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Ergodic Capacity and Outage Performance Analysis of Uplink Full-Duplex Cooperative NOMA System

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ABSTRACT We propose an uplink full-duplex (FD) cooperative non-orthogonal multiple access (NOMA) system, where a dedicated Full-duplex (FD) relay is used to help two uplink users transmitting information to the base station. A novel FD relay transmission mode is proposed, in which the FD relay utilizes successive interference cancellation (SIC) and self-interference cancellation to decode two users symbols at the relay receiving antenna, and the relay transmitting antenna transmits superimposed signal to the base station using superposition coding. In this paper, we also consider a more realistic scenario where self-interference cancellation is imperfect. Hence, the residual-self interference exists. Moreover, the ergodic sum rate and the outage probability of the proposed system are investigated and the accurate analytical expressions are derived. Simulation results validate that, compared with the uplink half-duplex (HD) cooperative NOMA system and the uplink HD cooperative orthogonal multiple access (OMA) system, our proposed system obtains better performance of the ergodic sum rate and outage probability in the main signal to noise ratio (SNR) regime.

INDEX TERMS NOMA, ergodic sum rate, full-duplex, outage probability, successive interference cancellation, self-interference cancellation.

I. INTRODUCTION

As a promising solution to obtain higher data rate and reliability, the non-orthogonal multiple access (NOMA) has fascinated enormous attention in both industry and academia [1]. The core concept of NOMA is to utilize the superposition coding at the transmitter as well as utilize the successive interference cancellation (SIC) at the receiver [2]. Comparing to the conventional orthogonal multiple access (OMA) schemes (e.g. code division multiple access (CDMA), frequency division multiple access (FDMA) and time division multiple access (TDMA)), the NOMA can service multiple users in the same resource by splitting them in the specified domain(e.g. time domain, frequency domain and code domain) [3].

In addition, cooperative communication is also an effective scheme to overcome multipath propagation as well as enhance reception reliability of communication systems. Integrating between cooperative communication and NOMA constitute the cooperative NOMA system which is widely studied in recent years. Based on the downlink cooperative NOMA system, there are some important research works as follows [4]–[11]. In [4], a basic cooperative NOMA system is proposed where the user of strong channel gain as the relay forwards the decoded messages to the user of poor channel. Compared with the conventional NOMA system and the conventional cooperative OMA system, paper [4] proposed cooperative NOMA system obtains higher ergodic sum rate and better fairness. The authors in [5] utilize the maximum ratio combining (MRC) technology to ameliorate the spatial diversity gain for cooperative NOMA system. In order to effectively drop the outage probability of the cooperative NOMA system, a two-phase relay selection scheme is

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proposed in [6]. To further improve the performance of the downlink cooperative NOMA system, the Full-duplex (FD) work mechanism is also applied in [7]–[11]. In [7], the authors propose a FD cooperative NOMA system with dual users, where a dedicated FD relay assists the information transmission to the user with weak channel condition. the proposed FD cooperative NOMA system obtains better performance compared to the half-duplex (HD) cooperative NOMA system. In [8], the authors consider the presence of imperfect successive interference cancellation and residual hardware impairments at transceivers. The paper [8] shows that the extent of the negative impact of the imperfect successive interference cancellation on the near user is serious than residual hardware impairments. In addition, the paper [9] first considers the presence of in-phase and quadrature-phase imbalance (IQI), and show which IQI has a deleterious effect on of the proposed FD/HD cooperative non-orthogonal multiple access relaying systems. As a more practical consideration, under the presence of imperfect channel state information, the paper [10] studies the outage probability and ergodic sum rate of the proposed FD/HD cooperative NOMA system. Next, in [11], authors apply full-duplex and non-orthogonal multiple access technologies to cognitive radio networks and proposes a cooperative non-orthogonal multiple access scheme in a FD relaying cognitive radio network. Numerical simulation shows that the proposed system not only achieves better system performance than conventional HD cognitive radio relaying networks,but also overcomes inherent issues of conventional cognitive radio networks.

The aforementioned works focus on downlink cooperative NOMA system, and there are also some research works on the uplink cooperative NOMA [12]–[15]. In [12], a relay-aided NOMA technique is proposed for multi-cell uplink cellular networks. The proposed scheme does not require any channel state information at users, which can greatly reduce the control overhead. In [13], the authors propose a novel uplink cooperative NOMA system with full-duplex relaying, where the closer user is considered as a full-duplex relay to aid the transmission from the far user to the base station. The proposed system achieves better performance of outage probability and average sum rate compared to the uplink conventional orthogonal multiple access and uplink NOMA with half-duplex relaying system. In addition, in [14], a two-user uplink cooperative NOMA system is proposed, where a cell-center user directly communicates with a base station. However, the cell-edge user needs the assistance of a half-duplex decode-and-forward relay to communicate with the base station. Simulation and analysis illustrate that the superiority of the proposed system over conventional multiple access. Besides, in [15], a novel device-to-device (D2D) communication assisted uplink coordinated direct and relay transmission using NOMA is proposed. Numerical results show that the proposed scheme obtains better performance of the system ergodic sum rate, outage performance and outage throughput, compared with conventional NOMA based uplink coordinated direct and relay transmission.

The aforementioned works on uplink cooperative NOMA schemes usually assume that there are direct links between the base station and the uplink users. However, for some typical scenarios of small cells in uplink 5G networks [16], the uplink users can not directly communicate with the base station. To the best of the authors' knowledge, the uplink cooperative NOMA system systems without direct links between the base station and the uplink users, has not yet been reported, which motivates the study of this paper. Moreover, we also propose a novel transmission mode with a dedicated FD relay.

In this work, the main contributions of this paper are as follows. First of all, we propose an uplink FD cooperative NOMA system, where a dedicated FD relay is used to help two uplink users transmitting information to the base station. Next, a novel FD relay transmission mode is proposed, in which the FD relay utilizes successive interference cancellation and self-interference cancellation to decode two users symbols at the relay receiving antenna and the relay transmitting antenna transmits superimposed signal to the base station using superposition coding technology. Finally, the simulation also shows that our proposed uplink FD cooperative NOMA system obtains better performance than the uplink HD cooperative NOMA system and the conventional uplink OMA cooperative system in the low to middle SNR regime.

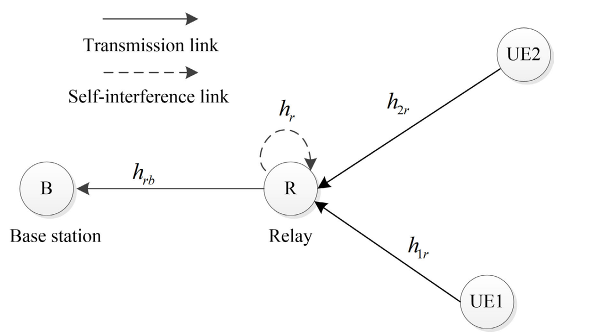

FIGURE 1. System model.

II. SYSTEM MODEL

Fig. 1 shows an uplink FD cooperative NOMA system where two users can not directly communicate with the base station because of physical obstacles or heavy shadowing. Hence, need a relay to help. The BS, UE1 and UE2 deploy one antenna, respectively. The relay deploys two antennas where one is used to transmit information and the other is used to receive information. All nodes adopt HD mode except the relay adopts FD mode. We assume that UE1 is closer to the relay than UE2 to the relay. In addition, we also assume that the relay adopts decode-and-forward (DF) transfer protocol. The channel coefficients for the link from UE1 to the relay, the link from UE2 to the relay, the link from the relay to the relay, and the link from the relay to the base station are denoted by h_{1r}, h_{2r}, h_r, and h_{rb}, respectively. We assume that all channels obey independently and identically distributed (i.i.d.) Rayleigh fading channel. Hence, all channel power gains obey exponential distributed. The mean of the channel power gains $|h_{1r}|^2$, $|h_{2r}|^2$, $|h_r|^2$, and $|h_{rb}|^2$ are defined as λ_{1r}, λ_{2r}, λ_r, and λ_{rb}, respectively. Here, h_r denotes the residual self-interference channel coefficient. In particular, when $\lambda_r = 0$ implies which perform perfect self-interference cancellation at the relay.

At the time slot n, UE1 transmits the symbol $S_1[n]$ to the relay with transmission power $\beta_1 P_t$ as well as UE2 transmits the symbol $S_2[n]$ to the relay with transmission power $\beta_2 P_t$, where P_t is total transmission power for UE1 and UE2, and β_1, β_2 are the power allocation coefficients for UE1 and UE2 with $\beta_1 + \beta_2 = 1$, $\beta_1 > \beta_2$. Since the relay adopts FD transmission mode as well as DF transfer protocol. Hence, the received signal at the relay receiving antenna can be given by

$$y_r[n] = h_{1r}\sqrt{P_t\beta_1}S_1[n] + h_{2r}\sqrt{P_t\beta_2}S_2[n] + h_r(\sqrt{P_r\alpha_1}S_1[n-\tau]+\sqrt{P_r\alpha_2}S_2[n-\tau]) + N_r[n], \tag{1}$$

where α_1 and α_2 denote power allocation coefficients with $\alpha_1 + \alpha_2 = 1, \alpha_1 > \alpha_2$. $N_r[n]$ denotes the additive white Gaussian noises (AWGN) at the relay, and we assume that the noise satisfy that both zero mean and variance for σ^2. P_r denotes total relay transmission power. For analysis convenience, without loss of generality, we assume that $P_t = P_r = P$ as well as $\rho_t = \frac{P_t}{\sigma^2}$, $\rho_r = \frac{P_r}{\sigma^2}$, $\rho = \frac{P}{\sigma^2}$. Hence, such that $\rho_t = \rho_r = \rho$. Here, ρ represents transmit SNR. This assumption also does not affect the analysis of related systems performance. The $\sqrt{P_r\alpha_1}S_1[n-\tau] + \sqrt{P_r\alpha_2}S_2[n-\tau]$ express the superimposed signals which is transmitted by the relay transmitting antenna using superposition coding technology. τ represents the processing delay at the relay with $\tau \geq 1$. Hence, the relay works in HD mode at the beginning τ time slots and not any symbol need be transmitted. The relay receiving antenna knows the symbol $S_1[n-\tau]$ and $S_2[n-\tau]$ because they were successfully decoded τ time slots ago, by SIC. Based on this point, self-interference cancellation can be applied to the relay receiving antenna. The relay receiving antenna receives the symbols from UE1 and UE2, also include self-interference link signal and the noise $N_r[n]$. Not like in [17], self-interference link signals is perfectly eliminated. In this paper, as a more realistic scenario, we consider the imperfect self-interference cancellation. According to NOMA principle, the relay decodes the symbol $S_1[n]$ by treating the symbol $S_2[n]$ and self-interference link signals $\sqrt{P_r\alpha_1}S_1[n-\tau] + \sqrt{P_r\alpha_2}S_2[n-\tau]$ as interference. Hence, the received signal to interference and noise ratio (SINR) for symbol $S_1[n]$ at the relay can be expressed as

$$\gamma_{1,r} = \frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t + |h_r|^2\rho_r + 1}. \tag{2}$$

Next, the symbol $S_1[n]$ is successfully decoded and the relay removes the symbol $S_1[n]$ by using SIC. Thus, the received SINR for symbol $S_2[n]$ at the relay can be given by

$$\gamma_{2,r} = \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r + 1}. \tag{3}$$

On the other hand, the relay transmitting antenna simultaneously transmits the superimposed signals $\sqrt{P_r\alpha_1}S_1[n-\tau] + \sqrt{P_r\alpha_2}S_2[n-\tau]$ to the base station by using the superposition coding technology. Thus, at the base station, the received signal can be expressed as

$$y_b[n] = h_{rb}(\sqrt{P_r\alpha_1}S_1[n-\tau]+\sqrt{P_r\alpha_2}S_2[n-\tau]) + N_b[n], \tag{4}$$

where $N_b[n]$ also denotes the AWGN at the base station, hence, we also assume that the noise both zero mean and variance for σ^2. Similarly, the base station decoded the symbol $S_1[n-\tau]$ by treating the symbol $S_2[n-\tau]$ as interference. Therefore, the received SINR for symbol $S_1[n-\tau]$ at the base station can be given by

$$\gamma_{1,b} = \frac{\alpha_1|h_{rb}|^2\rho_r}{\alpha_2|h_{rb}|^2\rho_r + 1}. \tag{5}$$

Next, the base station cancels the symbol $S_1[n-\tau]$ by utilizing SIC. Thus, the received signal to noise ratio (SNR) for symbol $S_2[n-\tau]$ at the base station can be given by

$$\gamma_{2,b} = \alpha_2|h_{rb}|^2\rho_r. \tag{6}$$

According to the relay two-hop decode-and-forward relaying protocol, the weakest link determine the maximum achievable rate. Thus, the achievable rate for symbol 1 (S_1) and symbol 2 (S_2) can be expressed as, respectively.

$$C_1 = \log_2(1 + \min\{\gamma_{1,r}, \gamma_{1,b}\}). \tag{7}$$

$$C_2 = \log_2(1 + \min\{\gamma_{2,r}, \gamma_{2,b}\}). \tag{8}$$

III. PERFORMANCE ANALYSIS

In this section, we give the detailed analysis to the ergodic sum rate and the outage performance of our proposed system.

A. ERGODIC SUM RATE

To obtain the accurate analytical expressions for ergodic rate of symbol 1 and symbol 2, we first give the following three lemmas.

Lemma 1: Assuming the random variables X, Y and Z obey exponentially distributed and the mean are λ_x, λ_y and λ_z, respectively. If a, b, c, and d are positive constant, the cumulative distribution function (CDF) of $R = \frac{aX}{bY+cZ+d}$ is given by

$$F_R(r) = 1 - e^{-\frac{-rd}{a\lambda_x}}\frac{a\lambda_x}{b\lambda_y r + a\lambda_x}\frac{a\lambda_x}{c\lambda_z r + a\lambda_x}. \tag{9}$$

Proof: According to the definition of random variable R, its CDF can be given by

$$\begin{aligned}F_R(r) &= P(R<r)\\ &= P(\frac{aX}{bY+cZ+d}<r)\\ &= P(X<\frac{r(bY+cZ+d)}{a})\\ &= F_X(\frac{r(bY+cZ+d)}{a})\\ &= 1-\int_0^{\infty}\int_0^{\infty}e^{-\frac{r(by+cz+d)}{a\lambda_x}}f_Y(y)f_Z(z)dydz\\ &= 1-e^{-\frac{rd}{a\lambda_x}}\int_0^{\infty}e^{-\frac{crz}{a\lambda_x}}\int_0^{\infty}e^{-\frac{bry}{a\lambda_x}}\frac{e^{-\frac{y}{\lambda_y}}}{\lambda_y}dy\frac{e^{-\frac{z}{\lambda_z}}}{\lambda_z}dz\\ &= 1-e^{-\frac{rd}{a\lambda_x}}\frac{a\lambda_x}{b\lambda_y r+a\lambda_x}\frac{a\lambda_x}{c\lambda_z r+a\lambda_x}. \end{aligned}\tag{10}$$

The proof is completed.

Lemma 2: Assuming the random variables $X>0$, the probability density function (PDF) and the CDF of can be expressed as $f_X(x)$ and $F_X(x)$, respectively. The following equation exists

$$\int_0^{\infty}\log_2(1+x)f_X(x)dx=\frac{1}{\ln 2}\int_0^{\infty}\frac{1-F_X(x)}{1+x}dx. \tag{11}$$

Proof: The proof process is as follows

$$\begin{aligned}&\int_0^{\infty}\log_2(1+x)f_X(x)dx\\ &= \int_0^{\infty}\log_2(1+x)dF_X(x)\\ &= \log_2(1+x)F_X(x)\Big|_0^{\infty}-\int_0^{\infty}F_X(x)d\log_2(1+x)\\ &= \log_2(1+x)\Big|_0^{\infty}-\int_0^{\infty}F_X(x)d\log_2(1+x)\\ &= \int_0^{\infty}d\log_2(1+x)-\int_0^{\infty}F_X(x)d\log_2(1+x)\\ &= \frac{1}{\ln 2}\int_0^{\infty}\frac{1-F_X(x)}{1+x}dx. \end{aligned}\tag{12}$$

The proof is completed.

Lemma 3: Assuming the random variables X obey exponentially distributed and the mean is λ_x. If a and b are positive constant, the CDF of $Y=\frac{aX}{bX+1}$ is given by

$$F_Y(y)=1-e^{-\frac{y}{\lambda_x(a-by)}}(\varepsilon(y)-\varepsilon(y-\frac{a}{b})), \tag{13}$$

where $\varepsilon(x)$ represents step function,

$$\varepsilon(x)=\begin{cases}1, & x\geq 0\\ 0, & x<0.\end{cases}$$

Proof: According to the definition of random variable Y, its CDF can be expressed as

$$\begin{aligned}F_Y(y) &= P(Y<y)\\ &= P(\frac{aX}{bX+1}<y)\\ &= P(X(a-by)<y), \end{aligned}\tag{14}$$

if $a-by>0$, then

$$\begin{aligned}F_Y(y) &= P(X<\frac{y}{a-by})\\ &= F_X(\frac{y}{a-by})\\ &= 1-e^{-\frac{y}{\lambda_x(a-by)}}, \end{aligned}\tag{15}$$

else

$$\begin{aligned}F_Y(y) &= P(X>\frac{y}{a-by})\\ &= 1. \end{aligned}\tag{16}$$

According to (15) and (16), the (13) is proved.

Proposition 1: The ergodic rate of the symbol 1 is given by

$$\begin{aligned}E\{C_1\}=\frac{1}{\ln 2}\int_0^{\frac{\alpha_1}{\alpha_2}}e^{-x\left(\frac{1}{\beta_1\rho_t\lambda_{1r}}+\frac{1}{\lambda_{rb}\rho_r(\alpha_1-\alpha_2 x)}\right)}\frac{1}{1+\frac{\beta_2\lambda_{2r}x}{\beta_1\lambda_{1r}}}\\ \times\frac{1}{1+\frac{\rho_r\lambda_r x}{\beta_1\rho_t\lambda_{1r}}}\frac{1}{1+x}dx. \end{aligned}\tag{17}$$

Proof: According to (7), we define that $Z=\min\{\gamma_{1,r},\gamma_{1,b}\}$, the CDF of the variable Z is given by

$$\begin{aligned}F_Z(x) &= P(\min\{\gamma_{1,r},\gamma_{1,b}\}<x)\\ &= 1-P(\gamma_{1,r}\geq x)P(\gamma_{1,b}\geq x), \end{aligned}\tag{18}$$

using (9) and (13), the CDF of the variable Z can be further expressed as

$$\begin{aligned}F_Z(x) &= 1-P(\gamma_{1,r}\geq x)P(\gamma_{1,b}\geq x)\\ &= 1-e^{-\frac{x}{\beta_1\rho_t\lambda_{1r}}}\frac{\beta_1\rho_t\lambda_{1r}}{\beta_2\rho_t\lambda_{2r}x+\beta_1\rho_t\lambda_{1r}}\\ &\quad\times\frac{\beta_1\rho_t\lambda_{1r}}{\rho_r\lambda_r x+\beta_1\rho_t\lambda_{1r}}e^{-\frac{x}{\lambda_{rb}\rho_r(a_1-a_2x)}}(\varepsilon(x)-\varepsilon(x-\frac{a_1}{a_2})). \end{aligned}\tag{19}$$

Utilizing (19) to (11), the proof is completed.

The best knowledge of the authors, the closed-form expressions of ergodic rate for symbol 1 can not be obtained. However, the ergodic rate for symbol 1 also can be effectively estimated via the definite integration (17).

Proposition 2: The ergodic rate of the symbol 2 is given by

$$E\{C_2\}=\frac{1}{\ln 2}\frac{e^m Ei(-m)-e^{\frac{m}{n}}Ei(-\frac{m}{n})}{n-1}, \tag{20}$$

where $m=\frac{1}{\beta_2\rho_t\lambda_{2r}}+\frac{1}{\alpha_2\rho_r\lambda_{rb}}$, $n=\frac{\lambda_r\rho_r}{\beta_2\rho_t\lambda_{2r}}$, $Ei(x)=\int_{-x}^{\infty}\frac{e^{-t}}{t}dt$, $Ei(x)$ denotes exponential integral.

Proof: In accordance with expression (8), we define that $R=\min\{\gamma_{2,r},\gamma_{2,b}\}$, the CDF of R is given by

$$\begin{aligned}F_R(x) &= P(\min\{\gamma_{2,r},\gamma_{2,b}\}<x)\\ &= 1-P(\gamma_{2,r}\geq x)P(\gamma_{2,b}\geq x)\\ &= 1-e^{-\frac{x}{\beta_2\rho_t\lambda_{2r}}}\frac{1}{1+\frac{\lambda_r\rho_r x}{\beta_2\rho_t\lambda_{2r}}}e^{-\frac{x}{\alpha_2\rho_r\lambda_{rb}}}. \end{aligned}\tag{21}$$

Utilizing (21) to (11), we can obtain that

$$\begin{aligned}
E\{C_2\} &= \frac{1}{\ln 2}\int_0^\infty e^{-\frac{x}{\beta_2\rho_t\lambda_{2r}}}\frac{1}{1+\frac{\lambda_r\rho_r x}{\beta_2\rho_t\lambda_{2r}}}e^{-\frac{x}{\alpha_2\rho_r\lambda_{rb}}}\frac{1}{1+x}dx\\
&= \frac{1}{\ln 2}\int_0^\infty e^{-x\left(\frac{1}{\beta_2\rho_t\lambda_{2r}}+\frac{1}{\alpha_2\rho_r\lambda_{rb}}\right)}\frac{1}{1+\frac{\lambda_r\rho_r x}{\beta_2\rho_t\lambda_{2r}}}\frac{1}{1+x}dx\\
&= \frac{1}{\ln 2}\int_0^\infty e^{-x\left(\frac{1}{\beta_2\rho_t\lambda_{2r}}+\frac{1}{\alpha_2\rho_r\lambda_{rb}}\right)}\\
&\quad\times\left(\frac{(1+x)^{-1}}{1-\frac{\lambda_r\rho_r}{\beta_2\rho_t\lambda_{2r}}}+\frac{1}{1-\frac{\beta_2\rho_t\lambda_{2r}}{\lambda_r\rho_r}}\frac{1}{1+\frac{\lambda_r\rho_r x}{\beta_2\rho_t\lambda_{2r}}}\right)dx.
\end{aligned}\tag{22}$$

Giving equation (3.352−4) in [18]

$$\int_0^\infty \frac{e^{-\mu x}}{x+\beta}dx = -\,e^{\beta\mu}Ei(-\mu\beta) \qquad |\arg\beta|<\pi,\ Re\mu>0.\tag{23}$$

Utilizing the equation (23) and (22), according to correspondence coefficient rule, we obtain the expression (20). The proof is completed.

To reflect ergodic sum rate performance advantages of our proposed system, the ergodic sum rate of the uplink cooperative TDMA system and the uplink cooperative FDMA system are individually given by

$$\begin{aligned}
C_{TDMA} &= \frac{1}{4}\log_2(1+\min\{|h_{1r}|^2\rho_t, |h_{rb}|^2\rho_r\})\\
&\quad+\frac{1}{4}\log_2(1+\min\{|h_{2r}|^2\rho_t, |h_{rb}|^2\rho_r\}), \qquad (24)\\
C_{FDMA} &= \frac{1}{4}\log_2(1+\min\{2|h_{1r}|^2\rho_t, 2|h_{rb}|^2\rho_r\})\\
&\quad+\frac{1}{4}\log_2(1+\min\{2|h_{2r}|^2\rho_t, 2|h_{rb}|^2\rho_r\}), \qquad (25)
\end{aligned}$$

For fair comparison, in the uplink cooperative TDMA system, a complete transmission cycle need four transmission slots where UE1 and UE2 need separately two transmission slots. In addition, in the uplink cooperative FDMA system, a complete transmission cycle need two transmission slots where UE1 and UE2 can transmit at same time and every user transmit using different half normalized bandwidth. Thus, the noise power only is half of other systems under the same wireless communication surroundings.

B. OUTAGE PROBABILITY

When the symbol 1 of UE1 and the symbol 2 of UE2 transmit at pre-defined objective rate R_1 and R_2, the outage phenomenon occurred when the user instantaneous SINR below a pre-fixed threshold. For analysis convenience,we give that pre-fixed threshold $u_1 = 2^{R_1}-1$ and $u_2 = 2^{R_2}-1$. In order to describe the outage performance of symbol 1and symbol 2 of our proposed system, we next give three propositions.

Proposition 3: when $u_1 < \frac{\alpha_1}{\alpha_2}$, the outage probability of symbol 1 is given by

$$\begin{aligned}
P_{out,1} &= 1-e^{-\left(\frac{u_2}{\beta_2\lambda_{2r}\rho_t}+\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r}\right)}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}}\\
&\quad+e^{-\left(\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r}-\frac{1}{\beta_2\lambda_{2r}\rho_t}\right)}\frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}}\frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}}.
\end{aligned}\tag{26}$$

Proof: The outage probability of symbol 1 is given by

$$\begin{aligned}
P_{out,1} &= 1-P(\log_2(1+\gamma_{1,r})>R_1, \log_2(1+\gamma_{2,r})>R_2,\\
&= 1-P(\gamma_{1,r}>u_1, \gamma_{2,r}>u_2, \gamma_{1,b}>u_1)\\
&= 1-P(\frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t+|h_r|^2\rho_r+1}>u_1,\\
&\quad \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r+1}>u_2, \frac{\alpha_1|h_{rb}|^2\rho_r}{\alpha_2|h_{rb}|^2\rho_r+1}>u_1)\\
&= 1-P(\frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t+|h_r|^2\rho_r+1}>u_1,\\
&\quad \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r+1}>u_2)P(\frac{\alpha_1|h_{rb}|^2\rho_r}{\alpha_2|h_{rb}|^2\rho_r+1}>u_1)\\
&= 1-P(\frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t+|h_r|^2\rho_r+1}>u_1,\\
&\quad \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r+1}>u_2)P((\alpha_1-u_1\alpha_2)|h_{rb}|^2\rho_r>u_1),
\end{aligned}\tag{27}$$

if $u_1 \geq \frac{\alpha_1}{\alpha_2}$, then$P_{out,1} = 1$. else

$$\begin{aligned}
P_{out,1} &= 1-P(\frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t+|h_r|^2\rho_r+1}>u_1,\\
&\quad \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r+1}>u_2)P(|h_{rb}|^2>\frac{u_1}{(\alpha_1-u_1\alpha_2)\rho_r})\\
&= 1-P(\frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t+|h_r|^2\rho_r+1}>u_1,\\
&\quad \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r+1}>u_2)e^{-\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r}}\\
&= 1-P(u_2|h_r|^2\rho_r+u_2<\beta_2|h_{2r}|^2\rho_t\\
&\quad <\frac{\beta_1|h_{1r}|^2\rho_t}{u_1}-|h_r|^2\rho_r-1)e^{-\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r}}\\
&= 1-(\int_0^\infty e^{-\frac{u_2 z\rho_r+u_2}{\beta_2\lambda_{2r}\rho_t}}\frac{e^{-\frac{z}{\lambda_r}}}{\lambda_r}dz\\
&\quad -\int_0^\infty\int_0^\infty e^{-\frac{\frac{\beta_1 y\rho_t}{u_1}-z\rho_r-1}{\beta_2\lambda_{2r}\rho_t}}\frac{e^{-\frac{y}{\lambda_{1r}}}}{\lambda_{1r}}\frac{e^{-\frac{z}{\lambda_r}}}{\lambda_r}dydz)\\
&\quad \times e^{-\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r}}\\
&= 1-e^{-\left(\frac{u_2}{\beta_2\lambda_{2r}\rho_t}+\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r}\right)}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}}\\
&\quad +e^{-\left(\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r}-\frac{1}{\beta_2\lambda_{2r}\rho_t}\right)}\frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}}\frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}}.
\end{aligned}\tag{28}$$

The proof is completed.

Proposition 4: when $\frac{\alpha_1 u_2}{\alpha_2(1+u_2)} \leq u_1 < \frac{\alpha_1}{\alpha_2}$, the outage probability of symbol 2 can be expressed as

$$P_{out,2} = 1 - e^{-(\frac{u_2}{\beta_2\lambda_{2r}\rho_t}+\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r})}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}} + e^{-(\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r}-\frac{1}{\beta_2\lambda_{2r}\rho_t})}\frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}}\frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}}. \tag{29}$$

Proof: The outage probability of symbol 2 is given by

$$\begin{aligned}
P_{out,2} &= 1 - P(\log_2(1+\gamma_{1,r}) > R_1, \log_2(1+\gamma_{2,r}) > R_2, \log_2(1+\gamma_{1,b}) > R_1, \log_2(1+\gamma_{2,b}) > R_2) \\
&= 1 - P(\gamma_{1,r} > u_1, \gamma_{2,r} > u_2, \gamma_{1,b} > u_1, \gamma_{2,b} > u_2) \\
&= 1 - P(\frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t+|h_r|^2\rho_r+1} > u_1, \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r+1} > u_2, \frac{\alpha_1|h_{rb}|^2\rho_r}{\alpha_2|h_{rb}|^2\rho_r+1} > u_1, \alpha_2|h_{rb}|^2\rho_r > u_2) \\
&= 1 - P(\frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t+|h_r|^2\rho_r+1} > u_1, \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r+1} > u_2) \times P(\frac{\alpha_1|h_{rb}|^2\rho_r}{\alpha_2|h_{rb}|^2\rho_r+1} > u_1, \alpha_2|h_{rb}|^2\rho_r > u_2) \\
&= 1 - P(\frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t+|h_r|^2\rho_r+1} > u_1, \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r+1} > u_2) \times P((\alpha_1-u_1\alpha_2)|h_{rb}|^2\rho_r > u_1, \alpha_2|h_{rb}|^2\rho_r > u_2).
\end{aligned} \tag{30}$$

Similarly, if $u_1 \geq \frac{\alpha_1}{\alpha_2}$, then $P_{out,2} = 1$. else

$$\begin{aligned}
P_{out,2} &= 1 - (e^{-\frac{u_2}{\beta_2\lambda_{2r}\rho_t}}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}} - e^{\frac{1}{\beta_2\lambda_{2r}\rho_t}}\frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}} \times \frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}})P(|h_{rb}|^2 > \frac{u_1}{(\alpha_1-u_1\alpha_2)\rho_r}, |h_{rb}|^2 > \frac{u_2}{\alpha_2\rho_r}) \\
&= 1 - (e^{-\frac{u_2}{\beta_2\lambda_{2r}\rho_t}}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}} - e^{\frac{1}{\beta_2\lambda_{2r}\rho_t}} \times \frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}}\frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}})P(|h_{rb}|^2 > \frac{u_1}{(\alpha_1-u_1\alpha_2)\rho_r}) \\
&= 1 - e^{-(\frac{u_2}{\beta_2\lambda_{2r}\rho_t}+\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r})}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}} + e^{-(\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r}-\frac{1}{\beta_2\lambda_{2r}\rho_t})}\frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}}\frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}}.
\end{aligned} \tag{31}$$

The (29) is proved.

Proposition 5: when $u_1 < \frac{\alpha_1 u_2}{\alpha_2(1+u_2)}$, the outage probability of symbol 2 can be expressed as

$$P_{out,2} = 1 - e^{-(\frac{u_2}{\beta_2\lambda_{2r}\rho_t}+\frac{u_2}{\lambda_{rb}\alpha_2\rho_r})}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}} + e^{-(\frac{u_2}{\lambda_{rb}\alpha_2\rho_r}-\frac{1}{\beta_2\lambda_{2r}\rho_t})}\frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}}\frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}}. \tag{32}$$

Proof: Similarly, the outage probability of symbol 2 can be expressed as

$$\begin{aligned}
P_{out,2} &= 1 - P(\log_2(1+\gamma_{1,r}) > R_1, \log_2(1+\gamma_{2,r}) > R_2, \log_2(1+\gamma_{1,b}) > R_1, \log_2(1+\gamma_{2,b}) > R_2) \\
&= 1 - P(\gamma_{1,r} > u_1, \gamma_{2,r} > u_2, \gamma_{1,b} > u_1, \gamma_{2,b} > u_2) \\
&= 1 - P(\frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t+|h_r|^2\rho_r+1} > u_1, \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r+1} > u_2, \frac{\alpha_1|h_{rb}|^2\rho_r}{\alpha_2|h_{rb}|^2\rho_r+1} > u_1, \alpha_2|h_{rb}|^2\rho_r > u_2) \\
&= 1 - P(\frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t+|h_r|^2\rho_r+1} > u_1, \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r+1} > u_2) \times P(\frac{\alpha_1|h_{rb}|^2\rho_r}{\alpha_2|h_{rb}|^2\rho_r+1} > u_1, \alpha_2|h_{rb}|^2\rho_r > u_2) \\
&= 1 - P(\frac{\beta_1|h_{1r}|^2\rho_t}{\beta_2|h_{2r}|^2\rho_t+|h_r|^2\rho_r+1} > u_1, \frac{\beta_2|h_{2r}|^2\rho_t}{|h_r|^2\rho_r+1} > u_2) \times P(\alpha_2|h_{rb}|^2\rho_r > u_2) \\
&= 1 - (e^{-\frac{u_2}{\beta_2\lambda_{2r}\rho_t}}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}} - e^{\frac{1}{\beta_2\lambda_{2r}\rho_t}}\frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}} \times \frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}})P(|h_{rb}|^2 > \frac{u_2}{\alpha_2\rho_r}) \\
&= 1 - e^{-(\frac{u_2}{\beta_2\lambda_{2r}\rho_t}+\frac{u_2}{\lambda_{rb}\alpha_2\rho_r})}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}} + e^{-(\frac{u_2}{\lambda_{rb}\alpha_2\rho_r}-\frac{1}{\beta_2\lambda_{2r}\rho_t})}\frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}}\frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}}.
\end{aligned} \tag{33}$$

The proposition 5 is proved.

In order to obtain more intuitive describe the outage probability of our proposed system, the outage probability of symbol 1 and symbol 2 can be respectively expressed as

$$P_{out,1} = \begin{cases} 1 - e^{-(\frac{u_2}{\beta_2\lambda_{2r}\rho_t}+\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r})}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}} + e^{-(\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r}-\frac{1}{\beta_2\lambda_{2r}\rho_t})}\frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}}\frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}}, & u_1 < \frac{\alpha_1}{\alpha_2} \\ 1, & u_1 \geq \frac{\alpha_1}{\alpha_2}. \end{cases} \tag{34}$$

$$P_{out,2} = \begin{cases} 1 - e^{-(\frac{u_2}{\beta_2\lambda_{2r}\rho_t}+\frac{u_2}{\lambda_{rb}\alpha_2\rho_r})}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}} + e^{-(\frac{u_2}{\lambda_{rb}\alpha_2\rho_r}-\frac{1}{\beta_2\lambda_{2r}\rho_t})}\frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}}\frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}}, & u_1 < \frac{\alpha_1 u_2}{\alpha_2(1+u_2)} \\ 1 - e^{-(\frac{u_2}{\beta_2\lambda_{2r}\rho_t}+\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r})}\frac{1}{1+\frac{u_2\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}} + e^{-(\frac{u_1}{\lambda_{rb}(\alpha_1-u_1\alpha_2)\rho_r}-\frac{1}{\beta_2\lambda_{2r}\rho_t})}\frac{1}{1+\frac{\beta_1\lambda_{1r}}{u_1\beta_2\lambda_{2r}}}\frac{1}{1-\frac{\lambda_r\rho_r}{\beta_2\lambda_{2r}\rho_t}}, & \frac{\alpha_1 u_2}{\alpha_2(1+u_2)} \leq u_1 < \frac{\alpha_1}{\alpha_2} \\ 1, & u_1 \geq \frac{\alpha_1}{\alpha_2}. \end{cases} \tag{35}$$

IV. SIMULATION RESULTS

In this section, the ergodic sum rate and the outage probability of our proposed uplink FD cooperative NOMA system and the compared systems are evaluated by Monte-Carlo simulations based on 100,000 independent channel realizations. We assume that the noise variance is set as $\sigma^2 = 1$ and the transmission power P varied from -10dB to 30dB. In addition, we also assume that the mean of all channel power gains are equivalent for all compared systems.

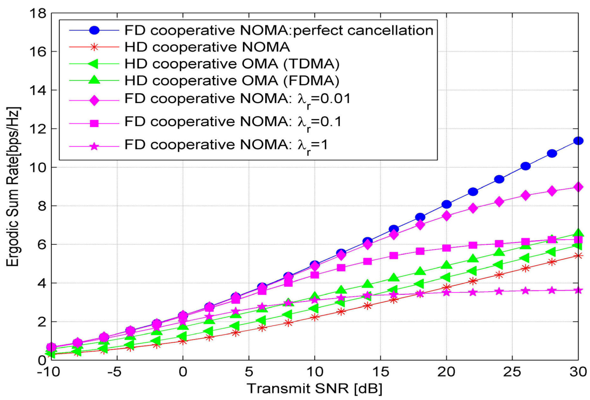

FIGURE 2. Ergodic sum rate versus transmit SNR.

Fig. 2 compares the ergodic sum rate among our proposed uplink FD cooperative NOMA system, the uplink HD cooperative NOMA system and the uplink HD cooperative OMA system. The simulation parameters are set to: $\alpha_1 = \beta_1 = 0.7, \alpha_2 = \beta_2 = 0.3, \lambda_{1r} = 16, \lambda_{2r} = 9, \lambda_{rb} = 16$. We can see that, under the moderate transmit SNR regime, when the mean of self-interference power gain λ_r relatively small, our proposed uplink FD cooperative NOMA system has higher ergodic sum rate than the other three systems (the uplink HD cooperative NOMA system, the uplink HD cooperative TDMA system and the uplink HD cooperative FDMA system). However, when the mean of self-interference power gain λ_r change large, our proposed uplink FD cooperative NOMA system has less ergodic sum rate than the other three compared systems. This is because our proposed system receives slight residual self-interference power when the mean of self-interference power gain λ_r relatively small. Thus, our proposed system obtains higher spectrum efficiency. In addition, we also can see that the ergodic sum rate of our proposed uplink FD cooperative NOMA system significantly decreases as increasing λ_r under high transmit SNR regime. E.g. when transmit SNR $\rho = 30dB$ and $\lambda_r = 0$, the ergodic sum rate of our proposed system is 11.4 bps/Hz. However, when transmit SNR $\rho = 30dB$ and $\lambda_r = 1$, the ergodic sum rate our proposed system is only 3.6 bps/Hz. This is due to the fact that the ergodic sum rate gain is more sensitive to residual self-interference power gain λ_r changing, especially in the high transmit SNR regime. Moreover, we also find that the performance gain of ergodic sum rate is less sensitive as λ_r change in the low transmit SNR regime. This is mainly because the residual self-interference power changes smaller when transmit power changes smaller. From above analysis, we find that it is particularly important to consider the influence of the residual self-interference when designing the practical uplink FD cooperative NOMA system.

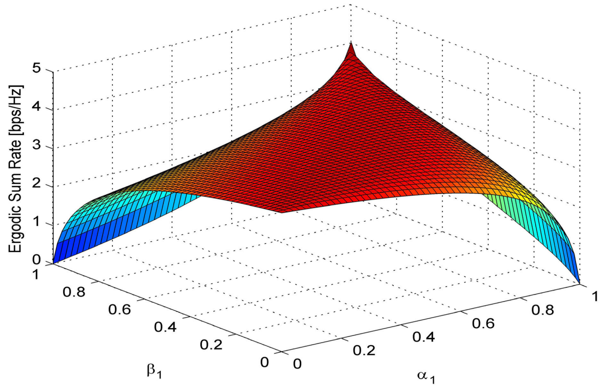

FIGURE 3. Ergodic sum rate versus α_1 and β_1 under perfect cancellation.

Fig. 3 shows the ergodic sum rate versus α_1 and β_1 for our proposed system under perfect cancellation. The simulation parameters are set to: $\lambda_{1r} = 16, \lambda_{2r} = 9, \lambda_{rb} = 16, \rho = 5dB$. From the three-dimensional figure, first of all, we can see that our proposed system obtains the maximum ergodic sum rate when $\alpha_1 \rightarrow 1$ and $\beta_1 \rightarrow 1$. However, from the perspective of fairness, when $\alpha_1 \rightarrow 1$ and $\beta_1 \rightarrow 1$, the symbol 2 of UE2 is allocated power extremely small. As a result, the ergodic rate and outage performance of symbol 2 are extremely deteriorated. So is unfair to UE2. In addition, we can also see that, when the difference between α_1 and β_1 is large, the ergodic sum rate of our proposed system tends to be extremely small. E.g. the ergodic sum rate tends to 0 bps/HZ when $\alpha_1 \rightarrow 1, \beta_1 \rightarrow 0$ or $\alpha_1 \rightarrow 0, \beta_1 \rightarrow 1$. Finally, from the figure, we can see that our proposed system can acquire better ergodic sum rate when the values of α_1 and β_1 are close, and α_1, β_1 Satisfy $\alpha_1 \in (0.5, 0.9), \beta_1 \in (0.5, 0.9)$. At the same time, so can better guarantee the communication performance of UE2.

Fig. 4 depicts the outage probability of two symbols for our proposed uplink FD cooperative NOMA system and the uplink HD cooperative NOMA system versus transmit SNR under $\frac{\alpha_1 u_2}{\alpha_2(1+u_2)} \leq u_1 < \frac{\alpha_1}{\alpha_2}$.The simulation parameters are set to: $\alpha_1 = 0.55, \alpha_2 = 0.45, \beta_1 = 0.9, \beta_2 = 0.1, \lambda_{1r} = 16, \lambda_{2r} = 9, \lambda_{rb} = 16, R_1 = R_2 = 0.5bps/Hz$. From the figure, we can see that, our proposed uplink FD cooperative NOMA system has much better outage performance than the uplink HD cooperative NOMA system for each symbol. This is due to this fact that, in order to maintain the same throughput, the uplink FD cooperative NOMA system only need half its transmission rate compared with the uplink HD cooperative NOMA system. In addition, we also see that the outage probability of two symbols are equal under the given system. That is to say, $P_{out,1} = P_{out,2}$ as the proposition 4.

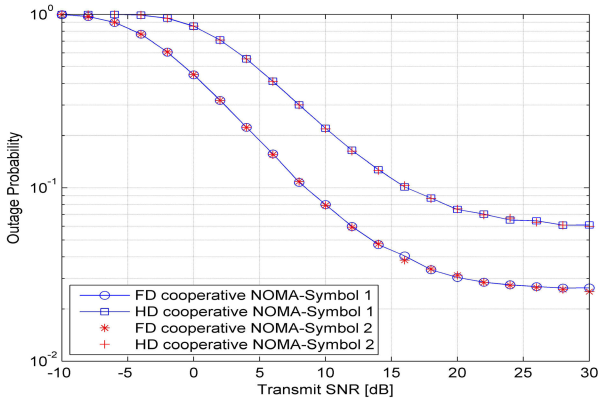

FIGURE 4. Outage probability versus transmit SNR under $\frac{\alpha_1 u_2}{\alpha_2(1+u_2)} \leq u_1 < \frac{\alpha_1}{\alpha_2}$.

The main reason is that, when the simulation parameters satisfied $\frac{\alpha_1 u_2}{\alpha_2(1+u_2)} \leq u_1 < \frac{\alpha_1}{\alpha_2}$, presence $P_{out,1} = P_{out,2}$. The detailed proof can refer to the proposition 4. The simulation verifies the proposition 4 well.

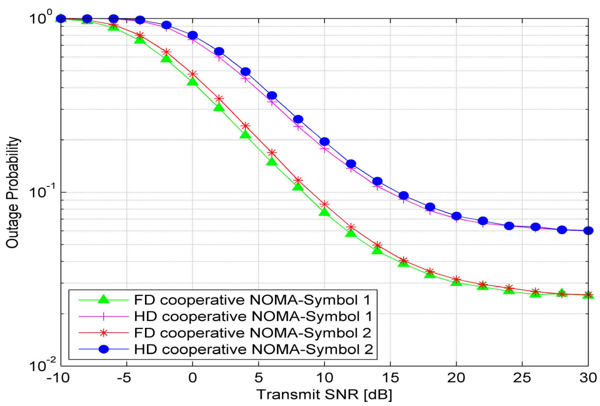

FIGURE 5. Outage probability versus transmit SNR under $u_1 < \frac{\alpha_1 u_2}{\alpha_2(1+u_2)}$.

In Fig. 5, also presents the outage probability of two symbols for our proposed uplink FD cooperative NOMA system and the HD cooperative NOMA system versus transmit SNR under $u_1 < \frac{\alpha_1 u_2}{\alpha_2(1+u_2)}$. The simulation parameters are set to: $\alpha_1 = 0.8, \alpha_2 = 0.2, \beta_1 = 0.9, \beta_2 = 0.1, \lambda_{1r} = 16, \lambda_{2r} = 9, \lambda_{rb} = 16, R_1 = R_2 = 0.5bps/Hz$. From this figure, we also can see that, the FD cooperative NOMA system has much better outage performance than the uplink HD cooperative NOMA system for each symbol. In addition, we also see that the outage performance of symbol 1 exceed symbol 2 based on the given system. This is due to this fact that, to ensure symbol 2 do not occur outage, the instantaneous transmit rate of symbol 1 and symbol 2 have to exceed the respectively target transmit rate. Thus, the symbol 2 more likely to happen outage phenomenon.

Fig. 6 depicts the outage probability versus transmit SNR for our proposed uplink FD cooperatve NOMA system under $u_1 < \frac{\alpha_1 u_2}{\alpha_2(1+u_2)}$. The simulation parameters for Fig. 6 are

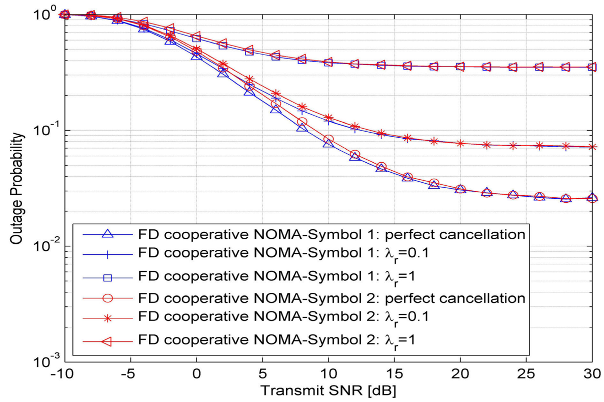

FIGURE 6. Outage probability versus transmit SNR.

the same as the Fig. 5. In the presence of residual self-interference, as we can see, the outage probability of symbol 1 and symbol 2 increase as increasing the mean of the residual self-interference power gain under the given transmit SNR. Furthermore, we also can see that, under given λ_r, as the transmit SNR gets larger, the outage probability of symbol 1 and symbol 2 is significantly reduced. Especially in the low to moderate transmit SNR regime. From the above analysis conclusion, we can also see that it is particularly important to consider the influence of the residual self-interference when designing practical uplink FD cooperative NOMA system.

V. CONCLUSION

In this paper, we propose an uplink cooperative NOMA system with a FD relay as the dedicated relay to receive and transmit information. Moreover, a novel FD relay transmission mode is proposed in which the FD relay utilizes SIC and self- interference cancellation to decode two users symbols at the relay receiving antenna, and the relay transmitting antenna transmits superimposed signal to base station by superposition coding technology. As a more realistic scenario, we also consider the existence of imperfect self-interference cancellation in this paper. The outage probability and the ergodic sum rate of our proposed system are investigated and the accurate analytical expressions are also derived. Simulation results show that our proposed system obtains better performance in the low to moderate transmit SNR regime, compared with the uplink HD cooperative TDMA/FDMA system and the uplink HD cooperative NOMA system.

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