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Research Article EAI.EU

Adaptive-Duplex Relay Selection for Cooperative Non-Orthogonal Multiple Access Networks

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Abstract

To further improve the spectral efficiency of the cooperative non-orthogonal multiple access (NOMA) network with half-duplex (HD) relaying and avoid the zero diversity gain due to the imperfect self interference estimation at high signa-to-noise ratio (SNR) value with full-duplex (FD) relaying, this paper developed a novel two-stage relay selection for a two-user multi-relay cooperative NOMA systems with adaptive-duplex (AD) relaying which can switch opportunistically between HD and FD relaying modes. An adaptive duplex based on fixed power allocation factor relay selection (AD-FPA-RS) scheme for cooperative NOMA networks is proposed in this paper, the relay can switch the work mode to the FD or HD state adaptively according to the current channel state information and the result of decode at the relay. Futhermore, the exact outage probability for the proposed AD-FPA-RS scheme is obtained in closed-form expression. The simulation and numerical results show that the proposed AD-FPA-RS scheme not only outperforms the existing HD-FPA-RS and FD-FPA-RS schemes in terms of outage behavior significantly, but also can obtain full diversity gain without the floor outage performance at high SNR region.

Received on 19 November 2023; accepted on 8 May 2024; published on 13 May 2024

Keywords: Cooperative NOMA, relay selection, adaptive-duplex relaying, outage performance.

doi:10.4108/ew.7182

1. Introduction

SPECTRAL efficiency, services with high data rates, and massive connectivity are the main factors to be satisfied in the next generation wireless communication systems. Non-orthogonal multiple access (NOMA) technique has recently received enormous interests due to the improvement on system spectral efficiency significantly[1–3]. Cooperative NOMA as an important application is emerging from various research directions, where users or dedicated relays cooperate to improve the transmission reliability. Specifically, in cooperative NOMA systems, two or more user signals can be multiplexed in the power domain at the source side and successive interference cancellation (SIC) is implemented at the strong user or decicated relay to assist the other users if using decode-and-forward (DF) relaying scheme. Moreover, in cooperative NOMA networks with multi-relay scenario, relay selection (RS) technology can further improve system outage performance and obtain spatial diversity gain.

In [4], a two-stage single relay selection (SRS) scheme was proposed for a two-user multi-relay cooperative NOMA system, and the closed-form expression for the exact outage probability is derived. The results illustrate that the outage performance of the proposed two-stage RS scheme is superior to the conventional max-min RS scheme and can obtain a better performance than orthogonal multiple access (OMA) significantly. While in [4], the power allocation factor is fixed, to further improve the syetem performance, the two-stage RS schemes based on half-dynamic power allocation and dynamic power allocation (DPA) are proposed in [5] and [6], respectively. The proposed schemes can adjust the power alloction value of the transmission link adaptively to guarantee the maximum user data rate according to a corresponding criterion. In addition, in [6], two dual-relay selection strategies with distributed space-time coding are discussed to achieve a better outage performance without sacrificing spectral

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efficiency. One is namely two-stage dual relay selection with fixed power allocation (DRS-FPA) and the other is two-stage dual relay selection with dynamic power allocation (DRS-DPA). It is to be noted that all the above cited works adopted half-duplex (HD) relaying cooperation mechanism for their study, where two orthogonal resources (time slots or frequency bands) are allocated for the respective reception and transmission at the relay to complete the communication process. It is straightforward to achieve full diversity gain with the HD mode but the allocation of two orthogonal resources imposes severe degradation in the multiplexing gain.

Full-duplex (FD) relay can transmit and receive signals simultaneously in the same frequency band, which can further improve the bandwidth usage efficiency of cooperative NOMA networks. Besides, the development of self-interference (SI) cancellation technology makes the application of FD technology in practical communication possible. In [7], a pair of RS schemes for FD/HD NOMA networks was investigated insightfully, the simulation and analytical results reveal that, the FD-based RS schemes outperform the HD-bases RS schemes in the low signal-to-noise ratio (SNR) region, while due to the impact of SI at the relay, the FD-based RS schemes olny obtain a zero diversity order. Ref. [8] and [9] studied the performances of FD relaying system with other channel model. In [8], two stage relay selection for cooperative NOMA system based transmission between a source and two end users over i.i.d. slow fading generalized-K distributed channels was introduced for HD/FD transmission with imperfect SI cancellation And Nakagami-m fading channel along with three specific relay selection schemes were studied in [9], the impact of the number of intermediate relays, the NOMA power allocation factor, and the Nakagami-m fading severity parameter on the outage performance of the NOMA users were evaluated. It was demonstrated that the FD relay used instead of HD relay in cooperative NOMA can, no doubt, yield better performance under perfect SI cancellation, but that performance gain depends very much on residual SI under imperfect self-interference cancellation. At high SNR region, the outage performance of FD NOMA converges to an error floor and results in a zero diversity order. Therefore, the superiority of FD NOMA is no longer apparent with the values of residual SI increasing.

To overcome the spectral efficiency loss and achieve a full diversity gain, a two-stage relay selection with adaptive-duplex (AD) protocol relaying for a cooperative NOMA network is investigated in this paper. The operation mode of the relays can switch between FD and HD mode adaptively according to the current channel conditions and the decoding results. The motivation for opportunistic mode selection stems from the fundamental trade-off between the spectral efficiency and diversity gian: The half-duplex mode avoids inherently the self-interference at the cost of halving the end-to-end symbol rate while the full-duplex mode achieves full symbol rate but, in practice, suffers from residual interference even after cancellation. Consequently, either mode can be favorable depending on the channel states (the status of relay set for decoding correctly). And then a closed-form expression of the outage probability of the proposed scheme is obtained. The simulation and numerical results show that the proposed AD-FPA-RS scheme not only yield better outage performance than both the existing FD and HD relay selection schemes, but also can achieve full diversity gain.

The rest of this paper is organized as follows. Section II introduces the system model of cooperative NOMA. The outage performance for the proposed AD-FPA-RS scheme are developed in Section III. Simulations and Numerical results are presented in Section IV to illustrate the performance of the proposed scheme. Finally, the conclusion is drawn in Section V.

2. System Model

Consider a two-user cooperative NOMA system consisting of a source S considered as a base station (BS), N full-duplex relays R, and two users U_1 and U_2. Assume that the BS and all the users are equipped with a single antenna, and each relay is equipped with two antennas, one for transmission and the other one for reception, and note that the relays can switch operation between FD and HD mode[1]. Besides, no direct link between the BS and users exists due to obstacles or heavy shadowing, therefore, the relays assist the users to communicate with the BS. Suppose all the relay utilize decode-and-forward (DF) scheme in this paper. Furthermore, assume that all links undergo quasi-static Rayleigh fading, and the instantaneous channel state information (CSI) can be perfectly estimated at the related receivers and fed back to the corresponding transmitter reliably without delay[2]. Therefore, the system comprises three wireless links, namely source-relay (SR), residual self-interference (SI), and relay-destination (SD) link, respectively.

During the time slot t, the BS broadcasts to all the relays a superimposed mixture of s_1 and s_2 intended for two users U_1 and U_2 respectively as:

$$x(t) = \sqrt{P_s \alpha_1} s_1(t) + \sqrt{P_s \alpha_2} s_2(t), \quad (1)$$

where P_s is the transmit power of the source, s_i is the desired signal for U_i and α_i denotes the power

[1] Here, we assume all the relays operate in the same mode at the same time.

[2] It is assumed that perfect CSI can be obtained, our future work will relax this idealized assumption.

allocation coefficient, $i \in \{1,\ 2\}$. Note that $\alpha_1 + \alpha_2 = 1$ and $\alpha_1 \geq \alpha_2$ according to the NOMA protocol, more power is assigned for the worse channel condition or low data rate QoS requirement[3][4].

2.1. Full Duplex (FD) Relay Model

Consider the relays work in FD mode, due to signal leakage, the self-interference exists, which can be weakened by adjusting the antenna, analog circuit and digital circuit. However, it is difficult to completely cancel SI. Therefore, we assume imperfect interference cancellation, i.e., residual interference exists, which is modeled as Rayleigh fading channel, similiar to [10]. The signal received by the relay R_n , $n \in \{1, \cdots, N\}$, at time slot t can be observed as

$$y_n(t) = \underbrace{g_n(t)x(t)}_{\text{Desired signal}} + \underbrace{\sqrt{\kappa}g_r(t)x_r(t)}_{\text{Self-interference}} + n_{R_n}(t), \tag{2}$$

where $g_n \sim \mathcal{CN}(0, \lambda_n)$ and $g_r \sim \mathcal{CN}(0, \lambda_r)$ denote the channel coefficient between BS and relay n and the self-interference channel coefficient of relay n, respectively. And $0 \leq \kappa \leq 1$ is the self-interference cancellation factor, defining the level of residual interference. In particular, $\kappa = 0$ implies perfect self-interference cancellation, while $\kappa = 1$ means no self-interference cancellation technique implemented. The noise n_{R_n} is the additive white Gaussian noise with zero mean and variance of N_0. SIC is performed at the relays to decode the signals for user 1 and user 2, respectively. Assume the relay node $R_{(N)}$ is selected to transmit the decoded signals for U_1 and U_2 among the available relay set, meanwhile $R_{(N)}$ recodes the signals at time slot t, which is shown as:

$$x_r(t) = \sqrt{P_r\alpha_1}s_1(t-\tau) + \sqrt{P_r\alpha_2}s_2(t-\tau) \tag{3}$$

where τ denotes the processing delay at the relay[3], and P_r is the relay transmit power, it is assumed $P_r = P_s$. According to the decoding principle of SIC detection, the conditions for a relay to decode the two signals, s_1 and s_2, are given by

$$R^{\mathrm{FD}}_{1\to \mathrm{r}} = \log_2\left(1 + \frac{\alpha_1|g_n|^2}{\alpha_2|g_n|^2 + \kappa b|g_r|^2 + 1/\rho}\right) \geq R_1, \tag{4}$$

$$R^{\mathrm{FD}}_{2\to \mathrm{r}} = \log_2\left(1 + \frac{\alpha_2|g_n|^2}{\kappa b|g_r|^2 + 1/\rho}\right) \geq R_2, \tag{5}$$

where $\rho = P_s/N_0$ denotes the transmit signal-to-noise ratio (SNR), and $R^{\mathrm{FD}}_{i\to \mathrm{r}}$, $i = 1, 2$ is the user data rate at the relay. Then the selected relay $R_{(N)}$ forwards the signals to the users. Hence, the received signal at user i is given by

$$y_i(t) = h_{(N)i}(t)x_r(t) + n_i(t), \tag{6}$$

where $h_{(N)i} \sim \mathcal{CN}(0, 1)$ is the channel coefficient between the selected best relay $R_{(N)}$ and user U_i, n_i is the additive white Gaussian noise with zero mean and variance of N_0. Therefore, the achievable instantaneous data rates for user 1 and user 2 in FD relay mode can be obtained as follows:

$$R^{\mathrm{FD}}_1 = \log_2\left(1 + \frac{\alpha_1|h_{(N)1}|^2}{\alpha_2|h_{(N)1}|^2 + 1/\rho}\right), \tag{7}$$

$$R^{\mathrm{FD}}_{1\to 2} = \log_2\left(1 + \frac{\alpha_1|h_{(N)2}|^2}{\alpha_2|h_{(N)2}|^2 + 1/\rho}\right), \tag{8}$$

$$R^{\mathrm{FD}}_2 = \log_2\left(1 + \rho\alpha_2|h_{(N)2}|^2\right). \tag{9}$$

where R^{FD}_i is the instantaneous rate for user U_i to detect its own signals in FD relay mode, the SIC is carried out at user 2 to remove the signal for user 1, and $R^{\mathrm{FD}}_{1\to 2}$ is the instantaneous rate for user 2 to detect the signal for user 1 in FD relay mode.

2.2. Half Duplex (HD) Relay Model

Different from FD relay mode, when the relays work in HD mode, two continuous slots are required to finish the information transmission, one slot is used for receiving of S-R link, and the other is used for sending signals of R-D link. Therefore, the signal received by the nth relay R_n, $n \in \{1, \cdots, N\}$ at time slot t can be observed as

$$y^{\mathrm{HD}}_n(t) = g_n(t)x(t) + n_{R_n}(t), \tag{10}$$

Similarly, the best relay is selected among the available set, SIC detection is used at the selected relay and all the users. Then the achievable instantaneous data rates for user 1 and user 2 at the relay can be given respectively as follows:

$$R^{\mathrm{HD}}_{1\to \mathrm{r}} = \frac{1}{2}\log_2\left(1 + \frac{\alpha_1|g_n|^2}{\alpha_2|g_n|^2 + 1/\rho}\right), \tag{11}$$

$$R^{\mathrm{HD}}_{2\to \mathrm{r}} = \frac{1}{2}\log_2\left(1 + \alpha_2\rho|g_n|^2\right), \tag{12}$$

The received signal at users U_i can be presented as

$$y^{\mathrm{HD}}_i(t+1) = h_{(n)i}(t+1)\left(\sqrt{P_r\alpha_1}s_1(t+1) + \sqrt{P_r\alpha_2}s_2(t+1)\right) + n_i(t+1), \tag{13}$$

[3]Assume that there is no the processing delay in this paper.

The achievable instantaneous data rate of user U_1 and U_2 can be written respectively:

$$R_1^{HD} = \frac{1}{2}\log_2\left(1 + \frac{\alpha_1|h_{(n)1}|^2}{\alpha_2|h_{(n)1}|^2 + 1/\rho}\right), \tag{14}$$

$$R_{1\to2}^{HD} = \frac{1}{2}\log_2\left(1 + \frac{\alpha_1|h_{(n)2}|^2}{\alpha_2|h_{(n)2}|^2 + 1/\rho}\right), \tag{15}$$

$$R_2^{HD} = \frac{1}{2}\log_2\left(1 + \rho\alpha_2|h_{(n)2}|^2\right). \tag{16}$$

where R_i^{HD} denotes the instantaneous rate for user U_i in HD relay mode, and $R_{1\to2}^{HD}$ denotes the instantaneous rate for user 2 to detect the signal for user 1 in HD relay mode.

2.3. Adaptive Duplex (AD) Relay Model

Compare the equations (7), (8), (9) at FD relay mode and the equations (14), (15), (16) at HD relay mode, it is easy to see that, if the channel conditions and the transmission power are the same for FD and HD relay modes, the instantaneous rates of the users under the FD relay mode are twice as high as that under the HD relay mode. In other words, as long as there is a relay that can successfully decode the NOMA signals from the BS, the FD relay mode can greatly improve the spectrum efficiency of the system. However, in fact, the existence of SI for FD relay mode limits the decoding accuracy and affect the system performance. In order to achieve a balance between the system reliability and the spectral efficiency, an adaptive duplex relay model is proposed in this paper. In the proposed model, the relay can adjust its work mode switching between the FD and HD state adaptively according to the decoding results of the relay. For the proposed adaptive duplex relay model, the signal received by the nst relay R_n, $n \in \{1, \cdots, N\}$ can be expressed as follows:

$$y_n(t) = g_n(t)x(t) + \varpi\sqrt{\kappa}g_r(t)x_r(t) + n_{R_n}(t), \tag{17}$$

Define ϖ as the relay work mode factor, where $\varpi = 1$ and $\varpi = 0$ denote the relay work in FD and HD mode, respectively. Therefore, the instantaneous user data rates at AD relay mode can be obtained as:

$$R_{i\to r}^{AD} = \begin{cases} R_{i\to r}^{FD}, & \varpi = 1 \\ R_{i\to r}^{HD}, & \varpi = 0 \end{cases} \quad i = 1, 2 \tag{18}$$

$$R_i^{AD} = \begin{cases} R_i^{FD}, & \varpi = 1 \\ R_i^{HD}, & \varpi = 0 \end{cases} \quad i = 1, 2 \tag{19}$$

$$R_{1\to2}^{AD} = \begin{cases} R_{1\to2}^{FD}, & \varpi = 1 \\ R_{1\to2}^{HD}, & \varpi = 0 \end{cases} \tag{20}$$

3. Adaptive Relay Selection Strategy

For the AD relay, its work mode can switch from FD to HD or in reverse adaptively. Due to the imperfect interference cancellation of FD relay mode, with the system SNR increasing, the impact of residual SI is dominant, then there will be an error floor. While HD relay is free from self-interference, which can improve the performance at high SNR. In order to exploit the tradeoff between the spectral efficiency loss of HD and the inherent SI of FD, we proposed an adaptive duplex based on fixed power allocation factor relay selection (AD-FPA-RS) scheme for cooperative NOMA networks. A two-stage AD relay selection scheme is studied in this section, in the proposed AD relay selection scheme, set the initial operating mode of all the relays at FD mode, the first stage is to find a subset of the relays which can successfully decode the messages of the two users U_1 and U_2 strictly, if the available relay set is not null set, then the relays work in FD mode, otherwise, switch all the relays to HD operation mode. In conclusion, the available subset S_r for the AD relay selection scheme can be expressed by:

$$\begin{aligned} S_r = \Bigg\{ n : \; & \log_2\left(1 + \frac{\alpha_1|g_n|^2}{\alpha_2|g_n|^2 + \kappa|g_r|^2 + 1/\rho}\right) \geq R_1, \\ & \log_2\left(1 + \frac{\alpha_2|g_n|^2}{\kappa|g_r|^2 + 1/\rho}\right) \geq R_2, \\ & \log_2\left(1 + \frac{\alpha_1|h_{n1}|^2}{\alpha_2|h_{n1}|^2 + 1/\rho}\right) \geq R_1 \\ & \log_2\left(1 + \frac{\alpha_1|h_{n2}|^2}{\alpha_2|h_{n2}|^2 + 1/\rho}\right) \geq R_1, \\ & \log_2\left(1 + \rho\alpha_2|h_{n2}|^2\right) \geq R_2, 1 \leq n \leq N \Bigg\} \end{aligned} \tag{21}$$

$$= \{f1_n \geq 0,\; f2_n \geq 0,\; f3_n \geq 0,\; f4_n \geq 0,\; f5_n \geq 0\}, \tag{22}$$

where $f1_n = |g_n|^2 - \xi_1\left(\rho\kappa|g_r|^2 + 1\right)$, $f2_n = |g_n|^2 - \xi_2\left(\rho\kappa|g_r|^2 + 1\right)$, $f3_n = |h_{n1}|^2 - \xi_1$, $f4_n = |h_{n2}|^2 - \xi_1$, $f5_n = |h_{n2}|^2 - \xi_2$. In addition, $\xi_1 = \frac{\epsilon_1/\rho}{\alpha_1 - \alpha_2\epsilon_1}$, $\xi_2 = \frac{\epsilon_2/\rho}{\alpha_2}$.

At the sencond stage, the max-min scheme is applied to select the best relay from the available subset in the first stage to assist the transmission. The details are as follows:

$$\text{ch}_{n^*} = \begin{cases} \max_n \min\{f1_n,\; f2_n,\; f3_n,\; f4_n,\; f5_n\}, & |S_r| \neq \varnothing \\ \max_n \min\{h1_n,\; h2_n,\; h3_n,\; h4_n,\; h5_n\}, & |S_r| = \varnothing \end{cases} \tag{23}$$

$$n_{AD}^* = \arg \text{ch}_{n^*}. \tag{24}$$

Similar to fj_n, $j = 1, \ldots, 5$, $h1_n = |g_n|^2 - \mu_1$, $h2_n = |g_n|^2 - \mu_2$, $h3_n = |h_{n1}|^2 - \mu_1$, $h4_n = |h_{n2}|^2 - \mu_1$, $h5_n = |h_{n2}|^2 - \mu_2$. Where $\varepsilon_i = 2^{2R_i} - 1$, $i = 1, 2$, $\mu_1 = \frac{\varepsilon_1/\rho}{\alpha_1 - \alpha_2\varepsilon_1}$, $\mu_2 = \frac{\varepsilon_2/\rho}{\alpha_2}$. The available set B_r for the HD relay mode should meet the condition $B_r = \{h1_n \geq 0,\; h2_n \geq 0,\; h3_n \geq 0,\; h4_n \geq 0,\; h5_n \geq 0\}$ to guarantee the system reliability. Compare the expressions of fj_n and hj_n, when the requirements of the power alloction factors, the target data rate and the channel fading condition are the same, it always satisfyies $f3_n > h3_n$, $f4_n > h4_n$, $f5_n > h5_n$, in other words, the main reason for the case that make the available FD relay set be null set while the HD relay set not depends on the value of residual SI. As the value of residual SI increases, at least one of the terms between $f1, n$ and $f2, n$ is less than 0, then the relay will switch its operation mode from FD to HD adaptively.

4. Outage Performance Analysis

In this section, the outage probability of the considered AD-FPA-RS scheme is analyzed. As we know, the performance of FD-RS scheme is limited by self-interference[7]. In the proposed scheme, when the FD-RS scheme is not available, that is, the system is in outage if using FD relay mode, then switch the relay to HD-RS scheme. Therefore, the AD-FPA-RS scheme is in outage if and only if both FD-RS and HD-RS are in outage, then the overall outage probability of AD-FPA-RS scheme can be expressed by

$$\begin{aligned} P_{\text{out}}^{\text{AD}} &= \Pr\left\{\max_n \min(fj_n) < 0,\ \max_n \min(hj_n) < 0\right\} \\ &= \Pr\left\{\max\left(\max_n \min(fj_n), \max_n \min(hj_n)\right) < 0\right\} \\ &= \Pr\left\{\max_n \max(\min(fj_n), \min(hj_n)) < 0\right\} \\ &= \Pr\{\min(fj_n) < 0,\ \min(hj_n) < 0\}^N, \end{aligned} \quad (25)$$

where $j = 1, \dots, 5$. Theorem 1. provides an exact expression for the overall outage probability achieved by the AD-FPA-RS scheme in cooperative NOMA, as well as its diversity gain.

Theorem 1. The overall outage probability in cooperative NOMA with the proposed AD-FPA-RS scheme is given by:

$$P_{\text{out}}^{\text{AD}} = \left(1 - \frac{e^{-\frac{2\gamma+\zeta}{\rho}}}{\gamma\kappa\lambda_r + 1} - e^{-\frac{1}{\rho}\left(\varphi+2\nu+\frac{d}{\lambda_r}\right)} + e^{-\frac{\varphi+\nu+\gamma}{\rho}} \frac{e^{-\left(\gamma\kappa+\frac{1}{\lambda_r}\right)\frac{d}{\rho}}}{\gamma\kappa\lambda_r + 1}\right)^N \quad (26)$$

Proof. According to the complementary principle of the probability,

$$\Pr\{\min(fj_n) < 0,\ \min(hj_n) < 0\} = 1 - Q_1 - Q_2, \quad (27)$$

where

$$Q_1 = \Pr\{\min(fj_n) > 0\},$$
$$Q_2 = \Pr\{\min(fj_n) < 0,\ \min(hj_n) > 0\},$$

According to the proposed AD-FPA-RS scheme, the value Q_1 and Q_2 can be calculated as respectively:

$$\begin{aligned} Q_1 &= \Pr\left\{|g_n|^2 \geq \frac{\gamma}{\rho}\left(\rho\kappa|g_r|^2 + 1\right),\ |h_{n1}|^2 \geq \frac{\zeta}{\rho},\ |h_{n2}|^2 \geq \frac{\gamma}{\rho}\right\} \\ &= \frac{e^{-\frac{2\gamma}{\rho}} e^{-\frac{\zeta}{\rho}}}{\gamma\kappa\lambda_r + 1}, \end{aligned} \quad (28)$$

$$\begin{aligned} Q_2 &= \Pr\left\{\frac{\nu}{\rho} \leq |g_n|^2 \leq \frac{\gamma}{\rho}\left(\rho\kappa|g_r|^2 + 1\right),\ |g_r|^2 \geq \frac{d}{\rho},\right. \\ &\qquad \left. |h_{n1}|^2 \geq \frac{\varphi}{\rho},\ |h_{n2}|^2 \geq \frac{\nu}{\rho}\right\} \\ &= e^{-\frac{\varphi}{\rho}} e^{-\frac{2\nu}{\rho}} e^{-\frac{d}{\rho\lambda_r}} - e^{\frac{\varphi}{\rho}} e^{-\frac{\nu}{\rho}} e^{-\frac{\gamma}{\rho}} \frac{e^{-\left(\gamma\kappa+\frac{1}{\lambda_r}\right)\frac{d}{\rho}}}{\gamma\kappa\lambda_r + 1}, \end{aligned} \quad (29)$$

where, $\zeta = \frac{\epsilon_1}{\alpha_1 - \alpha_2\epsilon_1}$, $\gamma = \max\left(\frac{\epsilon_1}{\alpha_1 - \alpha_2\epsilon_1}, \frac{\epsilon_2}{\alpha_2}\right)$, $\varphi = \frac{\varepsilon_1}{\alpha_1 - \alpha_2\varepsilon_1}$, $\nu = \max\left(\frac{\varepsilon_1}{\alpha_1 - \alpha_2\varepsilon_1}, \frac{\varepsilon_2}{\alpha_2}\right)$, $d = \max\left(0, \frac{\nu-\gamma}{\gamma\kappa}\right)$.

Plug the equations (28) and (29) into the equations (27) and (25), the equation (26) can be obtained. □

When $\rho \to \infty$, $\frac{1}{\rho} \to 0$, the function $e^{-\frac{x}{\rho}}$ can be approximated as $1 - \frac{x}{\rho}$. Therefore, the outage performance $P_{\text{out}}^{\text{AD}}$ for AD-FPA-RS scheme at high SNR can be expressed approximately as follows:

$$P_{\text{out}}^{\text{AD}} = \frac{1}{\rho^N}\left(\varphi + 2\nu + \frac{\gamma + \zeta - \varphi - \nu}{\gamma\kappa\lambda_r + 1}\right)^N. \quad (30)$$

The equation (30) shows that the AD-FPA-RS scheme can achieve full diversity.

5. Numerical and Simulation Results

In this section, the outage performance of the proposed AD-FPA-RS scheme for cooperative NOMA systems is evaluated by using computer simulation to vertify the accuracy of theoretical analysis. Suppose that all the channels are independent and identically distributed, i.e., $\mathcal{CN}(0, 1)$. The self-interference channel coefficient of FD relay, $g_r \sim \mathcal{CN}(0, 0.3)$ [11]. The proposed AD-FPA-RS scheme as AD-FPA for short in the figures. For the comparison with HD-FPA in [4] and FD-FPA in [7], the parameters are set as the target data rate $R_1 = 0.5 bits/s/Hz$, $R_2 = 2 bits/s/Hz$, $\alpha_1 = \frac{3}{4}$.

Figs. 1-3 show the outage probability for the proposed AD-FPA-RS scheme with different relay number N and self-interference cancellation factor $\kappa = 0, 0.1, 1$, respectively. We can see that for all the cases, the AD-FPA relay selection scheme not only yield better outage performance than the FD-FPA and HD-FPA relay selection schemes, but can also achieve full diversity gain. That's because the AD-FPA relay selection scheme adaptively adjusts the operation mode of the relay. When the residual SI is small, the relay works in FD mode for most of the time, then the spectral

Table 1. Numerical example for the case HD>FD

SI cancellation factor κ	SNR ρ critical point
$\kappa = 0.1$	$\rho = 25dB$
$\kappa = 1$	$\rho = 16.7dB$

efficiency of the system can be improved, otherwise, as the residual SI increases, HD mode is perfered to avoid error floor. Therefore, AD-FPA relay selection scheme can achieve a tradeoff between the reliability and the effectiveness.

Fig. 1 shows different outage probabilities of various relay selection schemes, i.e., AD-FPA, FD-FPA and HD-FPA, under the ideal self-interference cancellation state $\kappa = 0$. It can be seen that when the relay can completely eliminate the impact of self-interference, the outage performances of AD-FPA and FD-FPA are the same, and the available rate of FD mode is twice that of HD mode under the same channel condition, therefore, FD mode will always be selected in the proposed AD relay selection scheme. Fig. 2 and Fig. 3 give the outage case for $\kappa = 0.1$ and $\kappa = 1$ respectively. The smaller the value of κ, the better SI cancellation technology. When the residual SI is large, the system is limited by self-interference, if the relay still work at FD mode, the system may be always in outage state. At the moment, the transmission reliability is more important, the proposed AD-FPA scheme will automatically switch to HD mode, and the gain is smaller. As shown in Fig. 2 and Fig. 3, fix the number of relay, the gain of AD-FPA relative to HD-FPA with $\kappa = 1$ is obviously less than that of $\kappa = 0.1$, for example, the relay number $N = 8$, $P_{\text{out}} = 10^{-3}$, the proposed AD-FPA scheme outperforms the HD-FPA scheme with $\kappa = 1$ at a gain 1dB, while $\kappa = 0.1$, the gain is up to 4dB.

In addition, we also give a numerical example as shown in Table I, for a certain value of self-interference cancelation factor κ, when the value of SNR is greater than a critical point, the outage performance of HD mode is better than that of FD mode, it can be noticed that the SNR critical point is only related to the value of κ and independent of the relay number. For example, $\kappa = 0.1$ and the SNR threshold $\rho = 25dB$, however, $\kappa = 1$ the SNR threshold only $\rho = 16.7dB$. In conclusions, the proposed AD-FPA scheme has taken vadvantage of FD and HD relay mode, and improve the system performance significantly.

6. Conclusions

The adaptive duplex cooperative NOMA network with two users and multiple relays is considered, the relays can switch freely between FD and HD operation modes. An AD-FPA relay selection scheme is proposed to solve the zero diversity gain problem of FD relay selection scheme. The relay can flexibly switch to FD or HD operation mode according to the current channel state and decoding results, and the accurate closed expression of the system outage probability of the proposed scheme is obtained. The numerical and simulation results show that AD-FPA scheme is not only better than FD-FPA and HD-FPA schemes in outage

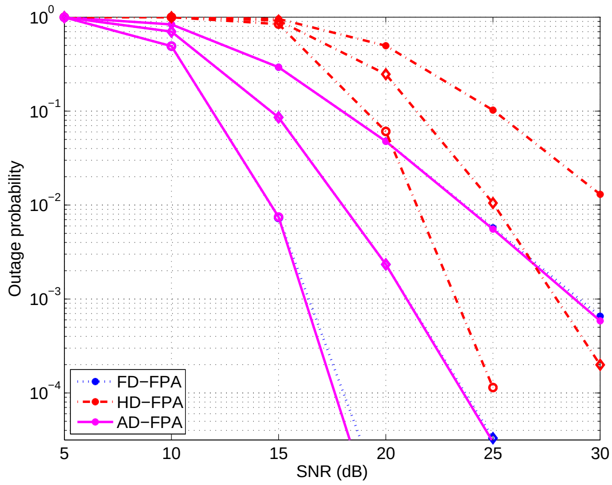

Figure 1. The outage performance of proposed schemes for cooperative NOMA, where $R_1 = 0.5$bits/s/Hz, $R_2 =$ 2bits/s/Hz, the power allocation factor $\alpha_1 = \frac{3}{4}$ and the self-interference cancellation factor $\kappa = 0$ (perfect cancellation technique) with relay numbers $N = 2$, $N = 4$, $N = 8$, respectively.

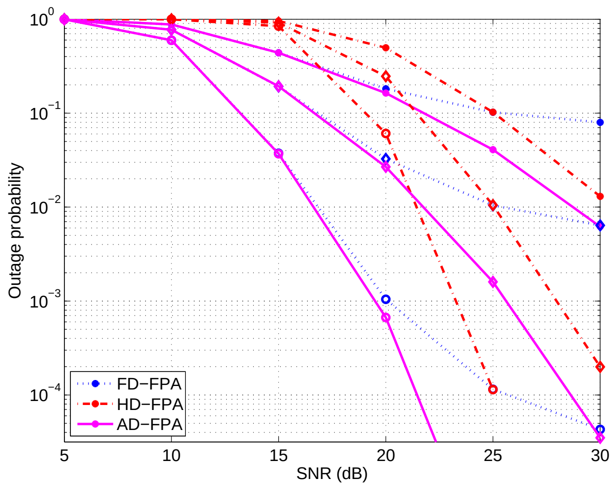

Figure 2. The outage performance of proposed schemes for cooperative NOMA, where $R_1 = 0.5$bits/s/Hz, $R_2 =$ 2bits/s/Hz, the power allocation factor $\alpha_1 = \frac{3}{4}$ and the self-interference cancellation factor $\kappa = 0.1$ with relay numbers $N =$ 2, $N = 4$, $N = 8$, respectively.

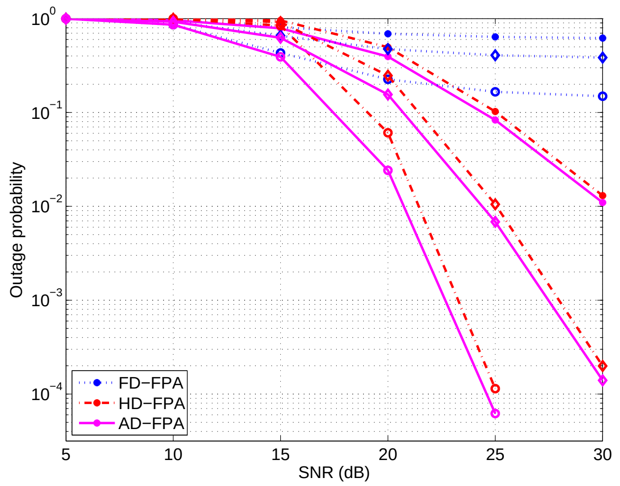

Figure 3. The outage performance of proposed schemes for cooperative NOMA, where $R_1 = 0.5$bits/s/Hz, $R_2 = 2$bits/s/Hz, the power allocation factor $\alpha_1 = \frac{3}{4}$ and the self-interference cancellation factor $\kappa = 1$ (no cancellation technique) with relay numbers $N = 2$, $N = 4$, $N = 8$, respectively.

performance, but also can obtain full diversity gain. The proposed AD-FPA scheme adaptively adjusts the relay between FD and HD mode to achieve a compromise between the system reliability and effectiveness with the maximum gain.

Acknowledgement. This work was supported by the Project: The Talent Project of Chengdu Technological University (2023RC013). The authors would like to thank all reviewers for their helpful comments and suggestions on this paper.

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