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Partial cooperative NOMA for improving outage performance of edge users

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ABSTRACT

Providing reliable service to cell edge users has been a practical challenge for network operators due to the deep fading effects and limited base station (BS) resources. The low received signal strength causes the Quality of Service (QoS) degradation of the cell edge users and hence demands appropriate solutions to improve the user connectivity. To address this issue, this article proposes a two-tier partial cooperative relaying scheme, deployed in a non-orthogonal multiple access (NOMA)-based downlink network that serves the edge users with the minimum required QoS. Comparative performance analysis has been presented for two relaying schemes: amplify-and-forward (AF) and partial decode-and-forward (DF) in terms of outage probability and overall sum rate of the edge users. Additionally, the maximal ratio combining (MRC) diversity technique is integrated with the relaying network to further enhance the QoS of cell edge users. The impact of successive interference cancellation (SIC) on the outage performance has been thoroughly investigated. It has been established through extensive simulation that the partial DF technique is a promising relaying technique to improve the overall performance of cell edge users.

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Amplify-and-forward relay; partial decode-and-forward relay; non-orthogonal multiple access (NOMA); outage probability

1. Introduction

Non-orthogonal multiple access (NOMA) is envisioned as an emerging technology for fifth-generation (5 G) and beyond-5 G (B5 G) wireless communication systems as it has the capacity to provide massive connectivity with ultra-reliable low latency (URLL), increased spectral efficiency, and enhanced fairness (Dai et al., 2015; Liu et al. 2022). NOMA serves multiple users over the same time and same frequency band. Power domain NOMA (PD-NOMA) and code domain NOMA (CD-NOMA) are two primary classifications of NOMA Ding et al. (2017). In this paper, NOMA indicates the PD-NOMA. A transmitter broadcasts a superimposed signal comprising signals of all users, and receivers apply successive

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interference cancellation (SIC) process to decode their signals. The transmitter allocates more power to the users with weaker channel gain than the users with stronger channel gains qualities. As a consequence, fairness among the users is maintained Liu et al. (2017); Sharma et al. (2019). The researchers validated the superiority of NOMA over classical orthogonal multiple access (OMA) (Ding et al., (2017); Sharma et al., 2019).

Cooperative NOMA incorporating relaying is a popular approach to strengthen communication systems performance. Cooperative NOMA effectively combats channel impairments, like fading, path loss and shadowing, and therefore, efficiently can increase the coverage area Zeng et al. (2020). Amplify-and-forward (AF) and decode-and-forward (DF) are two well-known relay protocols. In AF relaying, the relay node re-transmits the received signal with a finite gain but without decoding. Whereas the received signal at the relay node first decoded and then re-transmitted towards the destinations. The performance of the AF and DF relay schemes in NOMA-based systems has been exploited in (Liu et al., 2016; Uddin et al., 2018).

1.1. Related works

Various approaches are found in the literature to coverage range and improve the QoS of the edge-users. In Men and Ge (2015), the authors have analysed a NOMA-based multiple-antenna AF relaying network to aid transmissions from base station (BS) to users, where they found the location of the relay node significantly impacts the system performance. The performance of a cooperative NOMA-based downlink AF relay system considering perfect and imperfect knowledge of channel state information (CSI) over the Nakagami-*m* fading channel has been analysed in Men et al. (2017); Yue et al. (2017). A joint NOMA and partial relay selection with AF relaying protocol has been investigated in Lee et al. (2016), where authors validated that partial relay selection scheme enhances the outage performance of the system. Recently, Anand et al. proposed a coordinated direct and relay transmission (CDRT) technique, where both the near-user and the far-user receive a direct link from BS Jee et al. (2021). The authors proposed a coordinated direct and half-duplex /full-duplex DF relay-based NOMA system to analyse the outage and sum-rate performance Pei et al. (2020). Analyzing the power distribution issue of cooperative NOMA systems with coordinated direct and DF relaying for enhancing the average throughput is the prime objective of Yuan et al. (2021).

The authors have deployed an unmanned aerial vehicle (UAV) as a DF relay node to extend the coverage of BS to cell edge user of a NOMA-based cellular network Zaidi et al. (2019). The NOMA principles with DF relay protocol has also been employed in an UAV-aided macrocell network to maximise the data rate of the cell edge users Zhai et al. (2021). A two-stage relay selection strategy for AF and DF relaying protocol-based NOMA also proposed to decrease outage probability Yang et al. (2017). The DF relay has been employed in NOMA systems with multiple antennas to enhance cell edge coverage Liu and Wang (2016). Misra *et al*. proposed a DF relay-aided dual-ordered NOMA transmission technique and analysed its performance considering outage, ergodic rate and fairness performance metrics Misra and Sarma (2020). The DF relay with maximum ratio combining (MRC) diversity schemes employed in NOMA system under imperfect CSI Mondal et al. (2022). However, the primary aim was to analyse the outage performance of multihop cognitive radio system. Considering a non-negligible direct link between BS and users, coordinated transmissions scheme significantly improve the performance of cooperative NOMA systems Kim and Lee (2015); Pei et al. (2020); Xu et al. (2021); Zhang et al. (2017). However, coordinated transmissions require side information for interference cancellation, which introduces huge overhead in cooperative NOMA systems. In Liu et al. (2018), authors have applied DF relaying in a NOMA-based system considering both the direct and relay links. However, the performance of the relay-assisted users only has been analysed. The performance of whole system including the users located in the close vicinity of BS has not been also analysed in Fang et al. (2020); Misra and Sarma (2020).

Motivated by the aforementioned literature, we consider a partial decode-and-forward (DF) relay-enabled NOMA system with one BS and multiple users to improve the performance of edge users. In a partial DF relay scheme, the relay node decodes the received signal and then re-transmits only the signals of edge users following the NOMA principles. Unlike Jee et al. (2021) and Yuan et al. (2021), in our proposed method inner circle users do not receive signal from the relay node. The primary aim of citepei2020noma was to compare the performance between half-duplex NOMA and full-duplex NOMA. However, we present a comparative performance analysis between AF and DF relays. The performance of all users is analysed thoroughly with both the direct and relay links. However, the direct link between the BS and edge users may not be strong enough thus, a maximum ratio combining (MRC) diversity with relaying is adopted. The main contributions of this article are summarised as follows:

• An efficient partial relay scheme is proposed to fulfill the minimum QoS requirement of edge users of a NOMA-based system. A detailed performance comparison between AF relaying and partial DF relaying protocol in terms of the outage, overall system sum-rate, and user fairness has been presented.

• The MRC diversity technique has been incorporated in the AF and partial DF relay protocols to evaluate its capability in improving the outage performance and maintaining the fairness of users.

• A closed-form analytical expression of outage probability for both types of users applying DF relaying has been derived and validated with the simulation.

• The impact of imperfect SIC on the performance of the users of relay-based NOMA systems has been investigated. Finally, simulation results are presented to validate the theoretical analysis.

The rest of the article is organised as follows; Section 2 presents a cooperative relay-aided downlink NOMA system and its operations. Section 3 analyses the AF and partial DF relay schemes along with the MRC diversity technique. The simulation results with the detailed analysis are presented in section 4. Finally, section 5 concludes the research works.

2. System model

Consider a downlink cooperative NOMA system, as shown in Figure 1, where a base station (BS) aiming to serve a total of N, $(D_1, D_2, \ldots, D_N)$ users located under its coverage area, which is divided into two regions, inner-tier and outer-tier. It is assumed that out of $N = (L + M)$ users, L users, located near BS in the inner-tier receive strong signals from BS, and the remaining M users, located far from BS in the outer-tier may receive weak signals from BS. The BS, relay node, and users are equipped with a single antenna and operated

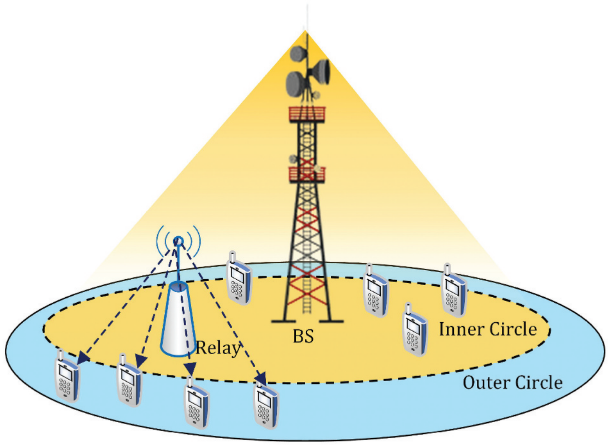

Figure 1. Two-tier partial cooperative NOMA. The BS transmits downlink signal directly to the inner-tier users, and the users located in the outer-tier only receive strong downlink signal via relay.

following half-duplex protocol. The BS directly communicates with L cell centre users, but indirectly with M cell edge users via a relay node. The inner-tier and outer tier users symbolically identified by $\mathcal{L} = \{\infty, \in, \ldots, \mathcal{L}\}$, and $\mathcal{M} = \{\mathcal{L} + \infty, \mathcal{L} + \in, \ldots, \mathcal{L} + \mathcal{M}\}$, respectively. Because of the deep fading and movement of users, the direct links between BS and outer-tier users may not be strong enough to meet the minimum QoS requirement of the outer-tier users.

The channel coefficient of BS-to-nth user, BS-to-relay and relay-to- nth users are denoted as h_{SD_n}, h_{SR}, and h_{RD_n}, $(n \in \mathcal{N} = \{1, 2, .., L, L+1, .., L+M\})$, respectively are assumed to be independent and identical complex Gaussian distributed random variables with zero means and λ_{SD}, λ_{SR}, and λ_{RD} variances. Without loss of generality, we assume $\lambda_{SD_1} < \lambda_{SD_2} \ldots < \lambda_{SD_L} < \lambda_{SR}$ and $\lambda_{RD_1} < \lambda_{RD_2} \ldots < \lambda_{RD_M}$ Wan et al. (2018). All the channels are modelled as block fading i.e. channels remain constant over a block time and can vary one block to another block. All the receiver experiences additive white Gaussian noise (AWGN) with zero means and N_0 variances $\mathcal{CN}(0, N_0)$. The availability of perfect instantaneous CSI at the transmitter is not a valid assumption in practice, particularly when users of systems like 5 G demand high mobile services. Unpredictable rapid movement of users frequently changes channel characteristics that make the perfect CSI estimation process challenging. The error in perfect channel estimation acts as a source of interference and degrades the overall system performance. The average sum rate, energy efficiency and the outage performance of the NOMA with perfect CSI always outperform NOMA with imperfect CSI Yang et al. (2016); Zamani et al. (2018). The The performance analysis under imperfect CSI is not the scope of this article. The symbols frequently used in the analysis are tabulated in Table 1.

The BS transmits signal during the first time slot, and relay node re-transmits received signal during second time slot. The BS broadcasts a superposed signal comprising signals for $(L+M)$ users during first time slot. The received signal at mth $(m \in \mathcal{N})$ destination during first time slot is given as

Table 1. List of important symbols.

Symbol	Description
L, M, N	Users in inner-tier, outer-tier, total in system
P_s, P_r	Transmit power of base station and relay
$\gamma_m^{(k)}$	SINR of kth signal at mth user
$\gamma_R^{(k)}$	SINR of kth signal at relay
$\gamma_{m,out}^{k}$	SINR of kth signal at mth user of outer tier
γ	Target SINR threshold
$\mathcal{O}_m^{AF}$	Outage probability of mth user for AF relay
$\mathcal{O}_m^{in}$	Outage probability of mth inner-tier user for partial DF relay
$\mathcal{O}_m^{ou}$	Outage probability of mth outer-tier user for partial DF relay

$$y_m = h_{SD_m} \sum_{m=1}^{L+M} \sqrt{a_m P_s} x_m + w_m, \qquad m \in \mathcal{N} \tag{1}$$

where P_s is the total transmit power of BS, a_m is the power allocation coefficient to mth destination such that $\sum_{m=1}^{N} a_m = 1$, $a_m > 0$, x_m is the normalised information signal broadcasted by BS i.e. $\mathbb{E}\{|x_m|^2\} = 1$, $\mathbb{E}\{.\}$ and $|.|$ denote expectation operator and absolute value respectively, and w_m is the baseband AWGN received at user end due to RF to baseband frequency conversion. According to the NOMA principle, the transmitter allocates higher power to the weaker user than the stronger user. The user ordering (strong or weak) depends on their average channel gains. The total available power is quantised into $(L + M)$ levels such a way that $a_1 < a_2 < \ldots < a_{L+M}$. The a_1 corresponds to the power of strongest user, and a_{L+M} corresponds to the power of weakest user. The generalised power allocation coefficient is expressed as $a_m = (L + M - m + 1)\Omega$, $\Omega = \frac{2}{(L+M)(L+M+1)}$ Mondal et al. (2020).

The receivers apply SIC process to decode its own signal. The mth user needs to decode the signals intended for ith user (which is weaker than mth user) in a successive manner. The mth user treats signals intended for weaker (ith) user as an interference. It is very challenging to design an ideal SIC decoder due to practical limitations, and the SIC process mostly impacted by residual power of the previous signals Thapar et al. (2021). The residual interference after SIC is represented by ζ $(0 \leq \zeta \leq 1)$, where $\zeta = 0$ and $\zeta = 1$ denote perfect SIC and complete unsuccessful SIC respectively. The imperfect SIC will affect all the received signals except signal with maximum power. $\gamma_m^{(k)}$, the received SINR of kth signal at mth user ($k, m \in \mathcal{M}, \mathcal{L},\ \| \leq \Updownarrow$) during the first time slot is given as

$$\gamma_m^{(k)} = \begin{cases} \dfrac{a_k \rho_s |h_{SD_m}|^2}{\rho_s |h_{SD_m}|^2 \sum\limits_{j=2}^{L+M} a_j + 1}, & k = 1 \\ \dfrac{a_k \rho_s |h_{SD_m}|^2}{\rho_s |g_{SD_m}|^2 \sum\limits_{j=1}^{k-1} a_j + \rho_s |h_{SD_m}|^2 \sum\limits_{j=k+1}^{L+M} a_j + 1}, & k \neq 1, N \\ \dfrac{a_k \rho_s |h_{SD_m}|^2}{\rho_s |g_{SD_m}|^2 \sum\limits_{j=1}^{L+M-1} a_j + 1}, & k = N \end{cases} \tag{2}$$

where $\rho_s = \frac{P_s}{N_0}$ and the residual interference is modelled as $g_{SD_m} \sim \mathcal{CN}(0, \zeta\lambda)$ Do and Nguyen (2019). In this paper, *first user* (or signal) indicates the weakest user (or signal), and *preceding signals* indicate the signals that are weaker than the present signal.

To understand the SIC decoding process and (2), let's consider a system with 8 users where, u_1, u_2, u_3 are in outer circle and $u_4, u_5, \ldots, u_8$ are in inner circle. Assume u_1 is the weakest and u_8 is the strongest user. u_1 decodes its signal using first part of (2) and considering other signals as an interference. However, others users, let us u_5 needs to decode all the preceding signals of u_1, u_2, u_3 and u_4 for decoding own signal. The u_5 first decodes signal of u_1 $(k = 1)$ using first part of (2), then decodes signals of u_2 $(k = 2), u_3$ $(k = 3)$, u_4 $(k = 4)$ using second part of (2), and finally own signal using second part of (2). The u_5 experiences residual interference after SIC from u_1, u_2, u_3 and u_4 due to imperfect SIC process. The strongest user u_8 decodes own signal using third part of (2), and experiences residual interference from all the preceding signals due to imperfect SIC process.

The edge users, as the direct links from BS to edge users are not strong enough, receive a copy of BS transmitted signal from the relay node. During the first time slot, the relay node receives a superposed signal of N users from BS which is given as follows:

$$y_R = h_{SR} \sum_{m=1}^{L+M} \sqrt{\alpha_m P_s} x_m + w_R \tag{3}$$

where w_R is the baseband AWGN received at the relay node along with RF to baseband frequency conversion noise. The relay node re-transmits y_R based on the relay protocol. In AF relaying, relay node amplifies y_R and forwards it. In partial DF, relay node first decodes the signals of outer-tier users from y_R then transmits a superimposed signal comprising only the signals of outer-tier users.

3. Cooperative relay schemes

Two types of NOMA cooperative transmission techniques are taken into account to analyse the performance of the edge users and overall system; Full cooperative AF relay scheme and Partial cooperative partial DF relay scheme.

3.1. Full cooperative AF relay transmission

In AF relaying protocol, received superimposed signal is first amplified and then forwarded towards the destination. In cooperative AF relay transmission, all the users, irrespective of outer and inner tier, receive second copy of their signals from the relay node during second transmission slot. The BS transmits a superimpose signal comprising signals of all users, and the relay amplifies the received signal with an amplification gain of G and forwards it to all users. Let P_s and P_r be the transmit power of BS and relay, respectively. The gain of AF relay can be expressed as Yue et al. (2017)

$$G = \sqrt{\frac{P_r}{P_s |h_{SR}|^2 + N_0}} \tag{4}$$

The received signal at mth ($m \in \mathcal{L}, \mathcal{M}$) user during second transmission phase is expressed as follows:

$$y_m^{AF} = Gh_{SR}h_{SD_m}\sum_{m=1}^{L+M}\sqrt{a_m P_s}x_m + Gh_{SR}w_R + w_m \tag{5}$$

The received SINR of kth signal using AF relaying at mth user ($k, m \in \mathcal{M}, \mathcal{L},\ \| \leq \Updownarrow$) during full cooperative is given as follows:

$$\gamma_m^{(k),AF} = \begin{cases} \dfrac{a_k \rho_s |h_{SR}|^2 \rho_r |h_{RD_m}|^2}{\rho_s |h_{SR}|^2 \rho_r |h_{RD_m}|^2 \sum\limits_{j=k+1}^{L+M} a_j + \psi + 1}, & k = 1 \\ \dfrac{a_k \rho_s |h_{SR}|^2 \rho_r |h_{RD_p}|^2}{\rho_r \rho_s |g_{SRD}|^2 \sum\limits_{j=1}^{k-1} a_j + \rho_s |h_{SR}|^2 \rho_r |h_{RD_m}|^2 \sum\limits_{j=k+1}^{L+M} a_j + \psi + 1}, & k \neq 1, N \\ \dfrac{a_k \rho_s |h_{SR}|^2 \rho_r |h_{RD_m}|^2}{\rho_r \rho_s |g_{SRD}|^2 \sum\limits_{j=1}^{k-1} a_j + \psi + 1} & k = N \end{cases} \tag{6}$$

where $\psi = \rho_s |h_{SR}|^2 + \rho_r |h_{RD_m}|^2$. The residual interference introduced by the previously decoded signal due to imperfect SIC process is modelled as $g_{SRD} \sim \mathcal{CN}(0, \zeta\lambda)$. A user receives own signal during first transmission slot from BS and also during second transmission slot from relay. The users apply MRC diversity technique considering both signals coming from direct link and through relaying link to enhance their performance Mondal et al. (2022). Cumulative SINR of mth users given as follows:

$$\gamma_{mrc}^{(m)} = \gamma_m^{(m)} + \gamma_m^{(m),AF}, \qquad m \in \mathcal{N} \tag{7}$$

A user decodes its signal successfully only when the user decodes preceding signals and own signal correctly. The outage probability of mth $(m \in \mathcal{N})$ users in cooperation with AF relay scheme is given by

$$O_m^{AF} = \begin{cases} 1 - \Pr\left\{\gamma_m^{(1)} \geq \gamma, \gamma_m^{(2)} \geq \gamma, .., \gamma_m^{(m)} \geq \gamma\right\}, & \text{without MRC} \\ 1 - \Pr\left\{\gamma_{mrc}^{(1)} \geq \gamma, \gamma_{mrc}^{(2)} \geq \gamma, .., \gamma_{mrc}^{(m)} \geq \gamma\right\}, & \text{with MRC} \end{cases} \tag{8}$$

Now, we find the sum-rate of the system when users are not in outage. When mth ($m \in \mathcal{N}$) user achieves SNR greater than the threshold SNR, sum-rate of the system using MRC diversity is given by Wan et al. (2018)

$$C_{AF} = \begin{cases} \sum\limits_{m=1}^{N} \frac{1}{2}\log\left(1 + \gamma_m^{(m)}\right), & \text{without MRC} \\ \sum\limits_{m=1}^{N} \frac{1}{2}\log\left(1 + \gamma_m^{(m),mrc}\right), & \text{with MRC.} \end{cases} \tag{9}$$

3.2. *Partial cooperative partial DF relay scheme*

In partial cooperative partial DF relay scheme, relay node decodes only the signals of outer-tier users, and only the users located outside the inner-tier receive BS transmitted signal through relay node during second time slot following NOMA principles. The relay node decodes y_R and then forwards it using NOMA protocol to edge users during the second time slot. At the relay node, $\gamma_R^{(k)}$, the received SINR of the signal intended for kth $(k \in \mathcal{N})$ user is given as follows:

$$\gamma_R^{(k)} = \begin{cases} \dfrac{\alpha_k \rho_s |h_{SR}|^2}{\rho_s |h_{SR}|^2 \sum\limits_{j=2}^{L+M} \alpha_j + 1}, & k = 1 \\ \dfrac{\alpha_k \rho_s |h_{SR}|^2}{\rho_s |g_{SR}|^2 \sum\limits_{j=1}^{k-1} \alpha_j + \rho_s |h_{SR}|^2 \sum\limits_{j=k+1}^{L+M} \alpha_j + 1}, & k \neq 1, N \\ \dfrac{\alpha_k \rho_s |h_{SR}|^2}{\rho_s |g_{SR}|^2 \sum\limits_{j=1}^{L+M-1} \alpha_j + 1}, & k = N \end{cases} \tag{10}$$

For partial cooperative partial DF relay transmission scheme, the relay node aims to serve only the user of the outer circle, thus not required to decode the signals of inner circle users. It first decodes signals of the outer-tier users using first and second parts of (10), then superimposes signals of M users and transmits them towards the destinations during the second time slot. It is to note that only the outer-tier users are benefited by partial cooperative partial DF relay.

The received signal at mth ($m \in \mathcal{M}$) destination during second time slot is given as

$$y_m^{ou} = h_{RD_m} \sum_{m=1}^{M} \sqrt{\beta_m P_s} x_m + n_m, \qquad m \in \mathcal{M} \tag{11}$$

At the receiver end, D_m decodes its signal from the superimposed signal considering other signals as interference through the SIC process. Assuming $\rho_r = P_r/N_0$, the received SINR of kth signal at mth user ($m, k \in \mathcal{M},\ \| \leq \Updownarrow$) of outer-tier, $\gamma_{m,ou}^{(k)}$ is given by

$$\gamma_{m,ou}^{(k)} = \begin{cases} \dfrac{\beta_k \rho_r |h_{RD_m}|^2}{\rho_s |h_{RD_m}|^2 \sum\limits_{j=2}^{L+M} \alpha_j + 1}, & k = 1 \\ \dfrac{\beta_k \rho_r |h_{RD_m}|^2}{\rho_r |g_{RD_m}|^2 \sum\limits_{j=1}^{k-1} \beta_j + \rho_s |h_{RD_m}|^2 \sum\limits_{j=k+1}^{L+M} \beta_j + 1}, & k \neq 1, M \\ \dfrac{\beta_k \rho_r |h_{RD_m}|^2}{\rho_r |g_{RD_m}|^2 \sum\limits_{j=1}^{k-1} \beta_j + 1}, & k = M \end{cases} \tag{12}$$

The mth inner-tier user can decode x_m signal correctly if and only if the preceding signals $x_1, x_2, \ldots, x_{m-1}$ are decoded successfully. In other words, inner-tier users first need to decode signals of all the outer-tier users correctly. The outage probability of mth, $m \in \mathcal{L}$ inner-tier user is given by

$$\begin{aligned} \mathcal{O}_m^{in} &= 1 - \Pr\left\{ \gamma_{m,ou}^{(L+1)} \geq \gamma, \gamma_{m,ou}^{(L+2)} \geq \gamma, \ldots, \gamma_{m,ou}^{(L+M)} \geq \gamma, \right\} \\ &\quad \Pr\left\{ \gamma_{m,in}^{(1)} \geq \gamma, \gamma_{m,in}^{(2)} \geq \gamma, \ldots, \gamma_{m,in}^{(m)} \geq \gamma \right\}, m \in \mathcal{L} \end{aligned} \tag{13}$$

The closed-form expression of (13) is derived as follows:

$$\mathcal{O}_m^{in} = \left(\zeta \delta_{SD}^{(m)} \rho_s \sum_{j=L+1}^{L+M} \sum_{j=1}^{m-1} \alpha_j + 1 \right)^{-1} e^{-\frac{\delta_{SD}^{(m)}}{\lambda_{SD_m}}}, \tag{14}$$

where $\Delta_{SD}^{(k)} = \dfrac{\gamma_{th}}{\rho_s \left(\alpha_k - \gamma_{th} \sum\limits_{j=k+1}^{L} \alpha_j \right)}$, $\delta_{SD}^{(m)} = \max\limits_{k=1,2,\ldots,m,L+1,..L+M} \left(\Delta_{SD}^{(k)} \right)$.

Proof: Please see Appendix A for details.

The mth user of outer-tier i.e, $m \in \mathcal{M}$ decodes its own signal x_m correctly when (a) it decodes the preceding signals $x_1, x_2, \ldots, x_{m-1}$ successfully, and (b) relay successfully decodes signals of all the outer circle users during first transmission slot. Now, $\mathcal{O}_m^{ou}$, $(m \in \mathcal{M})$ the outage probability of mth user located in outer circle is given by

$$\begin{aligned} \mathcal{O}_m^{ou} = 1 - \Pr\left\{\gamma_R^{(1)} \geq \gamma, \gamma_R^{(2)} \geq \gamma, \ldots, \gamma_R^{(m)} \geq \gamma\right\} \\ \Pr\left\{\gamma_{m,ou}^{(1)} \geq \gamma, \gamma_{m,ou}^{(2)} \geq \gamma, \ldots, \gamma_{m,ou}^{(m)} \geq \gamma\right\}, \ m \in \mathcal{M} \end{aligned} \tag{15}$$

Using (A1), (A2), (A3) and (A4), the closed-form expression of (13) can be derived as

$$\mathcal{O}_m^{ou} = 1 - \left[\left(\zeta\delta_{SR}^{(m)}\rho_s\sum_{j=1}^{m-1}\alpha_j + 1\right)\left(\zeta\delta_{RD}^{(m)}\rho_r\sum_{j=1}^{m-1}\beta_j + 1\right)\right]^{-1} e^{-\frac{\delta_{SR}^{(m)}}{\lambda_{SRm}} + \frac{\delta_{RD}^{(m)}}{\lambda_{RDm}}}, \tag{16}$$

where $\Delta_{SR}^{(k)} = \frac{\gamma_{th}}{\rho_s\left(\alpha_k - \gamma_{th}\sum_{j=k+1}^{L+M}\alpha_j\right)}$, $\Delta_{RD}^{(k)} \frac{\gamma_{th}}{\rho_r\left(\beta_k - \gamma_{th}\sum_{j=k+1}^{M}\alpha_j\right)}$, $\delta_{SR}^{(m)} = \max_{k=1,2,\ldots,m}\left(\Delta_{SR}^{(k)}\right)$, and

$\delta_{RD}^{(m)} = \max_{k=1,\ldots,m}\left(\Delta_{RD}^{(k)}\right)$.

Proof: Please see Appendix A for details.

The overall system sum-rate considering partial DF relay protocol when users are not in outage can be expressed as follows:

$$C_{DF} = \sum_{m=1, m\in\mathcal{L}}^{L} \tfrac{1}{2}\log\left(1 + \gamma_{m,in}^{(m)}\right) + \sum_{m=1, m\in\mathcal{M}}^{M} \tfrac{1}{2}\log\left(1 + \gamma_{m,ou}^{(m)}\right) \tag{17}$$

It is to remind that in partial DF relaying, outer-tier users only receives a copy of BS transmitted signal from the relay node during second transmission. Therefore, the MRC diversity technique is employed to the outer-tier users only. The cumulative SNIR of mth $(m \in \mathcal{M})$ user is given as

$$\gamma_{mrc}^{(m),DF} = \gamma_m^{(m)} + \gamma_{m,ou}^{(m)}, \quad m \in \mathcal{M}. \tag{18}$$

The outage probability of outer-tier users is given by

$$\begin{aligned} \mathcal{O}_m^{ou,DF} = 1 - \Pr\left\{\gamma_R^{(1)} \geq \gamma, \gamma_R^{(2)} \geq \gamma, \ldots, \gamma_R^{(m)} \geq \gamma\right\} \\ \Pr\left\{\gamma_{mrc}^{(1),DF} \geq \gamma, \gamma_{mrc}^{(2),DF} \geq \gamma, \ldots, \gamma_{mrc}^{(m),DF} \geq \gamma\right\}, \ m \in \mathcal{M}. \end{aligned} \tag{19}$$

The overall system sum-rate considering MRC diversity can be evaluated using (17) and (18).

4. Results and discussions

This section presents an extensive simulation results to validate the theoretical analysis. The Monte-Carlo simulation is carried out in Matlab software with minimum of 10^5 iterations. Total users in the system is $N = 4$, where $L = 2$ and $M = 2$. The users are indexed by m, where $m = 1$ indicates the user located nearest to the BS, and $m = 4$ indicates the user located farthest from the BS. Transmitting SNR of the BS varies from -20dB to 20dB, relay node with same power and $N_0 = 0.01$. The threshold SNR $\gamma = -2$dB, all the channels are Rayleigh distributed with $\lambda = 0.5$ for outer-tier users and $\lambda = 1$ for inner-tier user. We consider a perfect SIC decoding process in the simulation for Figures 2 to 5. The effect of imperfect SIC on the outage performance has been analysed in Figure 6. The simulation process is discussed below.

• The near users (stronger) and far users (weaker) are sorted in an ascending order individually based on their channel gain quality.

• Based on the power allocation process (explained in Sec: 2 after (1)) a_m fraction of total power is allocated to user m, $m \in \{1, 2, 3, 4\}$ and a superimposed signal is transmitted over the wireless channel.

• For AF relaying, the relay node simply amplify the received signal using (4) and transmits. For DF relaying, the relay node finds the SNR of the users using (10) and applies SIC to decode only the signals intended for far users then transmits a superimposed signal.

• For AF relaying, (2) and (6) are used to find the received SINR during the first and second time slot, respectively. Finally, (7) is applied to find the cumulative SINR of the users for MRC diversity.

• For DF relaying, to find the received SINR during the first and second time slot (2) and (12) are used, respectively. Cumulative SINR required for MRC diversity (7) is applied.

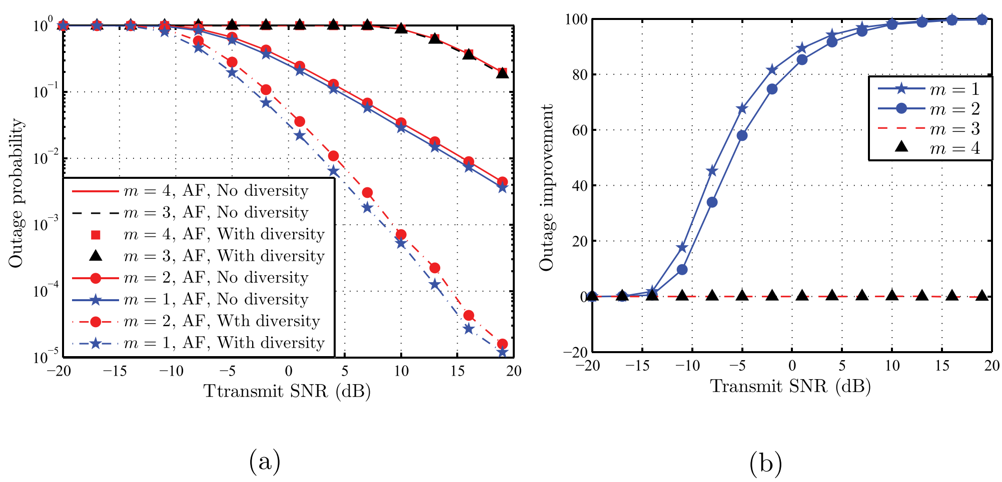

Figure 2. (A) Outage probability as a function of transmit SNR for cooperation AF relay transmission with and without diversity. Outer circle users $m = 3, 4$ do not achieve any benefit from diversity technique. (b) Outage probability improvement of users when diversity is employed. The user nearest to the BS achieves maximum improvement.

• The outage probability is evaluated using (8) and (13) for AF and DF relaying, respectively.

Figure 2 depicts the outage performance of each user for AF relay with respect to transmitting SNR considering diversity and without diversity. The primary purpose of applying the diversity technique is to enhance the outage performance of the users, particularly outer-tier users. However, improvement is observed only for the users located in the close vicinity of the BS ($m = 1, 2$), and the outer circle users ($m = 3, 4$) fail to improve significant outage performance from the diversity technique. It is because outer circle users are located so far from the BS that they receive a very weak signal that does not contribute any impact on the diversity technique. On the other hand, the outage performance of the inner circle users ($m = 1, 2$) improve as high as 100% when the diversity technique is employed. Figure 2 (a) also validates that numerical values of the simulation parameters that we have considered validates our assumption regarding the system model (we assumed edge users may receive a very weak signal). As the AF relay simply amplify and forwards the superposed signal comprising signal of all users including inner-tier and outer-tier users, so partial cooperation scheme with AF are not realistic. Therefore, from the fairness viewpoint, the AF relay fails to maintain user fairness even after employing diversity technique.

Now we analysis the outage probability employing DF relay protocol with and without diversity in Figure 3 (a). We have seen in Figure 2 that the edge users suffer from outage problems when AF relay is applied. It is to note that, unlike AF relay, partial DF relay decodes the superimposed signal first, then forwards towards the destination using NOMA principles. Therefore, the DF protocol can utilise its resources for partially forwarding the signals of outer-tier users. This characteristic of the partial DF relay effectively enhances the outage of outer-tier users ($m = 3, 4$), and the overall fairness of the users efficiently enhances. Similar to the AF relay, DF relay with diversity cannot improve the outage performance as the signal strength during the first time slot is too weak. However, diversity remarkably enriches the overall system sum-rate, as shown in Figure 3 (b). It is to

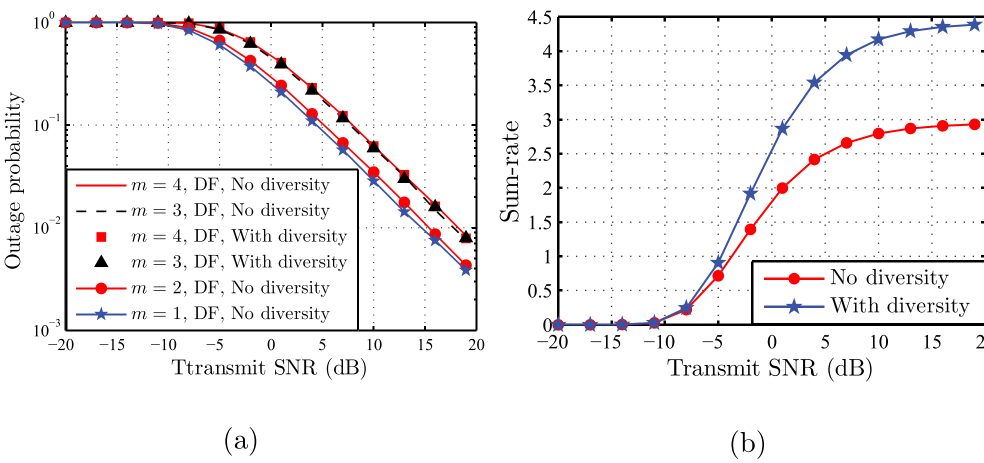

Figure 3. (A) Outage probability as a function of transmit SNR for cooperation partial DF relay transmission. Here relay node transmits only the signals of outer circle users $m = 3, 4$ using DF relay. (b) Average sum-rate improvement of the system when diversity is employed.

note that we calculate the sum-rate when users are *not* experiencing outage. The improvement of the overall system sum-rate increases as expected with the increase of transmitting SNR.

Like the DF relay, AF relay with diversity is also proficient in improving the system sum-rate, as shown in Figure 4 (a). An achievable average sum-rate of AF relay-based NOMA system with and without diversity has been depicted in Figure 3 (a). The MRC diversity efficiently enhances the overall system sum-rate. We see an interesting fact when the sum-rate performance of AF relay compared with that of partial DF relay. Figure 4 (b) shows the sum-rate improvement of a partial DF relay-based NOMA system over that of the AF relay-based NOMA system. For a lower region of transmitting SNR, the AF relay (with and without diversity) is superior to the DF relay, whereas the DF relay is superior to the AF relay for comparatively higher transmitting SNR. For instance, DF relay without diversity achieves -50% improvement than the AF relay (i.e. AF better than DF relay) for -15dB transmit SNR, however for 0db transmit SNR, DF relay achieves 50% improvement than the AF relay. The diversity technique further intensifies this characteristic. This is because the inner-tier users attain advantages from the diversity technique during AF relay transmission, whereas the diversity technique is not applied during partial DF relay transmission.

Now, we present a comparative performance analyse of AF relay and partial DF relay in terms of outage probability in Figure 5. The outage improvement of each user considering DF relay over the AF relay without applying diversity has been depicted in Figure 5. The inner-circle users ($m = 1, 2$) hardly achieve any outage improvement when relay protocol changes from AF to DF relay. However, outer circle users ($m = 3, 4$) achieve a huge improvement (up to 90%) in terms of outage applying DF relay over the AF relay. This figure validates that partial DF significantly improves the outage performance of outer-

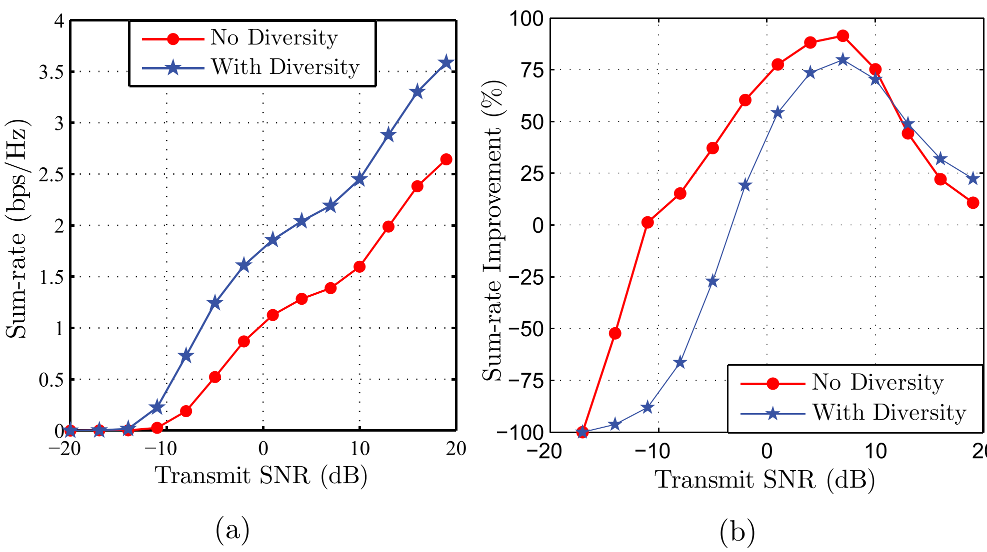

Figure 4. (A) Achievable average sum-rate of AF relay-based system with and without considering diversity, (b) Average sum-rate improvement of the DF relay-based system over AF relay-based system.

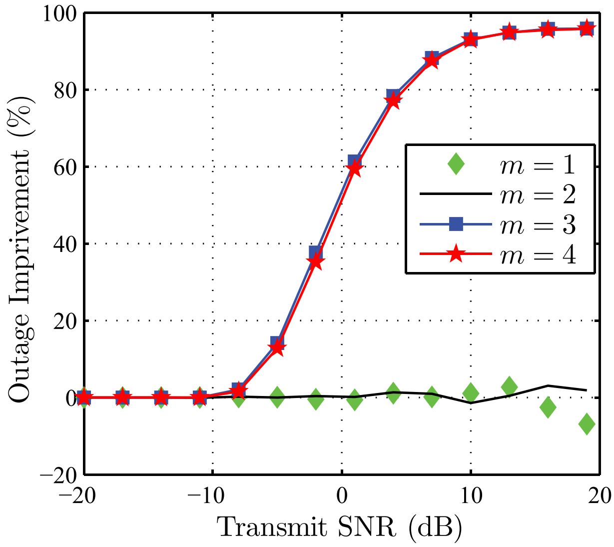

Figure 5. Improvement of outage probability using DF relay over that of using AF relay without considering diversity.

tier users maintaining the outage performance of inner-tier users same as that of by AF relay.

From the above discussion, we found that AF relaying fails to improve outage performance of edge users, and AF relay with diversity has no constructive effect on improving the outage performance of the outer-tier users. On the other hand side, partial DF relaying enhances both the sum-rate and outage performances of the outer-tier users efficiently without deteriorating the performance of inner-tier users even when diversity is not employed. The partial DF relay shows its proficiency over the AF relay technique in terms of outage, sum-rate and fairness.

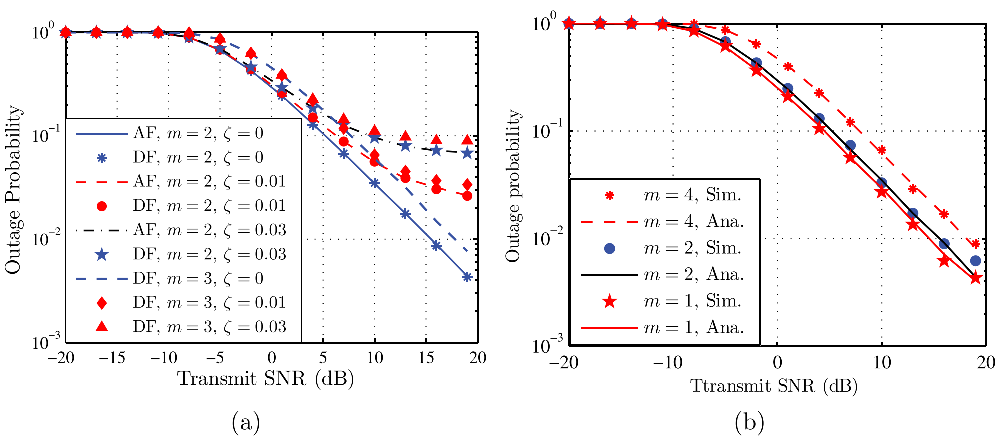

Figure 6. (A) Improvement of outage probability using DF relay over that of using AF relay without considering diversity. (b) Simulation and analytical outage probability.

Figure 6(a) depicts the effect of the imperfect SIC process on the outage performance. $\zeta = 0.01$ indicates that the SIC process fails to remove 1% power of the preceding signal, and this residue power introduces interference to the subsequent signal detection. Therefore, with the slight increasing of $\zeta = 0.01$ to $\zeta = 0.03$ (i.e. only 2%), outage performance degrades drastically. The performance of NOMA-based systems greatly depends on the accuracy of the SIC process. The partial DF relaying, as expected, shows its superiority to the AF relaying in terms of outage under an imperfect SIC process. Figure 6(b) depicts the analytical outage probability and simulation-based outage probability. The figure shows that the derived analytical outage probability matches with the simulation.

5. Conclusion

This paper finds an appropriate relay technique to enhance the QoS of the edge users of a NOMA-based system. AF and partial DF relay have been adopted and comparative performances analysis presented in terms of outage probability and average system sum-rate. AF relaying is an inefficient approach to improve the outage of the edge users. Whereas the partial DF relay scheme efficiently improves the outage performance, specifically for the outer-tier users with improved user fairness. The partial DF-based NOMA system also achieves a better sum-rate than the AF relay with diversity. Finally, we observe that the accuracy of the SIC process plays a crucial role in NOMA-based systems.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Dai, L., Wang, B., Yuan, Y., Han, S., Chih-Lin, I., & Wang, Z. (2015). Non-orthogonal multiple access for 5G: Solutions, challenges, opportunities, and future research trends. *IEEE Communications Magazine*, *53*(9), 74–81. https://doi.org/10.1109/MCOM.2015.7263349

Ding, Z., Liu, Y., Choi, J., Sun, Q., Elkashlan, M., Poor, H. V., & Poor, H. V. (2017). Application of non-orthogonal multiple access in LTE and 5G networks. *IEEE Communications Magazine*, *55*(2), 185–191. https://doi.org/10.1109/MCOM.2017.1500657CM

Do, D. -T., & Nguyen, T. -T. -T. (2019). Impacts of imperfect SIC and imperfect hardware in performance analysis on AF non-orthogonal multiple access network. *Telecommunication Systems*, *72*(4), 579–593. https://doi.org/10.1007/s11235-019-00583-7

Fang, Z., Shen, S., Liu, J., Ni, W., & Jamalipour, A. (2020). New noma-based two-way relay networks. *IEEE Transactions on Vehicular Technology*, *69*(12), 15314–15324. https://doi.org/10.1109/TVT.2020.3039286

Jee, A., Agrawal, K., & Prakriya, S. (2021). A coordinated direct af/df relay-aided noma framework for low outage. *IEEE Transactions on Communications*, *70*(3), 1559–1579. https://doi.org/10.1109/TCOMM.2021.3126632

Kim, J. -B., & Lee, I. -H. (2015). Non-orthogonal multiple access in coordinated direct and relay transmission. *IEEE Communications Letters*, *19*(11), 2037–2040. https://doi.org/10.1109/LCOMM.2015.2474856

Lee, S., Benevides da Costa, D., & Duong, T. Q. (2016). Outage probability of nonorthogonal multiple access schemes with partial relay selection. In *2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)* (pp.1–6), Dec. 2016, Valencia, Spain.

Liu, H., Ding, Z., Kim, K. J., Kwak, K. S., & Poor, H. V. (2018). Decode-and-forward relaying for cooperative NOMA systems with direct links. *IEEE Transactions on Wireless Communications*, *17*(12), 8077–8093. https://doi.org/10.1109/TWC.2018.2873999

Liu, Y., Pan, G., Zhang, H., & Song, M. (2016). Hybrid decode-forward amp; amplify-forward relaying with non-orthogonal multiple access. *IEEE Access*, *4*, 4912–4921. https://doi.org/10.1109/ACCESS.2016.2604341

Liu, Y., Qin, Z., Elkashlan, M., Ding, Z., Nallanathan, A., & Hanzo, L. (2017). Nonorthogonal multiple access for 5G and beyond. *Proceedings of the IEEE*, *105*(12), 2347–2381. https://doi.org/10.1109/JPROC.2017.2768666

Liu, X., & Wang, X. (2016). Outage probability and capacity analysis of the collaborative noma assisted relaying system in 5g. In *2016 IEEE/CIC International Conference on Communications in China (ICCC)* (pp. 1–5). Oct. 2016, Chengdu, China.

Liu, Y., Zhang, S., Mu, X., Ding, Z., Schober, R., Al-Dhahir, N., Hossain, E., & Shen, X. (2022). Evolution of noma toward next generation multiple access (NGMA) for 6G. *IEEE Journal on Selected Areas in Communications*, *40*, 1037–1071. https://doi.org/10.1109/JSAC.2022.3145234

Men, J., & Ge, J. (2015). Non-orthogonal multiple access for multiple-antenna relaying networks. *IEEE Communications Letters*, *19*(10), 1686–1689. https://doi.org/10.1109/LCOMM.2015.2472006

Men, J., Ge, J., & Zhang, C. (2017). Performance analysis for downlink relaying aided nonorthogonal multiple access networks with imperfect CSI over nakagami- *m* fading. *IEEE Access*, *5*, 998–1004. https://doi.org/10.1109/ACCESS.2016.2631482

Misra, A., & Sarma, K. K. (2020). Dual-ordered non-orthogonal multiple access with decode and forward relaying. *IET Communications*, *14*(17), 3065–3072. https://doi.org/10.1049/iet-com.2020.0352

Mondal, S., Bepari, D., & Biswas, S. (2022). Performance of a multihop cognitive radio network with diversity under imperfect csi. *International Journal of Electronics Letters*, (just–accepted), 1–14. https://doi.org/10.1080/21681724.2021.2025439

Mondal, S., Roy, S. D., & Kundu, S. (2020). Outage analysis for NOMA-based energy harvesting relay network with imperfect CSI and transmit antenna selection. *IET Communications*, *14*(14), 2240–2249. https://doi.org/10.1049/iet-com.2019.0841

Pei, X., Yu, H., Wen, M., Mumtaz, S., Al Otaibi, S., & Guizani, M. (2020). NOMA-based coordinated direct and relay transmission with a half-duplex/full-duplex relay. *IEEE Transactions on Communications*, *68*(11), 6750–6760. https://doi.org/10.1109/TCOMM.2020.3017002

Sharma, S., Deka, K., Bhatia, V., & Gupta, A. (2019). Joint power-domain and scma-based noma system for downlink in 5G and beyond. *IEEE Communications Letters*, *23*(6), 971–974. https://doi.org/10.1109/LCOMM.2019.2911082

Thapar, S., Mishra, D., & Saini, R. (2021). Decoding orders for securing untrusted NOMA. *IEEE Networking Letters*, *3*(1), 27–30. https://doi.org/10.1109/LNET.2021.3051757

Uddin, M. B., Kader, M. F., & Shin, S. Y. (2018). Cooperative amplify-and-forward relaying in NOMA. *Proc. Korean Institute of Communications and Information Sciences (KICS)* (pp.385–386), Korea.

Wan, D., Wen, M., Ji, F., Liu, Y., & Huang, Y. (2018). Cooperative NO*ma* Syste*ms* with partial channel state information over Nakag*ami*- $*m*$ fading channels. *IEEE Transactions on Communications*, *66*(3), 947–958. https://doi.org/10.1109/TCOMM.2017.2772273

Xu, Y., Cheng, J., Wang, G., & Leung, V. C. (2021). Coordinated direct and relay transmission for multiuser networks: NOMA or hybrid multiple access? *IEEE Wireless Communications Letters*, *10*(5), 976–980. https://doi.org/10.1109/LWC.2021.3052894

Yang, Z., Ding, Z., Fan, P., & Karagiannidis, G. K. (2016). On the performance of nonorthogonal multiple access systems with partial channel information. *IEEE Transactions on Communications*, *64*(2), 654–667. https://doi.org/10.1109/TCOMM.2015.2511078

Yang, Z., Ding, Z., Wu, Y., & Fan, P. (2017). Novel relay selection strategies for cooperative NOMA. *IEEE Transactions on Vehicular Technology*, *66*(11), 10114–10123. https://doi.org/10.1109/TVT.2017.2752264

Yuan, L., Yang, N., Fang, F., Du, Q., & Zheng, Z. (2021). Optimal power allocation for finite blocklength cooperative noma with coordinated direct and relay transmission. *IEEE Wireless Communications Letters*, *11*(3), 523–527. https://doi.org/10.1109/LWC.2021.3135299

Yue, X., Liu, Y., Kang, S., & Nallanathan, A. (2017). Performance analysis of NOMA with fixed gain relaying over nakagami-*m* fading channels. *IEEE Access*, *5*, 5445–5454. https://doi.org/10.1109/ACCESS.2017.2677504

Zaidi, S. K., Hasan, S. F., Gui, X., Siddique, N., & Ahmad, S. (2019). Exploiting UAV as NOMA based relay for coverage extension. In *2019 2nd International Conference on Computer Applications Information Security (ICCAIS)* (pp. 1–5), Riyadh, Saudi Arabia.

Zamani, M. R., Eslami, M., Khorramizadeh, M., & Ding, Z. (2018). Energy-efficient power allocation for noma with imperfect csi. *IEEE Transactions on Vehicular Technology*, *68*(1), 1009–1013. https://doi.org/10.1109/TVT.2018.2882500

Zeng, M., Hao, W., Dobre, O. A., & Ding, Z. (2020). Cooperative NOMA: State of the art, key techniques, and open challenges. *IEEE Network*, *34*(5), 205–211. https://doi.org/10.1109/MNET.011.1900601

Zhai, D., Li, H., Tang, X., Zhang, R., Ding, Z., & Yu, F. R. (2021). Height optimization and resource allocation for NOMA enhanced UAV-aided relay networks. *IEEE Transactions on Communications*, *69*(2), 962–975. https://doi.org/10.1109/TCOMM.2020.3037345
Zhang, Z., Ma, Z., Xiao, M., Ding, Z., & Fan, P. (2017). Full-duplex device-to-device-aided cooperative nonorthogonal multiple access. *IEEE Transactions on Vehicular Technology*, *66*(5), 4467–4471.

Appendix A

Following Mondal et al. (2020), the equation 15 can be re-written as follows:

$$\Pr\left\{\gamma_R^{(1)} \geq \gamma, \gamma_R^{(2)} \geq \gamma, \ldots, \gamma_R^{(m)} \geq \gamma\right\} = \Pr\left\{\frac{|h_{SR}|^2}{\rho_s |g_{SR}|^2 \sum_{j=1}^{m-1} \alpha_j + 1} \geq \max_{k=1,2,\ldots,m}\left(\Delta_{SR}^{(k)}\right)\right\}, \tag{A1}$$

where, $\Delta_{SR}^{(k)} = \frac{\gamma_{th}}{\rho_s\left(\alpha_k - \gamma_{th}\sum_{j=k+1}^{L+M}\alpha_j\right)}$ and $\delta_{SR}^{(m)} = \max_{k=1,2,\ldots,m}\left(\Delta_{RD}^{(k)}\right)$

$$\Pr\left\{\gamma_{m,ou}^{(1)} \geq \gamma, \gamma_{m,ou}^{(2)} \geq \gamma, \ldots, \gamma_{m,ou}^{(m)} \geq \gamma\right\} = \Pr\left\{\frac{|h_{RD_m}|^2}{\rho_r |g_{RD_m}|^2 \sum_{j=1}^{m-1} \beta_j + 1} \geq \max_{k=1\ldots m}\left(\Delta_{RD}^{(k)}\right)\right\} \tag{A2}$$

where, $\Delta_{RD}^{(k)} \frac{\gamma_{th}}{\rho_r\left(\alpha_k - \gamma_{th}\sum_{j=k+1}^{M}\beta_j\right)}$, and $\delta_{RD}^{(m)} = \max_{k=1,\ldots,m}\left(\Delta_{RD}^{(k)}\right)$.

The equation (A1) can be further derived as follows:

$$\begin{aligned}
\Pr\left\{\frac{|h_{SR}|^2}{\rho_s |g_{SR}|^2 \sum_{j=1}^{m-1} \alpha_j + 1} \geq \delta_{SR}^{(m)}\right\} &= 1 - \Pr\left\{|h_{SR}|^2 < \delta_{SR}^{(m)}\left(\rho_s |g_{SR}|^2 \sum_{j=1}^{m-1}\alpha_j + 1\right)\right\} \\
&= 1 - \int_0^\infty F_{|h_{SR}|^2}\left(\delta_{SR}^{(m)}\left(\rho_s |g_{SR}|^2 \sum_{j=1}^{m-1}\alpha_j + 1\right)\right) f_{|g_{SR}|^2}(y)dy \\
&= 1 - \int_0^\infty \left\{1 - e^{-\frac{\delta_{SR}^{(m)}\left(\rho_s y \sum_{j=1}^{m-1}\alpha_j + 1\right)}{\lambda_{SR}}}\right\} \frac{1}{\zeta\lambda_{SR}} e^{-\frac{y}{\zeta\lambda_{SR}}} dy \\
&= \frac{1}{\zeta\lambda_{SR}} e^{-\frac{\delta_{SR}^{(m)}}{\lambda_{SR}}} \int_0^\infty e^{-\left(\frac{\delta_{SR}^{(m)}\rho_s \sum_{j=1}^{m-1}\alpha_j}{\lambda_{SR}} + \frac{1}{\zeta\lambda_{SR}}\right) y} dy \\
&= \left(\zeta\delta_{SR}^{(m)}\rho_s \sum_{j=1}^{m-1}\alpha_j + 1\right)^{-1} e^{-\frac{\delta_{SR}^{(m)}}{\lambda_{SR}}}
\end{aligned} \tag{A3}$$

Similarly, (A2) can be derived as follows:

$$\Pr\left\{\frac{|h_{RD_m}|^2}{\rho_r |g_{RD_m}|^2 \sum_{j=1}^{m-1}\beta_j + 1} \geq \delta_{RD}^{(m)}\right\} = \left(\zeta\delta_{RD}^{(m)}\rho_r \sum_{j=1}^{m-1}\beta_j + 1\right)^{-1} e^{-\frac{\delta_{RD}^{(m)}}{\lambda_{RD_m}}} \tag{A4}$$

Similar procedure of (A3) is adapted to derive closed-form expression of (13)

$$\begin{aligned}\mathcal{O}_m^{in} &= 1-\Pr\left\{\gamma_{m,in}^{(L+1)}\geq\gamma,\gamma_{m,in}^{(L+2)}\geq\gamma,\ldots,\gamma_{m,in}^{(L+M)}\geq\gamma\right\}\Pr\left\{\gamma_{m,in}^{(1)}\geq\gamma,\gamma_{m,in}^{(2)}\geq\gamma,\ldots,\gamma_{m,in}^{(m)}\geq\gamma\right\}\\ &= 1-\Pr\left\{\frac{|h_{SD_m}|^2}{\rho_s|g_{SD_m}|^2\sum\limits_{j=L+1}^{L+M}\sum\limits_{j=1}^{m-1}\alpha_j+1}\geq\max_{k=1,2,\ldots,m,L+1,..L+M}\left(\Delta_{SD}^{(k)}\right)\right\},\\ &= \left(\zeta\delta_{SD}^{(m)}\rho_s\sum_{j=L+1}^{L+M}\sum_{j=1}^{m-1}\alpha_j+1\right)^{-1}e^{-\frac{\delta_{SD}^{(m)}}{\lambda_{SD_m}}}\end{aligned}\tag{A5}$$

where, $\Delta_{SD}^{(k)}=\frac{\gamma_{th}}{\rho_s\left(\alpha_k-\gamma_{th}\sum\limits_{j=k+1}^{L}\alpha_j\right)}$, $\delta_{SD}^{(m)}=\max\limits_{k=1,2,\ldots,m,L+1,..L+M}\left(\Delta_{SD}^{(k)}\right)$