Sum-Rate Maximization Based Relay Selection for Cooperative NOMA Over Nakagami-m Fading

Yan Li, Tao Li, Yongzhao Li, *Senior Member, IEEE*, Qiang Ni, *Senior Member, IEEE* and Charilaos Zarakovitis

***Abstract*—This paper proposes a new sum-rate maximization based relay selection (RS) scheme for cooperative non-orthogonal multiple access (NOMA) networks over Nakagami-m fading, where one base station communicates with two mobile users by means of multiple relays. The outage probability of the proposed scheme is derived in a closed-form expression, and the diversity order is also obtained. Simulation results are shown to compare the outage performance of the proposed scheme with that of the existing RS schemes.**

***Index Terms*—Sum-rate maximization, cooperative NOMA, Nakagami-m fading, outage probability, relay selection.**

I. INTRODUCTION

RECENTLY, non-orthogonal multiple access (NOMA) has been considered as a promising candidate technology to improve the spectral efficiency (SE) for the fifth generation (5G) wireless networks [1], [2]. To reduce the effect of fading and to harvest spatial degrees of freedom, cooperative communications have been applied into NOMA, forming cooperative NOMA [3].

Cooperative NOMA was initially proposed in [4], where users with stronger channel conditions acted as relays to assist other users. Afterwards, the works in [5], [6] established the communications between source nodes and destination nodes by virtue of a dedicated relay. Relay selection (RS) is an effective approach for exploiting space diversity and for increasing SE when multiple relays are deployed in cooperative NOMA, and several RS schemes have been proposed in the open literature [7]–[12]. In [7], a two-stage max-min RS scheme based on fixed power allocation (PA) was investigated, where a relay was selected to serve the high-rate user by adopting the max-min scheme while satisfying the quality of service (QoS) requirements of the low-rate user. The work in [8] redesigned the RS scheme in [7] to further improve the system outage performance, where dynamic PA using the instantaneous channel state information (ICSI) was considered. Nevertheless, the users in [7] and [8] were all ordered by their QoS requirements, which leads to the suboptimal outage performance. Therefore, in [9], [10], two types of RS schemes adopting the ICSI based user ordering strategy were proposed to achieve better outage performance. Moreover, in [11], a partial relay selection scheme based on the ICSI of the first steps was designed, where the full-duplex (FD) amplify-and-forward relays were considered. In [12], a buffer-aided relay selection scheme for cooperative NOMA networks in the Internet of Things was studied. It is worth noting that all these RS schemes were designed based on the fixed individual target rates of different users. However, in some practical situations, each user may have multiple target rates related to various services. For example, one user can at most have five categories of data flow regarding different QoS in IEEE 802.16/WiMAX, and for each data flow there exists a minimum reserved traffic rate (MRTR) to specify the minimum information rate [13]. In this case, RS schemes involving NOMA can be designed to satisfy all paired users' MRTR for basic real-time service firstly, while trying to provide the users having better ICSI with additional data transmission for non-real-time service as much as possible to improve the overall SE. Moreover, to our best knowledge, none of the existing RS schemes for cooperative NOMA has been proposed to maximize the sum rate of the considered networks, which motivates the study of this work.

In this paper, we propose a new sum-rate maximization based RS scheme for cooperative NOMA networks, where each user has two alternative target rates. Specifically, the proposed scheme consists of two stages, where the first stage is to find a subset of relays that can decode both users' signals correctly, and the second stage is to select from the subset an optimal relay that maximizes the sum rate of the considered networks with the constraint that the weak user's basic target rate is satisfied. Both users' adopted target rates are associated with their ICSI, and the user ordering and PA strategy are also based on the ICSI to achieve the goals of RS. In contrast to the existing works [7]–[10], Nakagami-m fading rather than Rayleigh fading is considered in the proposed scheme to depict a wider class of fading environments.[1] We derive a closed-form expression for the outage probability and approximate it in the high SNR region to obtain the diversity order. Simulation results are presented to compare the performance of the proposed RS scheme with that of the existing ones [7]–[10].

This work was supported in part by the National Key Research and Development Program of China under Grant 2016YFB1200202, 254, in part by the Postdoctoral Science Foundation of China under Grant 2019M663630, in part by the National Natural Science Foundation of China under Grant 61771365, in part by the Fundamental Research Funds for the Central Universities under Grant JB190115, JBF180101, in part by the 111 Project of China under Grant B08038, in part by the Innovation Fund of Xidian University under Grant 20109205456, and in part by the Royal Society project under Grant IEC170324.

Yan Li, Tao Li and Yongzhao Li are with the State Key Laboratory of Integrated Services Networks, Xidian University, Xi'an 710071, China. The corresponding authors are Tao Li (taoli@xidian.edu.cn) and Yongzhao Li (yzli@mail.xidian.edu.cn).

Qiang Ni and Charilaos Zarakovitis are with the School of Computing and Communications, Lancaster University, Lancaster LA1 4WA, UK.

[1] We note that there exist other fading models (i.e., correlated Nakagami-m fading considered in [14]) providing a more general or practical system setting, which are worth studying in our future work.

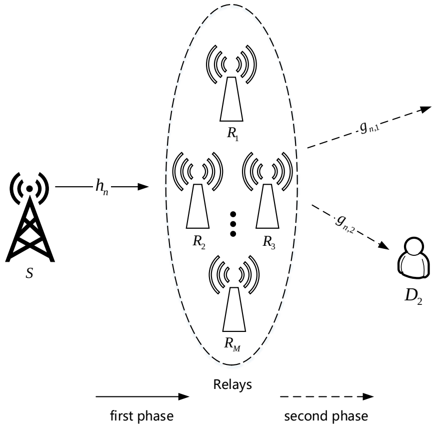

Fig. 1: The illustration of the considered downlink cooperative NOMA network.

II. System Model

We consider a downlink cooperative NOMA network with one base station (S), two users (D_1, D_2) and M half-duplex decode-and-forward (DF) relays[2] ($R_n, n = 1, ..., M$), as illustrated in Fig. 1. Each node is equipped with a single antenna. It is assumed that there is no direct link between the source and users [7]–[10]. All wireless channels experience independent quasi-static Nakagami-m fading and additive white Gaussian noise (AWGN). Furthermore, we assume that M relays are clustered closely together, and hence the channel gains between a certain node and the relays are independent and identically distributed (i.i.d.). Specifically, the channel coefficient between S and R_n is denoted by h_n with fading parameter m_0 and $E[|h_n|^2] = \Omega_0$, and the channel coefficient between R_n and D_k ($k = 1, 2$) is denoted by $g_{n,k}$ with fading parameter m_k and $E[|g_{n,k}|^2] = \Omega_k$. Both users are ordered according to their ICSI, and it is assumed that the weak user is denoted by $D_{n,f}$ with channel gain $|g_{n,f}|^2 = \min\{|g_{n,1}|^2, |g_{n,2}|^2\}$, and the strong user is denoted by $D_{n,c}$ with channel gain $|g_{n,c}|^2 = \max\{|g_{n,1}|^2, |g_{n,2}|^2\}$. Moreover, the alternative target rates for both two users are denoted by R_f and R_c. R_f will be adopted by $D_{n,f}$, and R_c will be adopted by $D_{n,c}$. Without loss of generality, $R_f \leq R_c$ is assumed. It is worth noting that perfect successive interference cancellation (SIC) is employed as in [7]-[10], our future work will relax this assumption.

There are two separate phases involved to achieve data transmission. Assume that R_n ($1 \leq n \leq M$) is selected as the optimal relay. In the first phase, S transmits a superposed signal, $\left(\sqrt{\gamma_{n,f}}x_f + \sqrt{\gamma_{n,c}}x_c\right)$, to R_n, where x_i ($i = f, c$) denotes $D_{n,i}$'s message; $\gamma_{n,i}$ denotes the PA coefficient for message x_i satisfying $\gamma_{n,i} > 0$ and $\gamma_{n,f} + \gamma_{n,c} = 1$. Therefore, R_n receives

$$y_n^r = \sqrt{P_s}h_n\left(\sqrt{\gamma_{n,f}}x_f + \sqrt{\gamma_{n,c}}x_c\right) + w_n^r, \tag{1}$$

where P_s denotes the transmit power of S; w_n^r denotes the AWGN with zero mean and variance σ^2 at R_n.

[2]FD DF relay can also be adopted in our system model, while the impact of residual loop self-interference should be carefully considered in the analysis.

Based on the basic principle of NOMA, the achievable rates for R_n to decode the messages x_f and x_c can be given by

$$R_f^n = \frac{1}{2}\log_2\left(1 + \frac{\gamma_{n,f}\rho|h_n|^2}{\gamma_{n,c}\rho|h_n|^2 + 1}\right), \tag{2}$$

$$R_c^n = \frac{1}{2}\log_2\left(1 + \gamma_{n,c}\rho|h_n|^2\right), \tag{3}$$

respectively, where $\rho = P_s/\sigma^2$ denotes the transmit signal-to-noise ratio (SNR).

In the second phase, R_n broadcasts the superposed signal, $\left(\sqrt{\alpha_{n,f}}x_f + \sqrt{\alpha_{n,c}}x_c\right)$, to the users, where $\alpha_{n,i}$ ($i = f, c$) denotes the PA coefficient for $D_{n,i}$ satisfying $\alpha_{n,i} > 0$ and $\alpha_{n,f} + \alpha_{n,c} = 1$. Therefore, $D_{n,i}$ observes

$$y_{n,i}^d = \sqrt{P_r}g_{n,i}\left(\sqrt{\alpha_{n,f}}x_f + \sqrt{\alpha_{n,c}}x_c\right) + w_{n,i}^d, \tag{4}$$

where P_r denotes the transmit power of R_n, to simplify the analysis, $P_s = P_r = P$ is assumed; $w_{n,i}^d$ denotes the AWGN with zero mean and variance σ^2 at $D_{n,i}$.

According to (2) and (3), the achievable rate for $D_{n,f}$ to decode its own message x_f is expressed as

$$\hat{R}_f^n = \frac{1}{2}\log_2\left(1 + \frac{\alpha_{n,f}\rho|g_{n,f}|^2}{\alpha_{n,c}\rho|g_{n,f}|^2 + 1}\right), \tag{5}$$

and the achievable rates for $D_{n,c}$ to decode both users' messages x_f and x_c are respectively expressed as

$$\hat{R}_{c\to f}^n = \frac{1}{2}\log_2\left(1 + \frac{\alpha_{n,f}\rho|g_{n,c}|^2}{\alpha_{n,c}\rho|g_{n,c}|^2 + 1}\right), \tag{6}$$

$$\hat{R}_c^n = \frac{1}{2}\log_2\left(1 + \alpha_{n,c}\rho|g_{n,c}|^2\right). \tag{7}$$

III. Relay Selection Scheme

Recall that the proposed RS scheme is to maximize the sum rate of considered NOMA systems, therefore the following theorem can be applied.

Theorem 1: In the case of using a specific relay R_n, the maximal sum rate of considered NOMA networks is $R_{\max}^{o,n} = \min\{R_{\max,1}^{o,n}, R_{\max,2}^{o,n}\}$, where $R_{\max,1}^{o,n}$ and $R_{\max,2}^{o,n}$ are the maximal sum rate of each phase, respectively.

Proof: The sum rate of the first phase is $R_{n,1}^o = R_f^n + R_c^n$, and that of the second phase is $R_{n,2}^o = \hat{R}_f^n + \hat{R}_c^n$. According to the character of DF protocol, the sum rate of NOMA systems is $R_n^o = \min\{R_f^n, \hat{R}_f^n\} + \min\{R_c^n, \hat{R}_c^n\}$. It is observed that $R_n^o \leq \min\{R_{n,1}^o, R_{n,2}^o\}$, thus we can derive $R_{\max}^{o,n} = \min\{R_{\max,1}^{o,n}, R_{\max,2}^{o,n}\}$, where $R_{\max}^{o,n}$, $R_{\max,1}^{o,n}$ and $R_{\max,2}^{o,n}$ are the maximal R_n^o, $R_{n,1}^o$ and $R_{n,2}^o$, respectively. ■

Based on Theorem 1, we can now focus on the realization of $R_{\max,1}^{o,n}$ and $R_{\max,2}^{o,n}$ to reach $R_{\max}^{o,n}$. It is deduced that $R_{n,1}^o = \frac{1}{2}\log_2(1 + \rho|h_n|^2)$, which is irrelevant to the PA coefficients of both users; while $R_{n,2}^o$ is proved to decrease with $\alpha_{n,f}$. As such, for $R_{n,2}^o$, we can just allocate opportune power to $D_{n,f}$ so as to satisfy its minimum rate constraint R_f ($\hat{R}_f^n = R_f$) and then to achieve $R_{\max,2}^{o,n}$, leading to $\alpha_{n,c} = \max\left\{0, \frac{\rho|g_{n,f}|^2 - \varepsilon_f}{\rho|g_{n,f}|^2(1+\varepsilon_f)}\right\}$, where $\varepsilon_f = 2^{2R_f} - 1$; while for $R_{n,1}^o$, the constraint $R_f^n = R_f$ is also applied to ensure that $R_n^o = \min\{R_{\max,1}^{o,n}, R_{\max,2}^{o,n}\}$ can be realized in each transmission. Similarly, $\gamma_{n,c} = \max\left\{0, \frac{\rho|h_n|^2 - \varepsilon_f}{\rho|h_n|^2(1+\varepsilon_f)}\right\}$ is derived.

Remark 1: The adopted dynamic PA strategy in the first phase can also result in the same optimal outage performance as that caused by the coding strategy in the first time slot in [10]. Due to limited space, the proof is omitted herein.

As a result, $R_{\max}^{o,n}$ can be achieved by using the proposed PA strategy above, and the optimal relay is the one which can obtain the maximal $R_{\max}^{o,n}$ among all the relays.

Due to the fact that the achievable rate for the weak user is always R_f, the optimal relay can be thus determined by the following two stages.

1) The first stage is to build a subset of relays by concentrating on correctly decoding both users' messages, which can be expressed as

$$S_n = \left\{ n : 1 \le n \le M, R_f^n \ge R_f, R_c^n \ge R_c \right\}. \tag{8}$$

2) The second stage is to select from S_n the optimal relay that maximizes $D_{n,c}$'s rate, which can be given by

$$n^* = \arg\max_n \left\{ \min\left\{ R_c^n, \hat{R}_c^n \right\}, n \in S_n, \hat{R}_f^n \ge R_f \right\}. \tag{9}$$

As a consequence, the maximal sum rate of considered NOMA networks after RS can be expressed as

$$R_{\max}^o = R_f + \min\left\{ R_c^{n^*}, \hat{R}_c^{n^*} \right\}. \tag{10}$$

IV. Performance Analysis

In this section, the outage probability and diversity order of the proposed RS scheme will be characterized. Before calculating the overall outage probability, we will firstly discuss the outage probability which occurs in the second stage for a specific relay R_n $(n \in S_n)$.

The coverage probability of R_n in the second stage can be written as

$$\begin{aligned} \mathrm{P}_\mathrm{c}^n =& \Pr\left\{ \hat{R}_c^n \ge R_c, |g_{n,c}|^2 \ge |g_{n,f}|^2, \frac{\rho |g_{n,f}|^2 - \varepsilon_f}{\rho |g_{n,f}|^2 (1+\varepsilon_f)} \ge 0 \right\} \\ =& \Pr\left\{ |g_{n,c}|^2 \ge |g_{n,f}|^2 \ge \frac{\varepsilon_f |g_{n,c}|^2}{\rho |g_{n,c}|^2 - \tau_1}, |g_{n,c}|^2 > \frac{\tau_2}{\rho} \right\}, \end{aligned} \tag{11}$$

where $\varepsilon_c = 2^{2R_c} - 1$, $\tau_1 = \varepsilon_c(\varepsilon_f + 1)$, $\tau_2 = \tau_1 + \varepsilon_f$.

Since $g_{n,k}$ $(k = 1, 2)$ follows Nakagami-m distribution with fading parameter m_k and $E[|g_{n,k}|^2] = \Omega_k$, the channel gain $|g_{n,k}|^2$ will follow a Gamma distribution with probability density function (PDF) [15]

$$f_{|g_{n,k}|^2}(y) = \frac{{m_k}^{m_k} y^{m_k - 1}}{\Omega_k^{m_k} \Gamma(m_k)} e^{-\frac{m_k y}{\Omega_k}}, \tag{12}$$

where m_k can take any real value greater than or equal to 0.5 (Rayleigh fading is a special case for $m_k = 1$), $\Gamma(\beta)$ denotes the Gamma function, and $\Gamma(\beta) = (\beta - 1)!$ when β takes integer values. In this paper, m_k is constrained to take integer values by following the same assumption as in [15], as a result, the corresponding cumulative distribution function (CDF) of $g_{n,k}$ can be expressed as

$$F_{|g_{n,k}|^2}(y) = 1 - e^{-\frac{y m_k}{\Omega_k}} \sum_{s=0}^{m_k - 1} \frac{\left(\frac{y m_k}{\Omega_k}\right)^s}{s!}. \tag{13}$$

Note that $|g_{n,c}|^2$ and $|g_{n,f}|^2$ have been ordered as $|g_{n,f}|^2 \le |g_{n,c}|^2$, hence the joint PDF of $|g_{n,c}|^2$ and $|g_{n,f}|^2$ can be given by [16]

$$f_{|g_{n,f}|^2, |g_{n,c}|^2}(x, y) = \sum_{i_1, i_2 \in \{1,2\}} f_{|g_{n,i_1}|^2}(x) f_{|g_{n,i_2}|^2}(y), \tag{14}$$

where $0 \le x \le y$, $i_1, i_2 \in \{1, 2\}$ means $i_1 = 1,\ i_2 = 2$ or $i_1 = 2,\ i_2 = 1$.

Based on (12)-(14), P_c^n can be further written as

$$\begin{aligned} \mathrm{P}_\mathrm{c}^n =& \sum_{i_1, i_2 \in \{1,2\}} \int_{\frac{\tau_2}{\rho}}^{\infty} f_{|g_{n,i_2}|^2}(y) \left(F_{|g_{n,i_1}|^2}(y) - F_{|g_{n,i_1}|^2}\left(\frac{\varepsilon_f y}{\rho y - \tau_1} \right) \right) dy \\ =& \sum_{i_1, i_2 \in \{1,2\}} \int_{\frac{\tau_2}{\rho}}^{\infty} f_{|g_{n,i_2}|^2}(y) (Q_1 - Q_2)\, dy, \end{aligned} \tag{15}$$

where Q_1 and Q_2 are respectively expressed as

$$Q_1 = e^{-\frac{m_{i_1} \varepsilon_f y}{\Omega_{i_1}(\rho y - \tau_1)}} \sum_{r=0}^{m_{i_1} - 1} \frac{\left(\frac{r \varepsilon_f y}{\Omega_{i_1}(\rho y - \tau_1)} \right)^r}{r!}, \tag{16}$$

$$Q_2 = e^{-\frac{m_{i_1} y}{\Omega_{i_1}}} \sum_{s=0}^{m_{i_1} - 1} \frac{\left(\frac{m_{i_1} y}{\Omega_{i_1}} \right)^s}{s!}. \tag{17}$$

From (15), we can firstly calculate the partial integral result R_1, which can be defined as

$$R_1 = \int_{\frac{\tau_2}{\rho}}^{\infty} f_{|g_{n,i_2}|^2}(y)\, Q_1\, dy. \tag{18}$$

Let $t = \frac{\varepsilon_f}{(\rho y - \tau_1)}$, then the above R_1 can be evaluated as

$$\begin{aligned} R_1 =& \sum_{r=0}^{m_{i_1} - 1} \frac{(m_{i_1}/(\Omega_{i_1}\rho))^r}{r!} \frac{{m_{i_2}}^{m_{i_2}} \varepsilon_f}{\Omega_{i_2}^{m_{i_2}} (m_{i_2} - 1)! \rho^{m_{i_2}}} \\ & \times \int_0^1 e^{-\frac{(\varepsilon_f + \tau_1 t)(\Omega_{i_1} m_{i_2} + \Omega_{i_2} m_{i_1} t)}{\Omega_{i_1} \Omega_{i_2} t \rho}} \frac{(\varepsilon_f + \tau_1 t)^{m_{i_2} + r - 1}}{t^{m_{i_2} + 1}} dt. \end{aligned} \tag{19}$$

Define the integral in (19) as I_1. It is difficult to find an exact expression for I_1, therefore Gauss-Chebyshev (G-C) quadrature [10] is applied to derive an approximation

$$I_1 \approx \sum_{j=1}^{N} \varphi\, e^{-\frac{(\varepsilon_f + \tau_1 t_j)(\Omega_{i_1} m_{i_2} + \Omega_{i_2} m_{i_1} t_j)}{\Omega_{i_1} \Omega_{i_2} t_j \rho}} \frac{(\varepsilon_f + \tau_1 t_j)^{m_{i_2} + r - 1}}{t_j^{m_{i_2} + 1}}, \tag{20}$$

where $\varphi = \frac{\pi}{2N} \left| \sin \frac{2i-1}{2N} \pi \right|$, $t_j = \frac{1}{2}\left(1 + \cos \frac{2j-1}{2N} \pi \right)$, and N is a complexity-accuracy tradeoff parameter.

Substituting (20) into (19), a closed-form approximate expression for R_1 can be obtained.

To proceed, another partial integral R_2 from (15) can be calculated, which is defined as

$$\begin{aligned} R_2 =& \int_{\frac{\tau_2}{\rho}}^{\infty} f_{|g_{n,i_2}|^2}(y)\, Q_2\, dy \\ =& \sum_{s=0}^{m_{i_1} - 1} \frac{{m_{i_2}}^{m_{i_2}} {m_{i_1}}^s}{{\Omega_{i_2}}^{m_{i_2}} (m_{i_2} - 1)! {\Omega_{i_1}}^s s!} \int_{\frac{\tau_2}{\rho}}^{\infty} e^{-\omega y} y^{m_{i_2} + s - 1} dy, \end{aligned} \tag{21}$$

where $\omega = \frac{m_{i_1}\Omega_{i_2} + m_{i_2}\Omega_{i_1}}{\Omega_{i_1}\Omega_{i_2}}$. Denote the integral in (21) as I_2, with the aid of (eq. 3.381.3) and (eq. 8.352.7) in [17], I_2 can be further expressed as

$$I_2 = (m_{i_2} + s - 1)!\, \omega^{-(m_{i_2} + s)} e^{-\frac{\tau_2 \omega}{\rho}} \sum_{q=0}^{m_{i_2} + s - 1} \frac{(\tau_2 \omega/\rho)^q}{q!}. \tag{22}$$

Substituting (22) into (21), a closed-form analytical expression for R_2 is obtained.

Based on (15), (19) and (21), a closed-form expression for P_c^n can be derived as

$$\mathrm{P}_{\mathrm{c}}^n = \sum_{i_1,i_2\in\{1,2\}} R_1 - R_2. \tag{23}$$

On the other hand, the probability that λ relays are in S_n for the first stage can be calculated as

$$\begin{aligned}\Pr\{|S_n|=\lambda\} = &\binom{M}{\lambda}\left(e^{-\frac{\tau_2 m_0}{\Omega_0\rho}}\sum_{u=0}^{m_0-1}\frac{\left(\frac{\tau_2 m_0}{\Omega_0\rho}\right)^u}{u!}\right)^{\lambda}\\ &\times\left(1-e^{-\frac{\tau_2 m_0}{\Omega_0\rho}}\sum_{u=0}^{m_0-1}\frac{\left(\frac{\tau_2 m_0}{\Omega_0\rho}\right)^u}{u!}\right)^{M-\lambda},\end{aligned} \tag{24}$$

where the similar CDF of h_n to (13) has been used.

Consequently, the outage probability expression of the proposed scheme can be summarized in the following theorem.

Theorem 2: The closed-form expression for the outage probability of the proposed RS scheme is given by

$$\mathrm{P}_{\mathrm{out}} = \sum_{\lambda=0}^{M}\left(1-\mathrm{P}_{\mathrm{c}}^n\right)^{\lambda}\Pr\{|S_n|=\lambda\}. \tag{25}$$

Proof: Note that the overall outage probability of considered NOMA networks can be written as

$$\mathrm{P}_{\mathrm{out}}=\sum_{\lambda=0}^{M}\underbrace{\Pr\left\{\min\left\{R_c^{n^*},\hat{R}_c^{n^*}\right\}<R_c|\,|S_n|=\lambda\right\}}_{W}\Pr\{|S_n|=\lambda\}, \tag{26}$$

where W can be further expressed as

$$\begin{aligned}W=&\left(1-\Pr\{R_c^n\geq R_c|\,|S_n|=\lambda\}\Pr\left\{\hat{R}_c^n\geq R_c|\,|S_n|=\lambda\right\}\right)^{\lambda}\\ =&\left(1-\Pr\left\{\hat{R}_c^n\geq R_c|\,|S_n|=\lambda\right\}\right)^{\lambda}=(1-\mathrm{P}_c^n)^{\lambda},\end{aligned} \tag{27}$$

substituting (27) into (26), the proof is thus completed. ■

It can be found that the statistics of all channels and two target rates have an impact on the outage probability of the proposed scheme. Afterwards, based on Theorem 2, the diversity order of the proposed RS scheme can be obtained by assuming $\rho\to\infty$, which is given in the following theorem.

Theorem 3: The diversity order of the proposed RS scheme is $d=-\lim_{\rho\to\infty}(\log\mathrm{P}_{\mathrm{out}})/(\log\rho)=M\min\{m_0,m_1,m_2\}$.

Proof: When $\rho\to\infty$, the following approximate expressions can be obtained:

$$\begin{aligned}R_1\approx&\sum_{r=0}^{m_{i_1}-1}\frac{\left(\frac{m_{i_1}\varepsilon_f}{\Omega_{i_1}\rho}\right)^r}{r!}\frac{{m_{i_2}}^{m_{i_2}}e^{-\frac{m_{i_1}\varepsilon_f}{\Omega_{i_1}\rho}}}{{\Omega_{i_2}}^{m_{i_2}}(m_{i_2}-1)!}\int_{\frac{\tau_2}{\rho}}^{\infty}e^{-\frac{m_{i_2}y}{\Omega_{i_2}}}y^{m_{i_2}-1}dy\\ \overset{a}{\approx}&1-\frac{\left(\frac{m_{i_1}\varepsilon_f}{\Omega_{i_1}\rho}\right)^{m_{i_1}}}{m_{i_1}!}-\frac{\left(\frac{m_{i_2}\tau_2}{\Omega_{i_2}\rho}\right)^{m_{i_2}}}{m_{i_2}!}+\frac{\left(\frac{m_{i_1}\varepsilon_f}{\Omega_{i_1}\rho}\right)^{m_{i_1}}\left(\frac{m_{i_2}\tau_2}{\Omega_{i_2}\rho}\right)^{m_{i_2}}}{m_{i_1}!m_{i_2}!},\end{aligned} \tag{28}$$

$$R_2\approx\sum_{s=0}^{m_{i_1}-1}\frac{{m_{i_2}}^{m_{i_2}}{m_{i_1}}^{s}(m_{i_2}+s-1)!}{{\Omega_{i_2}}^{m_{i_2}}(m_{i_2}-1)!{\Omega_{i_1}}^{s}s!}\omega^{-(m_{i_2}+s)}, \tag{29}$$

$$\Pr\{|S_n|=\lambda\}\approx\binom{M}{\lambda}\left(\frac{\left(\frac{\tau_2 m_0}{\Omega_0\rho}\right)^{m_0}}{m_0!}\right)^{M-\lambda}, \tag{30}$$

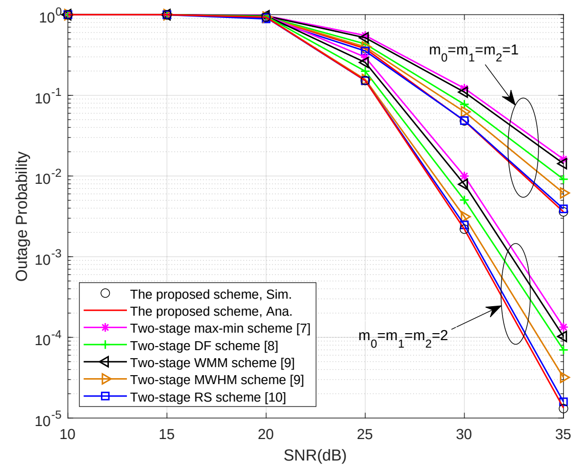

Fig. 2: Outage probability versus the transmit SNR ($M=2$, $d_0=d_2=1$ meter (m), $d_1=2$ m, $R_f=1$ bit per channel use (BPCU), $R_c=2.5$ BPCU, and different m_0,m_1,m_2).

where step a is obtained with the aid of (eq. 3.381.3) in [17], and $e^{-x}\approx 1-x$ has been used when $x\to 0$. Substituting (28)-(30) into (25), We have

$$\mathrm{P}_{\mathrm{out}}\propto\frac{1}{\rho^{m_0(M-\lambda)+\min\left\{m_{i_1},m_{i_2}\right\}\lambda}}\propto\frac{1}{\rho^{M\min\{m_0,m_1,m_2\}}}. \tag{31}$$

As a result, Theorem 3 is proved. ■

Remark 2: One can find that maximal diversity order can be achieved by the proposed scheme, which is determined by the number of relays and the minimum value of all channels' fading parameters. Despite that the diversity orders of other RS schemes [7]–[10] were not discussed under Nakagami-m fading, it is observed that the same full diversity order can be achieved by these schemes through simulations. However, the proposed RS scheme reaches lower outage probability than the ones in [7]–[9], and outperforms the RS scheme in [10] for some cases, which will be verified in Section V.

V. Simulation Results

In this section, we conduct simulations to evaluate the outage performance of several RS schemes in cooperative NOMA networks under Nakagami-m fading channels. The two-stage max-min RS scheme in [7], two-stage DF RS scheme in [8], two-stage weighted-max-min (WMM) RS scheme and max-weighted-harmonic-mean (MWHM) RS scheme in [9], and two-stage RS scheme in [10] are taken for comparisons with the proposed RS scheme. Specifically, it is assumed that $\Omega_i=d_i^{-\alpha}$, $i=0,1,2$, where d_i denotes the distance of corresponding link, α denotes the path loss exponent and $\alpha=3$ is set here. Moreover, the PA coefficients for fixed PA based RS schemes are set as $\gamma_{n,f}=\alpha_{n,f}=0.8$, and G-C complexity-accuracy tradeoff parameter is set as $N=100$. Without loss of generality, for the RS schemes in [7]–[10], R_f is adopted by D_1 and R_c is adopted by D_2, respectively.

Fig. 2 plots the outage probability versus the transmit SNR in different fading parameters. It is shown that the proposed RS scheme outperforms the RS schemes in [7]–[9], and achieves the similar performance to that in [10]. This is due to the

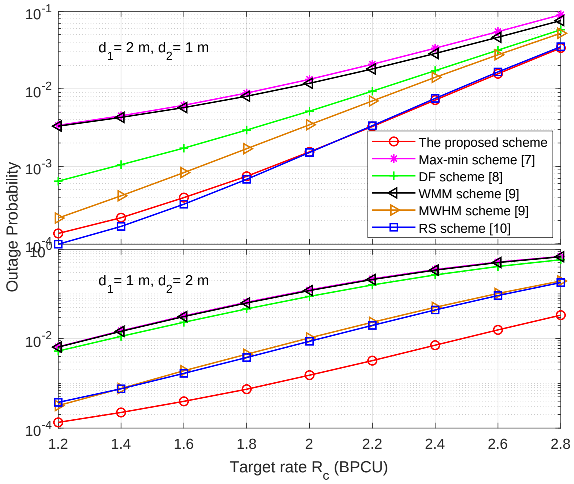

Fig. 3: Outage probability versus the target rate R_c ($M = 3$, $m_0 = m_1 = m_2 = 1$, $R_f = 1$ BPCU, $\rho = 30$ dB, $d_0 = 1$ m and different d_1, d_2).

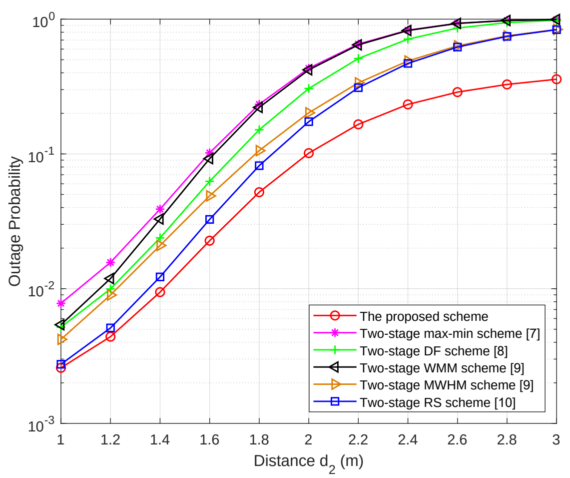

Fig. 4: Outage probability versus the distance d_2 ($M = 3$, $m_0 = 1$, $m_1 = m_2 = 2$, $R_f = 1$ BPCU, $R_c = 2.5$ BPCU, $d_0 = 1$ m, $d_1 = 2$ m, and $\rho = 30$ dB).

reason that in order to maximize the sum rate, the ICSI has been used in the joint design of user ordering and PA strategy for the proposed scheme, which benefits the outage performance, as concluded in [10]. Moreover, It is observed that all the curves under the identical m_0, m_1 and m_2 have the same slope, which means that the same diversity order can be achieved. In addition, the system under Rayleigh fading ($m_k = 1$, $k = 0, 1, 2$) exhibits a poorer performance than that under Nakagami-m fading, which demonstrates the necessity of investigating Nakagami-m fading.

Fig. 3 shows the outage probability versus the target rate R_c in different d_1 and d_2. It can be seen that the outage probability increases with R_c. Furthermore, It is observed that the situation that d_2 is larger than d_1 leads to the better outage performance of the proposed RS scheme than the RS scheme in [10]. The reason for this performance gain is that in the proposed scheme, the weak user is always associated with the lower target rate constraint, thus more remaining power can be allocated to the strong user to meet the higher target rate requirement; while in [10], the weak user may be associated with the higher target rate constraint, which leads to a noteworthy power loss for the strong user to meet another target rate requirement. The outage probability versus the distance (d_2) can be illustrated more intuitively in Fig. 4. One can find that the outage probability increases with d_2, and the performance gap between the proposed scheme and the RS scheme in [10] enlarges with d_2 as expected.

VI. Conclusions

We have proposed a new sum-rate maximization based RS scheme for cooperative NOMA networks under Nakagami-m fading in this paper, where each user has two alternative target rates. A closed-form outage probability expression and the diversity order of the proposed scheme have been derived to characterize the performance. Moreover, simulation results have been presented to compare the proposed RS scheme with other RS schemes in terms of outage probability.

References

[1] W. Yu, L. Musavian, and Q. Ni, "Link-layer capacity of NOMA under statistical delay QoS guarantees," *IEEE Trans. Commun.*, vol. 66, no. 10, pp. 4907–4922, Oct. 2018.

[2] Z. Shi, W. Gao, S. Zhang, J. Liu, and N. Kato, "AI-enhanced cooperative spectrum sensing for non-orthogonal multiple access," *IEEE Wirel. Commun.*, vol. 27, no. 2, pp. 173–179, Apr. 2020.

[3] S. M. R. Islam, N. Avazov, O. A. Dobre, and K. Kwak, "Power-domain non-orthogonal multiple access (NOMA) in 5G systems: Potentials and challenges," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 721–742, Secondquarter 2017.

[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. Li, Y. Li, Y. Chen, Y. Ye, and H. Zhang, "Performance analysis of cooperative NOMA with a shared AF relay," *IET Commun.*, vol. 12, no. 19, pp. 2438–2447, Nov. 2018.

[6] M. F. Kader and S. Y. Shin, "Cooperative relaying using space-time block coded non-orthogonal multiple access," *IEEE Trans. Veh. Technol.*, vol. 66, no. 7, pp. 5894–5903, Jul. 2017.

[7] Z. Ding, H. Dai, and H. V. Poor, "Relay selection for cooperative NOMA," *IEEE Wirel. Commun. Lett.*, vol. 5, no. 4, pp. 416–419, Aug. 2016.

[8] Z. Yang, Z. Ding, Y. Wu, and P. Fan, "Novel relay selection strategies for cooperative NOMA," *IEEE Trans. Veh. Technol.*, vol. 66, no. 11, pp. 10 114–10 123, Sept. 2017.

[9] P. Xu, Z. Yang, Z. Ding, and Z. Zhang, "Optimal relay selection schemes for cooperative NOMA," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 7851–7855, Aug. 2018.

[10] Y. Li, Y. Li, X. Chu, Y. Ye, and H. Zhang, "Performance analysis of relay selection in cooperative NOMA networks," *IEEE Commun. Lett.*, vol. 23, no. 4, pp. 760–763, Apr. 2019.

[11] A. Tregancini, E. E. B. Olivo, D. P. M. Osorio, C. H. M. de Lima, and H. Alves, "Performance analysis of full-duplex relay-aided NOMA systems using partial relay selection," *IEEE Trans. Veh. Technol.*, vol. 69, no. 1, pp. 622–635, Jan. 2020.

[12] M. Alkhawatrah, Y. Gong, G. Chen, S. Lambotharan, and J. A. Chambers, "Buffer-aided relay selection for cooperative NOMA in the internet of things," *IEEE Internet Things J.*, vol. 6, no. 3, pp. 5722–5731, Jun. 2019.

[13] B. Kamali, *The IEEE 802.16 Standards and the WiMAX Technology*, 1st ed. New Jersey, USA: Wiley-IEEE Standards Association, 2018.

[14] K. N. Le and V. W. Y. Tam, "Wireless secrecy under multivariate correlated Nakagami-m fading," *IEEE Access*, vol. 8, pp. 33 223–33 236, 2020.

[15] Z. Xiang, W. Yang, Y. Cai, Z. Ding, and Y. Song, "Secure transmission design in HARQ assisted cognitive NOMA networks," *IEEE Trans. Inf. Forensics Security*, vol. 15, pp. 2528–2541, Jan. 2020.

[16] H. A. David and H. N. Nagaraja, *Order Statistics*, 3rd ed. New York, NY, USA: John Wiley, 2003.

[17] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series and Products*, 7th ed. New York, NY, USA: Academic, 2007.