1462-1465, Aug. 2015.

[5] Y. Liu, Z. Ding, M. Elkashlan, and H. V. Poor, "Cooperative non-orthogonal multiple access with simultaneous wireless information and power transfer," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 938-953, April 2016.

[6] J. Choi, "Non-orthogonal multiple access in downlink coordinated two-point systems," *IEEE Commun. Lett.*, vol. 18, no. 2, pp. 313-316, Feb. 2014.

[7] N. Nonaka, Y. Kishiyama, and K. Higuchi, "Non-orthogonal multiple access using intra-beam superposition coding and SIC in base station cooperative MIMO cellular downlink," in *Proc. IEEE 80th Veh. Technol. Conf. (VTC Fall)*, Sep. 2014, pp. 1-5.

[8] J. Kim and I. Lee, "Capacity analysis of cooperative relaying systems using non-orthogonal multiple access," *IEEE Commun. Lett.*, vol. 19, no. 11, pp. 1949-1952, Nov. 2015.

[9] J. Men and J. Ge, "Non-orthogonal multiple access for multiple-antenna relaying networks," *IEEE Commun. Lett.*, vol. 19, no. 10, pp. 1686-1689, Oct. 2015.

[10] M. N. Tehrani, M. Uysal, and H. Yanikomeroglu, "Device-to-device communication in 5G cellular networks: Challenges, solutions, and future directions," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 86-92, May 2014.

[11] J. I. Choiy, M. Jainy, K. Srinivasany, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proc. ACM Int. Conf. Mobile Comput. Netw. (MobiCom)*, Sep. 2010, pp. 1-12.

[12] L. Wang, F. Tian, T. Svensson, D. Feng, M. Song, and S. Li, "Exploiting full duplex for device-to-device communications in heterogeneous networks," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 146-152, May 2015.