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Performance of Cooperative NOMA System with a Full-Duplex Relay over Nakagami-m Fading Channels

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***Abstract*—In this paper, we investigate the outage performance of a system combining techniques of non-orthogonal multiple access (NOMA) and full-duplex (FD) in cooperative communication over Nakagami-m fading channels. The NOMA-user with better channel condition play a role of a decode-and-forward (DF) relaying node to assist the NOMA-user with worse channel condition in forwarding its messages. The closed-form expressions for outage probability of two users are derived with a realistic assumption that residual self-interference (RI) suppression and successive interference cancellation (SIC) are imperfect. The mathematical results afford some insights into the impact of RI parameter, imperfect SIC coefficient and multipath fading factor on the system. The Monte-Carlo simulation results verify the accuracy of theoretical analysis and provide an clear system observation.**

***Index Terms*—Non-orthogonal multiple access, full-duplex relaying, decode-and-forward, cooperative communication.**

I. Introduction

With rapid growth of massive connections and requirements for high-quality and real-time services, especially in the era of Industry 4.0 and Internet of Things (IoT), spectrum-efficient technical solutions is crucial for wireless communications. One promising candidate for increasing spectral efficiency is the in-band full-duplex (IBFD) wireless communication which henceforward is referred to as FD. The idea of FD was in fact not innovative, but it overcame the previous barrier that wireless terminals were impossible for simultaneous transmitting and receiving over the same frequency band at the same time due to excessive self-interference. Thanks to great development of digital signal processing (DSP) and modern antennas design techniques, the elimination of most self-interference in FD can be accomplished in practice [1]–[3]. Hence, FD is considered as a potential method in the fifth generation (5G) networks for doubling the spectral efficiency [3], [4].

On the other hand, design of multiple access schemes is an essential aspect for cellular networks [5]. The orthogonal frequency division multiple access (OFDMA) currently being used in the 4G network cannot satisfy requirements of high throughput and spectral efficiency of the 5G network. Hence, non-orthogonal multiple access (NOMA) has been gaining enormous attention as a promising radio access technique for future wireless networks [6], [7]. By allowing multiple users to share the same frequency and the same time resources, NOMA not only achieves superior spectral efficiency, but also increases the number of simultaneously served users [8]. There are two categories of main NOMA schemes: power-domain NOMA and code-domain NOMA. The key feature of these NOMA schemes is to allow multiplexing in either the power or code domain. In the scope of this paper, due to its popularity we focus our attention on the power-domain NOMA which uses superposition coding at the transmitter and SIC at the receiver [5], [9].

Besides, cooperative communication has been proved to gain advantage in extending network coverage, improving connectivity reliability and increasing system capacity by allowing users in a network to collaborate with each other for relaying information. Therefore, although having been widely studied over the last decade, cooperative communication is still attracting great interest, especially when it is applied to advanced wireless systems such as NOMA and FD [10].

In this paper, the advancements of the three technologies, namely NOMA, FD and cooperative communication are combined and explored for possible application in the next generation networks. The combinations of NOMA and FD with cooperative operation were investigated previously in [11]–[14], but these works only focused on the system behaviour over the Rayleigh fading channels. In [15], a NOMA system aided with a FD relaying node over the Nakagami-m fading channel was studied for the case with perfect SIC. Motivated by advantages of cooperative NOMA system in a general scenario, we derive closed-form expressions of the outage performance for the cooperative NOMA system with a decode-and-forward FD relay over the Nakagami-m. Moreover, the impact of residual self-interference and imperfect SIC on the system are also considered in an overall evaluation model.

The rest of this paper is organized as follows: Section II introduces the detailed system model. Section III derives outage performance for each user. Simulation results and discussions are presented in IV Section. Our conclusions are outlined in Section V.

II. System Model

Let us consider a simple two-user downlink NOMA system using decode-and-forward cooperative communication as illustrated in Fig. 1. The system includes a base station (BS) and two single-antenna users $\mathrm{U}_1, \mathrm{U}_2$.

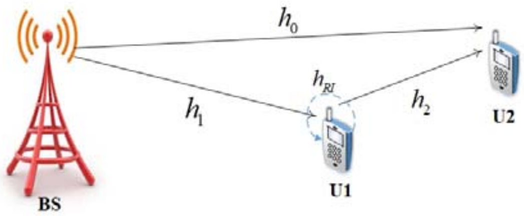

Figure 1. Cooperative NOMA-FD system model

Assuming that user $\mathrm{U_1}$ serves as a DF relay node and works in full-duplex mode for receiving the signal from BS and transmitting it to $\mathrm{U_2}$ simultaneously. At $\mathrm{U_2}$, the signals from BS and $\mathrm{U_1}$ are first combined using selection combining (SC) and then separated using SIC to retrieve its signal. The channels between BS and $\mathrm{U_1}$, BS and $\mathrm{U_2}$, and $\mathrm{U_1}$ and $\mathrm{U_2}$ are all assumed to be flat, non-selective frequency fading and subject to independent and identically distribution (i.i.d) Nakagami-m fading with complex channel coefficients h_1, h_0, h_2 respectively. Without loss of generality, it is assumed that the channel gain between BS and $\mathrm{U_1}$ is higher than that between BS and $\mathrm{U_2}$, i.e. $|h_1|^2 > |h_0|^2$. The residual self-interference noise due to imperfect interference cancellation for the FD mode at $\mathrm{U_1}$ is modeled as a Rayleigh random variable h_{RI} with variance Ω_{RI}. The term $n_i \sim CN\left(0,\sigma_n^2\right)$ denotes the additive white Gaussian noise (AWGN) at $\mathrm{U_i}$, $i = 1,2$ with zero-mean and variance σ_n^2.

Let $x_1(t)$ and $x_2(t)$ respectively denote the signals of $\mathrm{U_1}$ and $\mathrm{U_2}$. We assume that $\mathrm{E}\left[|x_1(t)|^2\right] = \mathrm{E}\left[|x_2(t)|^2\right] = 1$, where $\mathrm{E}\{.\}$ denotes the expectation operation. Then, the superposed signal to be sent to the two users from the BS can be expressed as

$$s(t) = \sqrt{a_1 P_s} x_1(t) + \sqrt{a_2 P_s} x_2(t), \tag{1}$$

where P_s is the transmit power of BS; a_1, a_2 denote respectively the power allocation coefficients for $\mathrm{U_1}$ and $\mathrm{U_2}$ which are subject to the constraints $a_1 + a_2 = 1$ and $a_1 < a_2$. Assuming that all channels are influenced by slow fading so that the time index for channel coefficients can be ignored. Hence, the received signal at $\mathrm{U_1}$ is expressed as

$$\begin{aligned} y_1(t) = h_1 &\left(\sqrt{a_1 P_s} x_1(t) + \sqrt{a_2 P_s} x_2(t)\right) \\ &+ h_{RI}\sqrt{P_r}\tilde{x}_1(t) + n_1(t), \end{aligned} \tag{2}$$

where $\tilde{x}_1(t)$ is the forwarding signal to $\mathrm{U_2}$, $E\left[|\tilde{x}_1(t)|^2\right] = 1$, P_r is the transmit power of $\mathrm{U_1}$. To simplify analysis, we assume that $P_s = P_r = P$, and define $\rho = \frac{P}{\sigma_n^2}$. $\mathrm{U_1}$ uses SIC technique to detect successively the signals of the two users. Since $a_1 < a_2$, $\mathrm{U_1}$ can detect the signal of $\mathrm{U_2}$ first, and then subtracts it from the superposed signal and detect that of $\mathrm{U_1}$ from the residue. Thus, the signal-to-interference-plus-noise-ratio (SINR) at $\mathrm{U_1}$ to detect x_2 is given by

$$\gamma_{1,\mathrm{U_2}} = \frac{|h_1|^2 a_2 \rho}{|h_1|^2 a_1 \rho + |h_{RI}|^2 \rho + 1}. \tag{3}$$

If SIC at $\mathrm{U_1}$ is performed perfectly, the SINR to detect its own message is given by

$$\gamma_{1,\mathrm{U_1}}^{\mathrm{perfSIC}} = \frac{|h_1|^2 a_1 \rho}{|h_{RI}|^2 \rho + 1}. \tag{4}$$

Otherwise, in the case of imperfect SIC at $\mathrm{U_1}$, the SINR for detecting x_1 is given by

$$\gamma_{1,\mathrm{U1}} = \frac{|h_1|^2 a_1 \rho}{|h_1|^2 a_2 \epsilon \rho + |h_{RI}|^2 \rho + 1}, \tag{5}$$

where $0 \le \epsilon \le 1$ is residual power factor after imperfect SIC. For the case $\epsilon = 0, \gamma_{1,\mathrm{U1}} = \gamma_{1,\mathrm{U_1}}^{\mathrm{perfSIC}}$. Upon successful detection $\mathrm{U_1}$ forwards x_2 to $\mathrm{U_2}$. The received signals of the direct link and the relay link at $\mathrm{U_2}$ are respectively expressed as follows:

$$y_2^S(t) = h_0\left(\sqrt{a_1 P_s} x_1(t) + \sqrt{a_2 P_s} x_2(t)\right) + n_2^S(t), \tag{6}$$

$$y_2^{\mathrm{U_1}}(t) = h_2\sqrt{P_r} x_2(t-\tau) + n_2^{\mathrm{U_1}}(t), \tag{7}$$

where τ is a processing delay. The SINRs at $\mathrm{U_2}$ corresponding to the direct link and the relay link, denoted respectively by $\gamma_{2,\mathrm{U_2}}^S$, $\gamma_{2,\mathrm{U_2}}^{\mathrm{U_1}}$ can be determined as follows:

$$\gamma_{2,\mathrm{U_2}}^S = \frac{|h_0|^2 a_2 \rho}{|h_0|^2 a_1 \rho + 1}, \tag{8}$$

$$\gamma_{2,\mathrm{U_2}}^{\mathrm{U_1}} = |h_2|^2 \rho. \tag{9}$$

III. Outage Performance Analysis

In this section, we provide detailed performance analysis of the considered cooperative NOMA-FD system in terms of outage probability.

A. Outage probability of $\mathrm{U_1}$

The outage probability defined as the probability that the received SNR falls below a given threshold [16] is expressed mathematically as follows

$$\mathrm{OP} = \Pr\left(\gamma_s \le \gamma_{\mathrm{gh}}\right) = \int_0^{\gamma_{\mathrm{gh}}} f_{\gamma_s(\gamma)} d\gamma, \tag{10}$$

where γ_{gh} is the given SNR threshold required for acceptable performance, $f_{\gamma_s(\gamma)}$ is probability density function (PDF) of the instantaneous SNR of a receiver. It is deduced from (10) that the outage event at $\mathrm{U_1}$ occurs when $\mathrm{U_1}$ can not decode x_1 or x_2. Therefore, the outage probability of $\mathrm{U_1}$ can be obtained as follows

$$P_{\mathrm{U_1}} = 1 - \Pr\left(\gamma_{1,\mathrm{U_2}} > \gamma_{\mathrm{gh2}}, \gamma_{1,\mathrm{U_1}} > \gamma_{\mathrm{gh1}}\right), \tag{11}$$

where the threshold $\gamma_{\mathrm{gh}i} = 2^{R_i} - 1$ with R_i being the target transmit rate of user $\mathrm{U_i}$, $i = 1,2$. Substituting (3) and (5) into (11), we obtain

$$\begin{aligned} P_{\mathrm{U_1}} &= 1 - \Pr\begin{pmatrix} |h_1|^2 > \alpha\left(|h_{RI}|^2 \rho + 1\right) \\ |h_1|^2 > \beta\left(|h_{RI}|^2 \rho + 1\right) \end{pmatrix} \\ &= 1 - \Pr\left(|h_1|^2 > \varphi\left(|h_{RI}|^2 \rho + 1\right)\right), \end{aligned} \tag{12}$$

where $\alpha = \frac{\gamma_{\rm gh2}}{\rho(a_2 - a_1\gamma_{\rm gh2})}, \beta = \frac{\gamma_{\rm gh1}}{\rho(a_1 - a_2\epsilon\gamma_{\rm gh1})}$, $\varphi = \max(\alpha,\beta)$. It is noted that the conditions to occur the expression (12) are $\gamma_{\rm gh2} < \frac{a_2}{a_1}$ and $\gamma_{\rm gh1} < \frac{a_1}{a_2\epsilon}$, otherwise the outage probability $P_{\rm U_1} = 1$. According to the theory of conditional probability [17], (12) is derived as

$$P_{\rm U_1} = 1 - \int_0^\infty \left[1 - F_{|h_1|^2}\left(\varphi\left(z\rho+1\right)\right)\right] f_{|h_{RI}|^2}(z)dz, \tag{13}$$

where $F_{|h_1|^2}(.)$ is the cumulative distribution function (CDF) of $|h_1|^2$. As the magnitude of channel coefficients $|h_i|$ is i.i.d Nakagami-m distribution, $|h_i|^2$ has i.i.d Gamma distribution, where $i = 0, 1, 2$. The PDF and CDF of the square of the Nakagami random variable are respectively written using [18] and [19] as

$$f_X(x) = \left(\frac{m_X}{\Omega_X}\right)^{m_X} \frac{x^{m_X-1}}{\Gamma(m_X)} \exp(-x\frac{m_X}{\Omega_X}), \tag{14}$$

$$\begin{aligned} F_X(x) &= 1 - \frac{1}{\Gamma(m_X)}\Gamma\left(m_X, x\frac{m_X}{\Omega_X}\right) \\ &= 1 - \exp\left(-x\frac{m_X}{\Omega_X}\right)\sum_{k=0}^{m_X-1}\left(x\frac{m_X}{\Omega_X}\right)^k\frac{1}{k!}, \end{aligned} \tag{15}$$

where m is the Nakagami multipath fading parameter which must be larger than $\frac{1}{2}$, Ω_X is the variance of the channel, $\Gamma(.), \Gamma(.,.)$ are respectively the Gamma function and incomplete Gamma function determined in [20]. Thus, $F_{|h_1|^2}(.)$ can be expressed as

$$\begin{aligned} F_{|h_1|^2}\left(\varphi\left(z\rho+1\right)\right) &= 1 - \exp\left(-\frac{m_1\varphi\left(z\rho+1\right)}{\Omega_1}\right) \\ &\times \sum_{k=0}^{m_1-1}\left(\frac{m_1\varphi\left(z\rho+1\right)}{\Omega_1}\right)^k\frac{1}{k!}, \end{aligned} \tag{16}$$

Because of the assumption that h_{RI} has the Rayleigh distribution, the PDF of $|h_{RI}|^2$ random variable has an exponential distribution and can be written as in [18]

$$f_{|h_{RI}|^2}(z) = \frac{1}{\Omega_{\rm RI}}\exp\left(-\frac{z}{\Omega_{\rm RI}}\right). \tag{17}$$

Substituting (16) and (17) into (13), we have

$$\begin{aligned} P_{\rm U_1} &= 1 - \frac{1}{\Omega_{\rm RI}}\exp\left(-\frac{m_1\varphi}{\Omega_1}\right)\sum_{k=0}^{m_1-1}\left(\frac{m_1\varphi}{\Omega_1}\right)^k\frac{1}{k!} \\ &\times \int_0^\infty (z\rho+1)^k \exp\left(-\frac{m_1\varphi\rho z}{\Omega_1} - \frac{z}{\Omega_{\rm RI}}\right)dz. \end{aligned} \tag{18}$$

Letting $c = \frac{m_1\varphi}{\Omega_1}$ and by using binomial expansion [20, eq.(1.111)], outage probability $P_{\rm U_1}$ is given by

$$\begin{aligned} P_{\rm U_1} &= 1 - \frac{1}{\Omega_{\rm RI}}\exp\left(-c\right)\sum_{k=0}^{m_1-1} \\ &\times \frac{c^k}{k!}\sum_{t=0}^{k}\rho^t\binom{k}{t}\int_0^\infty z^t\exp\left(-c\rho z - \frac{z}{\Omega_{\rm RI}}\right)dz. \end{aligned} \tag{19}$$

Thanks to the help of [20, eq.(3.351.3)], after some manipulations, the closed-form expression of outage probability $P_{\rm U_1}$ is obtained as

$$\begin{aligned} P_{\rm U_1} &= 1 - \frac{1}{\Omega_{\rm RI}}\exp\left(-c\right) \\ &\times \sum_{k=0}^{m_1-1}\sum_{t=0}^{k}\frac{c^k}{k!}\binom{k}{t}\rho^t t!\left(c\rho + \frac{1}{\Omega_{\rm RI}}\right)^{-t-1}. \end{aligned} \tag{20}$$

B. Outage probability of $\rm U_2$

It is worthy noting that once SC is adopted at $\rm U_2$, the signal corresponding to the largest SINR will be picked up [16] as the output signal and it is given by

$$\gamma_{\rm U_2}^{\rm SC} = \max\left\{\min\left(\gamma_{1,\rm U_2}, \gamma_{2,\rm U_2}^{\rm U_1}\right), \gamma_{2,\rm U_2}^{S}\right\}, \tag{21}$$

where $\gamma_{\rm U_2}^{\rm SC}$ is the output SINR at the combiner output. The outage probability of $\rm U_2$ is given by

$$\begin{aligned} P_{\rm U_2} &= \Pr\left(\gamma_{\rm U_2}^{\rm SC} \le \gamma_{\rm gh2}\right) \\ &= \Pr\left\{\max\left\{\min\left(\gamma_{1,\rm U_2}, \gamma_{2,\rm U_2}^{\rm U_1}\right), \gamma_{2,\rm U_2}^{S}\right\} \le \gamma_{\rm gh2}\right\}. \end{aligned} \tag{22}$$

Since the channels are assumed to undergo independent i.i.d. Nakagami-m fading, equation (22) can be derived as follows

$$\begin{aligned} P_{\rm U_2} &= \Pr\left\{\min\left(\gamma_{1,\rm U_2}, \gamma_{2,\rm U_2}^{\rm U_1}\right) \le \gamma_{\rm gh2}\right\} \\ &\times \Pr\left(\gamma_{2,\rm U_2}^{S} \le \gamma_{\rm gh2}\right), \end{aligned} \tag{23}$$

$$\begin{aligned} P_{\rm U_2} &= \left[1 - \Pr\left(\gamma_{1,\rm U_2} > \gamma_{\rm gh2}\right)\Pr\left(\gamma_{2,\rm U_2}^{\rm U_1} > \gamma_{\rm gh2}\right)\right] \\ &\times \Pr\left(\gamma_{2,\rm U_2}^{S} \le \gamma_{\rm gh2}\right). \end{aligned} \tag{24}$$

By calculating each part of (24), we obtain

$$\begin{aligned} \Pr\left(\gamma_{1,\rm U_2} > \gamma_{\rm gh2}\right) &= 1 - \Pr\left(|h_1|^2 > \alpha\left(|h_{RI}|^2\rho + 1\right)\right) \\ &= \frac{1}{\Omega_{\rm RI}}\exp\left(-c_1\right)\sum_{k=0}^{m_1-1}\sum_{t=0}^{k}\frac{c_1^k}{k!} \\ &\times \binom{k}{t}\rho^t t!\left(c_1\rho + \frac{1}{\Omega_{\rm RI}}\right)^{-t-1}, \end{aligned} \tag{25}$$

$$\Pr\left(\gamma_{2,\mathrm{U}_2}^{\mathrm{U}_1} > \gamma_{\mathrm{gh}2}\right) = 1 - \Pr\left(|h_2|^2 \le \frac{\gamma_{\mathrm{gh}2}}{\rho}\right) = \frac{1}{\Gamma(m_2)}\Gamma\left(m_2, \frac{m_2\gamma_{\mathrm{gh}2}}{\rho\Omega_2}\right), \quad (26)$$

$$\Pr\left(\gamma_{2,\mathrm{U}_2}^{S} \le \gamma_{\mathrm{gh}2}\right) = \Pr\left(|h_0|^2 \le \alpha\right) = 1 - \frac{1}{\Gamma(m_0)}\Gamma\left(m_0, \frac{m_0\alpha}{\Omega_0}\right), \quad (27)$$

where $c_1 = \frac{m_1\alpha}{\Omega_1}$, $d_1 = c_1\rho + \frac{1}{\Omega_{\mathrm{RI}}}$. Substituting (25), (26) and (27) into (24), the closed-form expression of P_{U_2} is finally expressed as

$$P_{\mathrm{U2}} = \left[1 - \frac{1}{\Omega_{\mathrm{RI}}}\exp(-c_1)\sum_{k=0}^{m_1-1}\sum_{t=0}^{k}\frac{c_1^k}{k!}\binom{k}{t} \times \rho^t t! d_1^{-t-1}\frac{1}{\Gamma(m_2)}\Gamma\left(m_2, \frac{m_2\gamma_{\mathrm{gh}2}}{\rho\Omega_2}\right)\right] \times \left[1 - \frac{1}{\Gamma(m_0)}\Gamma\left(m_0, \frac{m_0\alpha}{\Omega_0}\right)\right]. \quad (28)$$

IV. Performance Evaluation

In this section, we evaluate performance of the considered system and use Monte-Carlo simulations to validate the numerical results. The parameters used for simulations are set as follows. The power allocation coefficients are $a_1 = 0.3$ and $a_2 = 0,7$, the target rates are $R_1 = R_2 = 1$ bit per channel use (bpcu), the channel gains are set as $\mathrm{E}\left\{|h_0|^2\right\} = \Omega_0 = 1$, $\mathrm{E}\left\{|h_1|^2\right\} = \Omega_1 = 2$, $\mathrm{E}\left\{|h_2|^2\right\} = \Omega_2 = 1$.

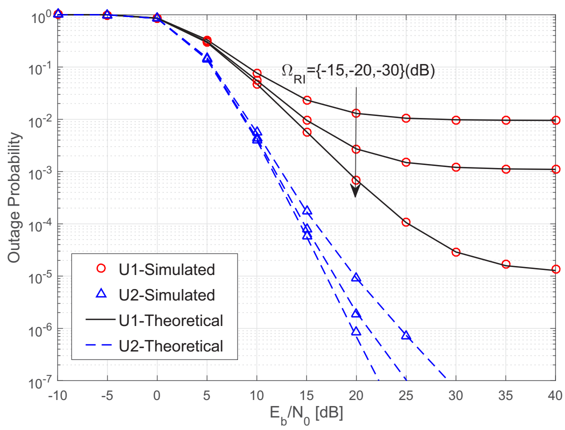

Figure 2. Outage probability versus the transmit E_b/N_0 for different values of residual self-interference

Fig. 2 shows the outage probability of U_1 and U_2 with $\Omega_{\mathrm{RI}} = \{-15, -20, -30\}$ (dB). In this case, we set $m_0 = m_1 = m_2 = 2$ and $\epsilon = 0.01$. The figure shows the perfect match between the simulation results and numerical results. This proves the accurateness of our analysis in Section III. Moreover, it is clear that the residual self-interference has a significant effect on the outage performance in the high E_b/N_0 region and is neglected in the low region. Ω_{RI} is also the cause for saturated outage probability of U_1 due to the full-duplex operation of U_2. Obviously, the outage performance of U_2 outperforms that of U_1 and do not exhibit the saturation in the plots since U_2 receives both the signals from BS and U_1. Therefore, U_2 is superior in achieving diversity to U_1.

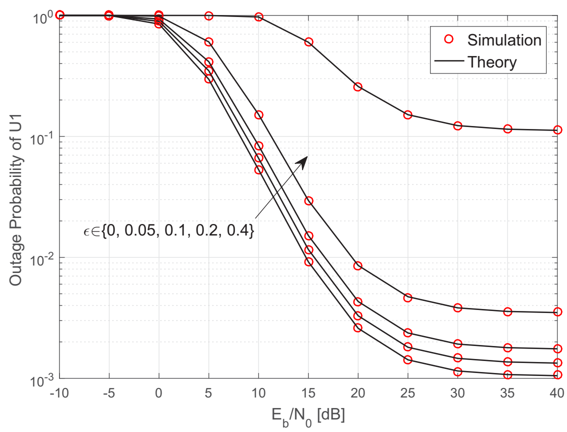

Figure 3. Outage probability of U_1 versus the transmit E_b/N_0 for different values of imperfect SIC factor.

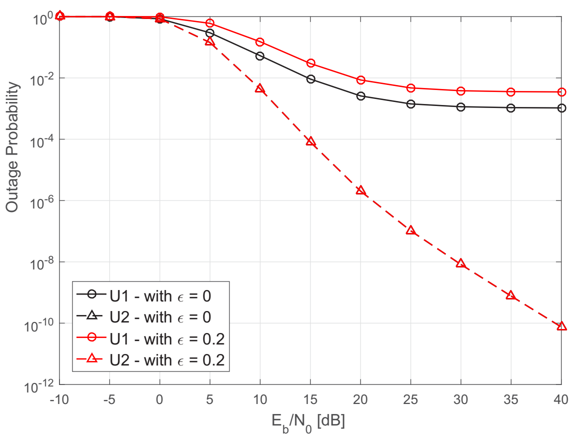

Figure 4. The impact of ϵ on the outage probabilities of U_1 and U_2.

Fig. 3 and Fig. 4 illustrate the impact of ϵ on the outage probability of U_1 and U_2 where ϵ and Ω_{RI} are chosen respectively as $\{0,\ 0.05,\ 0.1,\ 0.2,\ 0.4\}$ and $\Omega_{\mathrm{RI}} = -20$ (dB), while other parameters are set exactly the same as in Fig. 2. The figure indicates that the outage performance of U_1 declines noticeably when $\epsilon > 0.1$ whereas that of U_2 is constant. According to the analysis in Section III, the values of ϵ need to satisfy the condition $\epsilon\gamma_{\mathrm{gh}1} < \frac{a_1}{a_2}$, so if $\epsilon \ge \frac{a_1}{a_2\gamma_{\mathrm{gh}1}}$, the detection at U_1 is not successful. Also, note that the problem of imperfect SIC at U_1 does not affect to the outage probability of U_2 as proved by equation (28).

Fig. 5 compares the outage performance of the two users over the Nakagami-m fading channels with $m_0 = m_1 = m_2 = m = \{1,\ 2,\ 3\}$. As shown in the figure, the performance are improved when the value of m increases. Especially, with $m_0 = m_1 = m_2 = m = 1$, the Nakagami-m fading channel becomes the Rayleigh fading channel and the performance is poorest. It is

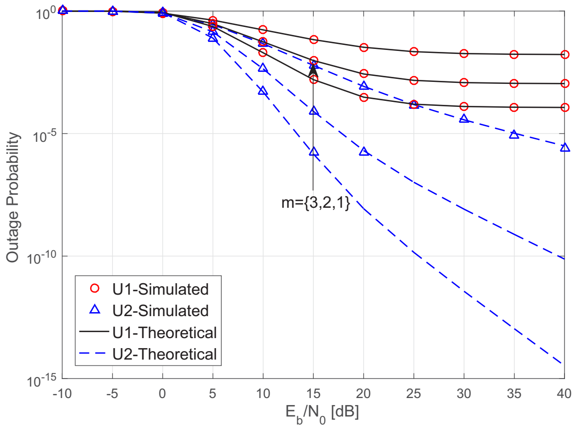

Figure 5. Outage probability versus the transmit E_b/N_0 for different values of m_0, m_1, m_2

evident that upon obtaining the analytical expression for the Nakagami-m fading channel, we can use it to study other different fading channels.

V. Conclusions

This paper has investigated the outage performance of the cooperative NOMA-FD communication system under the effect of the Nakagami-m fading and imperfect SIC. It has been shown that when residual self-interference and imperfect SIC factor increase, the outage probabilities of both users decreases significantly in the high E_b/N_0 regime. In addition, the limit of the imperfect SIC factor ϵ to ensure successful decoding at the relay user has also been derived as a general guide for system design.

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