Research Article

Performance Analysis of Cooperative NOMA Systems with Incremental Relaying

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In this paper, we investigate the performance of the non-orthogonal multiple access (NOMA) system with incremental relaying, where the relay is employed with amplify-and-forward (AF) or decode-and-forward (DF) protocols. To characterize the outage behaviors of the incremental cooperative NOMA (ICN) system, new closed-form expressions of both exact and asymptotic outage probability for two users are derived. In addition, the performance of the conventional cooperative NOMA (CCN) system is analyzed as a benchmark for the purpose of comparison. We confirm that the outage performance of the distant user is enhanced when ICN system is employed. Numerical results are presented to demonstrate that (1) the near user of the ICN system achieves better outage behavior than that of the CCN system in the low signal-to-noise ratio (SNR) region; (2) the outage performance of distant user for the DF-based ICN system is superior to that of the AF-based ICN system when the system works in cooperative NOMA transmission mode; and (3) in the low SNR, the throughput of the ICN system is higher than that of the CCN system.

1. Introduction

With the rapid development of the Internet of Things (IoT), spectrum efficiency becomes a key factor in guaranteeing the quality of service (QoS) of IoT applications. Nonorthogonal multiple access (NOMA) (NOMA schemes can be classified into two categories, namely, power-domain NOMA and code-domain NOMA. In this paper, we focus on power-domain NOMA and use NOMA to represent power-domain NOMA.) technology has been a revolutionary multiple access technology to enhance spectrum efficiency, user access ability, and user fairness [1–3]. Compared with the previous orthogonal multiple access technology (OMA), i.e., time division multiple access and frequency division multiple access, the key characteristic of NOMA is that multiuser signals are multiplexed in the same time/frequency/code resources with different power factors. Superposition coding and successive interference cancellation (SIC) has been used at the transmitter and receivers [4], respectively. The NOMA schemes has been proved to achieve higher spectral efficiency and system throughput in large-scale heterogeneous data traffic [5–7].

The initial research focused on the point-to-point downlink NOMA system extensively [8–10]. The outage behavior and ergodic rate of NOMA users were investigated where the users were deployed randomly [8]. In addition, the authors of [9] have researched the performance of a downlink single-cell NOMA network when assuming imperfect channel state information (CSI) and second-order statistics. Furthermore, the authors in [10] consider the scenario that each user only feedback one bit of its CSI to a base station (BS) and analyzed the outage performance. Apart from these researches, there are a lot of studies on improving the secrecy performance of multiple users [11, 12], where the external and internal eavesdropping scenarios have been considered.

Up to now, NOMA has been extended to cooperative communication systems [13, 14], as the higher diversity and extended coverage can be obtained in wireless networks. The authors have analyzed the outage performance of NOMA system with decode and forward (DF) relay employing full-duplex (FD) and half-duplex (HD) mode, where the near user was selected as a relay to deliver information and improve transmission reliability of distance users [15]. Inspired by this, simultaneous wireless information and

power transfer have been applied to cooperative NOMA from the perspective of enhancing spectrum efficiency and energy efficiency [16, 17]; the main feature is that the user relay harvests energy from BS. Especially, the system performance of [16] was comprehensively analyzed with considering DF and amplify-and-forward (AF) protocols. Moreover, cooperative NOMA schemes with dedicated relays have been widely investigated. The authors of [18, 19] have investigated the cooperative NOMA systems with dedicated AF relays, and it was proved that the performance of the NOMA system is obviously superior to that of the cooperative NOMA. Additionally, the performance of the cooperative NOMA system with dedicated DF relay has been researched by evaluating outage probability and sum rate over Nakagami-m fading [20]. The authors of [21] have researched a unified framework for hybrid satellite/unmanned aerial vehicle (UAV) terrestrial NOMA networks, where satellite communicated with ground users with the aid of a DF-UAV relay. In [22], the CSI was available in the cooperative NOMA system to determine the decoding order of cell-edge users data, where the outage behaviors have been analyzed under considering DF and AF relaying protocols. To further improve spectral efficiency, the FD mode has been employed in cooperative NOMA systems. The outage probability and ergodic rate of two-way relay NOMA system have been investigated [23]. In addition, the performance of FD cooperative NOMA systems in the presence of in-phase and quadrature-phase imbalance and imperfect SIC is analyzed and evaluated [24]. Furthermore, the authors have researched relay selection schemes to take advantages of space diversity and enhance spectral efficiency in cooperative NOMA systems [25, 26]. Very recently, the impact of residual transceiver hardware impairments on cooperative NOMA networks has been investigated in [27], which has also been researched in satellite-terrestrial cooperative NOMA networks [28] and two-way multiple relay NOMA networks [29].

The conventional cooperative NOMA (CCN) system described above can enhance the spectral efficiency, whether cooperative NOMA system employs the HD or FD. However, there are still some problems in the CCN system. On the one hand, the HD relay in the CCN system leads to a decline in spectral efficiency, as the HD relay needs half of the communication time to forward information compared to noncooperative NOMA networks. On the other hand, the existence of loop interference (LI) in the CCN system with FD relay will seriously affect the diversity gain. Recall that the incremental relaying (IR) protocol [30] is widely adopted in conventional cooperative networks, since it can achieve higher spectral efficiency by introducing a negligible one-bit-feedback overhead. Specifically, the IR protocol invokes a relay for cooperation only when the source to destination channel gain is below a predetermined threshold. Driven by this, the performance of cooperative systems with IR protocol has been investigated in NOMA systems [31, 32], which has the higher throughput compared to the conventional cooperative communications.

1.1. Motivation and Contributions. While the aforementioned research on cooperative NOMA and user relay

NOMA systems with IR protocol has laid a solid foundation for understanding the IR protocol [31–33], the incremental cooperative NOMA (ICN) system is still under exploration. It is worth pointing out that, from a practical perspective, the NOMA communication networks can be employed to support IoT scenarios, especially when two NOMA users are classified into two types by their quality of service (QoS) [25], i.e., the nearby user and distant user. The nearby user requires a high targeted rate and can be served opportunistically; e.g., it is to download video files or perform some background tasks and so on. The distant user should be served quickly for a small packet with a lower target data rate, as a further example, which is as a medical sensor to send the pivotal safety information containing such as pulse and heart rates in a few bytes. Hence, it is important to further enhance the communication reliability of the distant user in the NOMA systems. Moreover, there are some issues in cooperative systems, i.e., HD relay systems restrict the enhancement of spectral efficiency, while the LI of FD relay seriously affects the diversity gain. Motivated by these, we specifically consider a cooperative NOMA system with IR protocol (i.e., ICN system), where the dedicated relay is used when source to weak user channel gain is below the predetermined threshold. More specifically, the performance of our proposed system is characterized when AF and DF protocols are implemented at the relay, respectively. The main contributions of our paper are summarized as follows:

- (1) We derive the outage probability expressions of two users for AF-based ICN system. To get further insights, the asymptotic outage probability of two users is derived. Based on the analytical results, we acquire the diversity orders of two users for AF-based ICN system. We confirm that the use of the ICN system is able to improve the outage performance of the distant user
- (2) We also investigate the outage behaviors of the DF-based ICN system. We further derive the closed-form and asymptotic expressions of outage probability for two users. Additionally, we obtain the diversity orders of two users. The distant user in the DF-based ICN system is capable of achieving better outage behavior than that of the CCN system
- (3) We confirm that the near user of ICN system achieves better outage behavior than that of the CCN system in the low signal-to-noise ratio (SNR) region. The outage performance of distant user for DF-based NOMA system is superior to that of the AF-based NOMA system. Furthermore, better system throughput of the ICN system is achieved in the low SNR region over delay-limited transmission

1.2. Organization. The rest of this paper is organized as follows. In Section 2, the model of the ICN system is presented. In Section 3, the outage behaviors of two users for AF-based ICN system are investigated. Furthermore, the outage behaviors of two users for DF-based ICN system are studied in Section 4. In Section 5, numerical results are provided for

performance evaluation and comparison. Finally, Section 6 concludes the paper.

2. System Model

2.1. Network Description. Consider a downlink cooperative NOMA network including one BS, one relay R and two users, i.e., the nearby user D_1 and distant user D_2 , as shown in Figure 1. Moreover, the AF and DF protocols are considered at R . The relay employs HD mode and all nodes in the network have a single antenna. All wireless channels in the scenario considered are assumed to be independent nonselective block Rayleigh fading and are disturbed by additive white Gaussian noise with mean power σ^2 . $h_{1,b} \sim \text{CN}(0, \Omega_{1,b})$, $h_{2,b} \sim \text{CN}(0, \Omega_{2,b})$, and $h_{r,b} \sim \text{CN}(0, \Omega_{r,b})$ denote the complex channel coefficient of $BS \rightarrow D_1$, $BS \rightarrow D_2$, and $BS \rightarrow R$, respectively. Similarly, $h_{r,1} \sim \text{CN}(0, \Omega_{r,1})$ and $h_{r,2} \sim \text{CN}(0, \Omega_{r,2})$ are the complex channel coefficient of $R \rightarrow D_1$ and $R \rightarrow D_2$, respectively. In addition, we assume $d_{1,b}$, $d_{r,b}$, and $d_{2,b}$ denote the distance from BS to D_1 , R , and D_2 , respectively; $d_{r,1}$ and $d_{r,2}$ are the distance from R to D_1 and D_2 , respectively. Without loss of generality, assuming that $d_{1,b} > d_{r,b} > d_{2,b}$ and $\Omega_{1,b} > \Omega_{r,b} > \Omega_{2,b}$. In the next subsection, the ICN system and communication process will be introduced in detail.

2.2. ICN System. The transmission process of the ICN system is described as follows. At the beginning of each transmission block, BS broadcasts a pilot signal to D_1 , R , and D_2 . Based on the received pilot signal, D_2 performs channel estimation of $h_{2,b}$ and compares with a predefined threshold. If D_2 judges that it can correctly decode its desired information through direct transmission, it feedbacks 1-bit positive acknowledgement to BS and R . After receiving the positive feedback, BS adopts a direct NOMA transmission mode, i.e., it sends the superimposed signal directly to D_1 and D_2 within the whole transmission block. If D_2 observes that it is unable to decode its desired message without cooperation, it feedbacks 1-bit negative acknowledge to BS and R . Upon hearing the negative feedback, BS adopts a cooperative NOMA transmission mode, i.e., BS broadcasts the superimposed signal in the first half of the transmission block, and then R forwards the superimposed signal to the two users in the second half of the transmission block. Different from ICN system, the transmission block of CCN system is divided into two phases with equal duration. During the first phase, BS sends the superimposed signal to D_1 , D_2 , and R ; then, R will forward it to users in the second phase. Obviously, the ICN system is an adaptive system, which can adaptively switch between the direct NOMA transmission mode and cooperative NOMA transmission mode based on the 1-bit indicator.

2.3. Signal Model

2.3.1. Direct NOMA Transmission Mode. In the first time slot, BS broadcasts the superposed signal $\sqrt{a_1 P_s} x_1 + \sqrt{a_2 P_s} x_2$ to D_1 , D_2 , and R according to NOMA principle, where x_1 and x_2 are the unit power signals for D_1 and D_2 , respectively. The corresponding power allocation coefficients of D_1 and

FIGURE 1: An illustration of cooperative NOMA system with IR protocol.

D_2 are a_1 and a_2 , respectively. Specially, we assume that $a_1 \leq a_2$ with $a_1 + a_2 = 1$ to ensure better user fairness and QoS requirements between the users, which is also consistent with many existing NOMA contributions [6]. Therefore, the received signal at D_1 , D_2 , and R can be given by

$$y_1 = \sqrt{a_1 P_s} h_{1,b} x_1 + \sqrt{a_2 P_s} h_{1,b} x_2 + \omega_1, \quad (1)$$

$$y_2 = \sqrt{a_1 P_s} h_{2,b} x_1 + \sqrt{a_2 P_s} h_{2,b} x_2 + \omega_2, \quad (2)$$

$$y_r = \sqrt{a_1 P_s} h_{r,b} x_1 + \sqrt{a_2 P_s} h_{r,b} x_2 + \omega_r, \quad (3)$$

respectively; where P_s represents normalized transmission power of BS. ω_1 , ω_2 , and ω_r denote the Gaussian noise with zero mean and variance σ^2 at D_1 , D_2 , and R , respectively.

The SIC scheme is first employed at D_1 to detect the signal x_2 of D_2 . Hence, the received signal-to-interference-plus-noise ratio (SINR) at D_1 to detect x_2 is given by

$$\gamma_{1,2} = \frac{a_2 \rho_s |h_{1,b}|^2}{a_1 \rho_s |h_{1,b}|^2 + 1}, \quad (4)$$

where $\rho_s = P_s / \sigma^2$ is the transmit SNR of the link between BS and users and R . After decoding the message of D_2 and subtracting it, D_1 is further to detect its own information with the following SNR:

$$\gamma_1 = a_1 \rho_s |h_{1,b}|^2. \quad (5)$$

The received SINR at D_2 to detect its own message is given by

$$\gamma_2 = \frac{a_2 \rho_s |h_{2,b}|^2}{a_1 \rho_s |h_{2,b}|^2 + 1}. \quad (6)$$

2.3.2. Cooperative NOMA Transmission Mode. In cooperative NOMA transmission mode, the entire transmission

block consists of two phases with equal duration. In the first phase, the received signal and SINR at D_1 , D_2 , and R is the same as described in direct NOMA transmission mode. Then, in the second phase, R forwards the received signal y_r to users with transmit power P_r , which is assumed $P_r = P_s$. Specially, the observations from the BS and the relaying node are combined at the users with selection combining. More importantly, as the relay is employed with AF and DF modes, the transmission process for AF and DF protocols will be explained in the next part in detail, respectively.

(1) *Amplify-and-Forward*. For AF case, R amplifies and forwards its received signals to D_1 and D_2 in the second time slot. Therefore, the observation at D_1 and D_2 in the second phase can be given as

$$y_1^{AF} = Gh_{r,1}y_r + n_1, \quad (7)$$

$$y_2^{AF} = Gh_{r,2}y_r + n_2, \quad (8)$$

respectively, where $G = \sqrt{P_r/(P_s|h_{r,b}|^2 + \sigma^2)}$ is the amplifying factor of the AF relay. Similarly, the received SINR at D_1 to detect x_2 with SIC scheme is given by

$$\gamma_{1,2}^{AF} = \frac{a_2\rho_s|h_{r,b}|^2|h_{r,1}|^2}{a_1\rho_s|h_{r,b}|^2|h_{r,1}|^2 + |h_{r,1}|^2 + |h_{r,b}|^2 + (1/\rho_s)}, \quad (9)$$

After decoding the message of D_2 and subtracting it, D_1 is further to detect its own information with the following SNR:

$$\gamma_1^{AF} = \frac{a_1\rho_s|h_{r,b}|^2|h_{r,1}|^2}{|h_{r,1}|^2 + |h_{r,b}|^2 + (1/\rho_s)}. \quad (10)$$

The received SINR at D_2 to detect its own message is given by

$$\gamma_2^{AF} = \frac{a_2\rho_s|h_{r,b}|^2|h_{r,2}|^2}{a_1\rho_s|h_{r,b}|^2|h_{r,2}|^2 + |h_{r,2}|^2 + |h_{r,b}|^2 + (1/\rho_s)}. \quad (11)$$

(2) *Decode-and-Forward*. For simplicity, assuming that R is capable of decoding the two NOMA users information, therefore, the observation at D_1 and D_2 in the second slot can be expressed as

$$y_1^{DF} = \sqrt{a_1P_r}h_{r,1}x_1 + \sqrt{a_2P_r}h_{r,1}x_2 + n_1, \quad (12)$$

$$y_2^{DF} = \sqrt{a_1P_r}h_{r,2}x_1 + \sqrt{a_2P_r}h_{r,2}x_2 + n_2, \quad (13)$$

respectively, where n_1 and n_2 are the AWGN at D_1 and D_2 with zero mean and variance σ^2 .

By using SIC scheme, the received SINR at D_1 to detect x_2 is given by

$$\gamma_{1,2}^{DF} = \frac{a_2\rho_s|h_{r,1}|^2}{a_1\rho_s|h_{r,1}|^2 + 1}. \quad (14)$$

Then, D_1 further detects its own information with the following SINR:

$$\gamma_1^{DF} = a_1\rho_s|h_{r,1}|^2. \quad (15)$$

The received SINR at D_2 to detect its own message is given by

$$\gamma_2^{DF} = \frac{a_2\rho_s|h_{r,2}|^2}{a_1\rho_s|h_{r,2}|^2 + 1}. \quad (16)$$

3. Outage Performance Evaluation for AF-Based NOMA System

In this section, the outage behaviors are characterized for AF-based ICN and CCN systems, which are detailed in the following.

3.1. *Outage Performance Analysis of ICN System*. In this subsection, the outage behaviors of the AF-based ICN system are investigated.

3.1.1. *Outage Probability of D_1* . According to the ICN protocol, the outage probability of D_1 can be expressed as

$$P_{1,AF}^{ICN} = \Pr(\gamma_2 \geq \gamma_{th2})[1 - \Pr(\gamma_{1,2} \geq \gamma_{th2}, \gamma_1 \geq \gamma_{th1})] + \Pr(\gamma_2 < \gamma_{th2})P_{1,AF}^{CNT}, \quad (17)$$

where $P_r(\gamma_2 \geq \gamma_{th2})$ represents the system works in the direct NOMA transmission mode, and $P_r(\gamma_2 < \gamma_{th2})$ indicates that the system works in the cooperative NOMA transmission mode. In addition, $\gamma_{th1} = 2^{R_1} - 1$ and $\gamma_{th2} = 2^{R_2} - 1$ are the decoding threshold under direct NOMA transmission mode with R_1 and R_2 being the target rate of D_1 and D_2 . Besides, $P_{1,AF}^{CNT}$ is the outage probability of D_1 with AF relay in the cooperative NOMA transmission mode, which can be given as

$$P_{1,AF}^{CNT} = \left[1 - \Pr(\gamma_{1,2} \geq \gamma'_{th2}, \gamma_1 \geq \gamma'_{th1})\right] \times \left[1 - \Pr(\gamma_{1,2}^{AF} \geq \gamma'_{th2}, \gamma_1^{AF} \geq \gamma'_{th1})\right], \quad (18)$$

where $\gamma'_{th1} = 2^{2R_1} - 1$ and $\gamma'_{th2} = 2^{2R_2} - 1$ are the decoding threshold with R_1 and R_2 being the target rate of D_1 and D_2 in cooperative NOMA transmission mode.

The following theorem provides the outage probability of D_1 in the AF-based ICN system.

Theorem 1. *The closed-form expression of outage probability for D_1 in the AF-based ICN system is given as*

$$P_{1,AF}^{ICN} = \begin{cases} 1 - e^{-\tau/\Omega_{2,b}} e^{-\theta/\Omega_{1,b}} - (1 - e^{-\tau/\Omega_{2,b}}) \\ \quad \times \left[e^{-\theta'/\Omega_{1,b}} + (1 - e^{-\theta'/\Omega_{1,b}}) e^{-\theta'/\Omega_{r,b} - \theta'/\Omega_{r,l}} \right] \\ \quad \times \sqrt{\frac{4\theta'(\rho_s\theta' + 1)}{\rho_s\Omega_{r,l}\Omega_{r,b}}} K_1 \left(\sqrt{\frac{4\theta'(\rho_s\theta' + 1)}{\rho_s\Omega_{r,l}\Omega_{r,b}}} \right) \Bigg], \frac{a_2}{a_1} > \gamma'_{th2}, \\ 1 - e^{-\tau/\Omega_{2,b}} e^{-\theta/\Omega_{1,b}}, \gamma_{th2} < \frac{a_2}{a_1} \leq \gamma'_{th2} \\ 1, 0 < \frac{a_2}{a_1} \leq \gamma_{th2}, \end{cases} \quad (19)$$

where $\tau = \gamma_{th2}'(\rho_s(a_2 - a_1\gamma_{th2}'))$, $\sigma = \gamma_{th1}'/a_1\rho_s$, and $\theta = \max(\tau, \sigma)$; $\tau' = \gamma_{th2}'(\rho_s(a_2 - a_1\gamma_{th2}'))$, $\sigma' = \gamma_{th1}'/a_1\rho_s$, and $\theta' = \max(\tau', \sigma')$. $K_1(\cdot)$ is the first-order modified Bessel function of the second kind.

Proof. See Appendix A.

3.1.2. Outage Probability of D_2 . Based on the ICN protocol, the outage event cannot occur when $\gamma_2 \geq \gamma_{th2}$. Hence, the outage event can only occur in cooperative NOMA transmission mode, i.e., the information of D_2 failed to be successfully decoded in the first and second phases when $\gamma_2 < \gamma_{th2}$. The outage probability of D_2 in AF-based NOMA system can be expressed as

$$P_{2,AF}^{ICN} = \Pr(\gamma_2 < \gamma_{th2}, \gamma_2 < \gamma'_{th2}, \gamma_2^{AF} < \gamma'_{th2}). \quad (20)$$

As $\gamma_{th2} < \gamma'_{th2}$, (20) can be further rewritten as

$$P_{2,AF}^{ICN} = \Pr(\gamma_2 < \gamma_{th2}, \gamma_2^{AF} < \gamma'_{th2}). \quad (21)$$

Similar to the proof process of Theorem 1, the following theorem provides the outage probability of D_2 in the AF-based ICN system.

Theorem 2. *The closed-form expression of outage probability for D_2 in the AF-based ICN system is given as*

$$P_{2,AF}^{ICN} = \begin{cases} (1 - e^{-\tau/\Omega_{2,b}}) \left[1 - e^{-\tau'/\Omega_{r,b}} e^{-\tau'/\Omega_{r,2}} \sqrt{\frac{4\tau'(\rho_s\tau' + 1)}{\rho_s\Omega_{r,2}\Omega_{r,b}}} \right. \\ \quad \times K_1 \left(\sqrt{\frac{4\tau'(\rho_s\tau' + 1)}{\rho_s\Omega_{r,2}\Omega_{r,b}}} \right) \Bigg], \frac{a_2}{a_1} > \gamma'_{th2} \\ (1 - e^{-\tau/\Omega_{2,b}}), \gamma_{th2} < \frac{a_2}{a_1} \leq \gamma'_{th2} \\ 1, 0 < \frac{a_2}{a_1} \leq \gamma_{th2}, \end{cases} \quad (22)$$

Proof. See Appendix B.

From the above derivations, it is obvious that $P_{1,AF}^{ICN}$ and $P_{2,AF}^{ICN}$ are both equal to one when $0 < a_2/a_1 \leq \gamma_{th2}$. Thus, in the following, we only focus on the remaining region, i.e., $a_2/a_1 > \gamma_{th2}$.

3.1.3. Diversity Analysis. To gain more insights, the outage probability in high SNR region is investigated in this section, and the diversity order achieved by the users can be obtained based on the above analytical results. The diversity order [26] is defined as

$$d = -\lim_{\rho \rightarrow \infty} \frac{\log(P(\rho))}{\log \rho}. \quad (23)$$

(1) *Diversity Order of D_1 .* When $\rho \rightarrow \infty$, according to $K_1(x) \approx 1/x$ and $e^{-x} \approx 1 - x(x \rightarrow 0)$, we can derive the asymptotic outage probability of D_1 for the AF-based ICN system in the following corollary.

Corollary 3. *The asymptotic outage probability of D_1 in the AF-based ICN system is given as*

$$P_{1,AF}^{ICN,\infty} = \begin{cases} \frac{\theta}{\Omega_{1,b}} + \frac{\tau}{\Omega_{2,b}} \frac{\theta'}{\Omega_{1,b}} \left(\frac{\theta'}{\Omega_{r,b}} + \frac{\theta'}{\Omega_{r,l}} \right), \frac{a_2}{a_1} > \gamma'_{th2} \\ \frac{\tau}{\Omega_{2,b}} + \frac{\theta}{\Omega_{1,b}} - \frac{\tau\theta}{\Omega_{1,b}\Omega_{2,b}}, \gamma_{th2} < \frac{a_2}{a_1} \leq \gamma'_{th2} \end{cases} \quad (24)$$

Substituting (24) into (23), we can obtain the diversity order of D_1 in the AF-based ICN system as

$$d_{1,AF}^{ICN} = 1, \quad (25)$$

Remark 4. The diversity order of D_1 is one, which is obtained with direct link. It indicates that the performance of D_1 mainly depends on the direct link in the AF-based NOMA ICN system.

(2) *Diversity Order of D_2 .* Similarly, we can derive the asymptotic outage probability of D_2 for the AF-based ICN system in the following corollary.

Corollary 5. The closed-form expression of outage probability for D_2 in the AF-based ICN system is given as

$$P_{2,AF}^{ICN,\infty} = \begin{cases} \frac{\tau}{\Omega_{2,b}} \left(\frac{\tau'}{\Omega_{r,b}} + \frac{\tau'}{\Omega_{r,2}} \right), \frac{a_2}{a_1} > \gamma'_{th2} \\ \frac{\tau}{\Omega_{2,b}}, \gamma_{th2} < \frac{a_2}{a_1} \leq \gamma'_{th2} \end{cases} \quad (26)$$

Substituting (26) into (23), we can obtain the diversity order of D_2 in the AF-based ICN system as

$$d_{2,AF}^{ICN} = \begin{cases} 2, \frac{a_2}{a_1} > \gamma'_{th2} \\ 1, \gamma_{th2} < \frac{a_2}{a_1} \leq \gamma'_{th2} \end{cases} \quad (27)$$

where (26) and (27) are also derived on the condition of $a_2/a_1 > \gamma'_{th2}$.

Remark 6. When $a_2/a_1 > \gamma'_{th2}$, the diversity order of D_2 is two, which is obtained with direct link and relaying link. When $\gamma_{th2} < a_2/a_1 \leq \gamma'_{th2}$, the diversity order of D_2 is one, which is obtained with direct link.

3.1.4. Throughput Analysis. In this section, the throughput will be considered in delay-limited transmission for AF-based ICN system. In our considered system, the BS transmits information at a constant rate, which is subject to the effect of outage probability due to wireless fading channels. The system throughput for AF-based ICN system is given as

$$R_{AF}^{ICN} = (1 - P_{1,AF}^{ICN})R_1 + (1 - P_{2,AF}^{ICN})R_2, \quad (28)$$

where $P_{1,AF}^{ICN}$ and $P_{2,AF}^{ICN}$ are obtained from (19) and (22), respectively.

3.2. Outage Performance Analysis with CCN Protocol. In this subsection, the outage behaviors of the AF-based CCN system are investigated, which will be served as a benchmark for the outage performance employing ICN protocol.

3.2.1. Outage Probability of D_1 . According to the CCN protocol, the expression of the outage probability for D_1 is the same with (18). Hence, the closed-form expression of outage probability for D_1 in the AF-based NOMA system with CCN protocol is given as

$$P_{1,AF}^{CCN} = \left(1 - e^{-\theta'/\Omega_{1,b}}\right) \left[1 - e^{-\theta'/\Omega_{r,b} - \theta'/\Omega_{r,1}} \sqrt{\frac{4\theta'(\rho_s\theta' + 1)}{\rho_s\Omega_{r,1}\Omega_{r,b}}}\right] \times K_1 \left(\sqrt{\frac{4\theta'(\rho_s\theta' + 1)}{\rho_s\Omega_{r,1}\Omega_{r,b}}} \right), \quad (29)$$

where (29) is derived on the condition of $a_2/a_1 > \gamma'_{th2}$, otherwise $P_{1,AF}^{CCN} = 1$.

Comparing (17) and (18) or (19) and (29), it is impossible to judge directly that the performance of D_1 for the ICN system is better than that of the CCN system. However, the derivation results can be used for simulation verification and comparison.

3.2.2. Outage Probability of D_2 . According to the CCN protocol, the expression of the outage probability for D_2 can be given as

$$P_{2,AF}^{CCN} = \Pr(\gamma_2 < \gamma'_{th2}) \Pr(\gamma_2^{AF} < \gamma'_{th2}). \quad (30)$$

The closed-form expression of outage probability for D_2 in the AF-based NOMA system with CCN protocol is given as

$$P_{2,AF}^{CCN} = \left(1 - e^{-\tau'/\Omega_{2,b}}\right) \left[1 - e^{-\tau'/\Omega_{r,b}} e^{-\tau'/\Omega_{r,2}} \times \sqrt{\frac{4\tau'(\rho_s\tau' + 1)}{\rho_s\Omega_{r,2}\Omega_{r,b}}} K_1 \left(\sqrt{\frac{4\tau'(\rho_s\tau' + 1)}{\rho_s\Omega_{r,2}\Omega_{r,b}}} \right) \right], \quad (31)$$

where (30) is also derived on the condition of $a_2/a_1 > \gamma'_{th2}$, otherwise $P_{2,AF}^{CCN} = 1$.

Remark 7. It is obvious that $P_{2,AF}^{ICN} < P_{2,AF}^{CCN}$, i.e., the outage behavior of D_2 in the cooperative NOMA system is enhanced by employing ICN protocol.

Proof. See Appendix C.

3.2.3. Diversity Analysis

(1) *Diversity Order of D_1 .* When $\rho \rightarrow \infty$, based on $K_1(x) \approx 1/x$ and $e^{-x} \approx 1 - x$ ($x \rightarrow 0$), the asymptotic outage probability of D_1 for the AF-based CCN system is given as

$$P_{1,AF}^{CCN,\infty} = \frac{\theta'}{\Omega_{1,b}} \left(\frac{\theta'}{\Omega_{r,b}} + \frac{\theta'}{\Omega_{r,1}} \right). \quad (32)$$

Substituting (32) into (23), we can obtain $d_{1,AF}^{CCN} = 2$.

(2) *Diversity Order of D_2* . Similarly, the asymptotic outage probability of D_2 for the AF-based CCN system can be obtained as

$$P_{2,AF}^{CCN,\infty} = \frac{\tau'}{\Omega_{2,b}} \left(\frac{\tau'}{\Omega_{r,b}} + \frac{\tau'}{\Omega_{r,2}} \right). \quad (33)$$

Substituting (33) into (23), we can obtain $d_{2,AF}^{CCN} = 2$. It is noting that (32) and (33) are derived on the condition of $a_2/a_1 > \gamma'_{th2}$. One observation is that D_1 of CCN system can obtain higher diversity order than that of ICN system. Another observation is that D_2 of CCN and ICN systems obtains the same diversity order.

3.2.4. Throughput Analysis. Similarly, the throughput in delay-limited transmission for AF-based CCN system is given by

$$R_{AF}^{CCN} = (1 - P_{1,AF}^{CCN})R_1 + (1 - P_{2,AF}^{CCN})R_2. \quad (34)$$

where $P_{1,AF}^{CCN}$ and $P_{2,AF}^{CCN}$ are obtained from (29) and (31), respectively.

4. Outage Performance Evaluation for DF-Based NOMA System

In this section, the outage behaviors are characterized for DF-based ICN and CCN systems, which are detailed in the following.

4.1. Outage Performance Analysis with ICN Protocol. In this subsection, the outage behaviors of the DF-based ICN system are investigated.

4.1.1. Outage Probability of D_1 . According to the ICN protocol, the outage probability of D_1 can be expressed as

$$P_{1,DF}^{ICN} = \Pr(\gamma_2 \geq \gamma_{th2}) [1 - \Pr(\gamma_{1,2} \geq \gamma_{th2}, \gamma_1 \geq \gamma_{th1})] + \Pr(\gamma_2 < \gamma_{th2}) P_{1,DF}^{CNT}, \quad (35)$$

where $P_{1,DF}^{CNT}$ is the outage probability of D_1 in the CNT mode, which can be given as

$$P_{1,DF}^{CNT} = \left[1 - \Pr(\gamma_{1,2} \geq \gamma'_{th2}, \gamma_1 \geq \gamma'_{th1}) \right] \times \left[1 - \Pr(\gamma_{1,2}^{DF} \geq \gamma'_{th2}, \gamma_1^{DF} \geq \gamma'_{th1}) \right]. \quad (36)$$

Referring to the proof process of Theorem 1, the following theorem provides the outage probability of D_1 in the DF-based ICN system.

Theorem 8. *The closed-form expression of outage probability for D_1 in the DF-based ICN system is given as*

$$P_{1,DF}^{ICN} = \begin{cases} 1 - e^{-\tau/\Omega_{2,b}} e^{-\theta/\Omega_{1,b}} - (1 - e^{-\tau/\Omega_{2,b}}) \\ \times \left(e^{-\theta'/\Omega_{1,b}} + e^{-\theta'/\Omega_{r,1}} (1 - e^{-\theta'/\Omega_{1,b}}) \right), \frac{a_2}{a_1} > \gamma'_{th2} \\ 1 - e^{-\tau/\Omega_{2,b}} e^{-\theta/\Omega_{1,b}}, \gamma_{th2} < \frac{a_2}{a_1} \leq \gamma'_{th2} \\ 1, 0 < \frac{a_2}{a_1} \leq \gamma_{th2}. \end{cases} \quad (37)$$

4.1.2. Outage Probability of D_2 . Similar to the case of AF-based NOMA system, the outage probability of D_2 can be expressed as

$$P_{2,DF}^{ICN} = \Pr(\gamma_2 < \gamma_{th2}, \gamma_2 < \gamma'_{th2}, \gamma_2^{DF} < \gamma'_{th2}). \quad (38)$$

As $\gamma_{th2} < \gamma'_{th2}$, (39) can be further rewritten as

$$P_{2,DF}^{ICN} = \Pr(\gamma_2 < \gamma_{th2}, \gamma_2^{DF} < \gamma'_{th2}). \quad (39)$$

Similarly, referring to the proof process of Theorem 2, the following theorem provides the outage probability of D_2 in the DF-based ICN system.

Theorem 9. *The closed-form expression of outage probability for D_2 in the DF-based ICN system is given as*

$$P_{2,DF}^{ICN} = \begin{cases} (1 - e^{-\tau/\Omega_{2,b}}) (1 - e^{-\tau'/\Omega_{r,2}}), \frac{a_2}{a_1} > \gamma'_{th2} \\ 1 - e^{-\tau/\Omega_{2,b}}, \gamma_{th2} < \frac{a_2}{a_1} \leq \gamma'_{th2} \\ 1, 0 < \frac{a_2}{a_1} \leq \gamma_{th2} \end{cases}. \quad (40)$$

Similar to the AF-based ICN system, we only focus on the remaining region $a_2/a_1 > \gamma_{th2}$ in the following.

4.1.3. Diversity Analysis. Similarly, the outage probability in high SNR region is investigated in this section, and the diversity order achieved by the users can be obtained based on the above analytical results.

(1) *Diversity Order of D_1* . When $\rho \rightarrow \infty$, according to $e^{-x} \approx 1 - x$ ($x \rightarrow 0$), we can derive the asymptotic outage probability of D_1 for the DF-based ICN system in the following corollary.

Corollary 10. *The asymptotic outage probability of D_1 in the DF-based ICN system is given as*

$$P_{1,DF}^{ICN,\infty} = \begin{cases} \frac{\tau}{\Omega_{2,b}} + \frac{\theta}{\Omega_{1,b}} - \frac{\tau\theta}{\Omega_{1,b}\Omega_{2,b}} \\ -\frac{\tau}{\Omega_{2,b}} \left[1 - \frac{\theta'^2}{\Omega_{1,b}\Omega_{r,1}} \right], \frac{a_2}{a_1} > \gamma'_{th2} \\ \frac{\tau}{\Omega_{2,b}} + \frac{\theta}{\Omega_{1,b}} - \frac{\tau}{\Omega_{2,b}} \frac{\theta}{\Omega_{1,b}}, \gamma_{th2} < \frac{a_2}{a_1} \leq \gamma'_{th2} \end{cases}. \quad (41)$$

Substituting (41) into (23), we can obtain the diversity order of D_1 in the DF-based ICN system as

$$d_{1,DF}^{ICN} = 1, \quad (42)$$

Remark 11. The diversity order of D_1 in DF-based ICN system is one, which is the same as the diversity order of D_1 in AF-based ICN system.

(2) *Diversity Order of D_2* . Similarly, we can derive the asymptotic outage probability of D_2 for the DF-based ICN system in the following corollary.

Corollary 12. *The closed-form expression of outage probability for D_2 in the DF-based ICN system is given as*

$$P_{2,DF}^{ICN,\infty} = \begin{cases} \frac{\tau\tau'}{\Omega_{r,2}\Omega_{2,b}}, \frac{a_2}{a_1} > \gamma'_{th2} \\ \frac{\tau}{\Omega_{2,b}}, \gamma_{th2} < \frac{a_2}{a_1} \leq \gamma'_{th2} \end{cases}. \quad (43)$$

Substituting (43) into (23), we can obtain the diversity order of D_2 in the DF-based ICN system as

$$d_{2,DF}^{ICN} = \begin{cases} 2, \frac{a_2}{a_1} > \gamma'_{th2} \\ 1, \gamma_{th2} < \frac{a_2}{a_1} \leq \gamma'_{th2} \end{cases}. \quad (44)$$

Remark 13. The diversity order of D_2 in DF-based ICN system is the same as the diversity order in AF-based ICN system.

4.1.4. Throughput Analysis. Similarly, the throughput is considered in delay-limited transmission for DF-based ICN system, which can be given as

$$R_{DF}^{ICN} = (1 - P_{1,DF}^{ICN})R_1 + (1 - P_{2,DF}^{ICN})R_2, \quad (45)$$

where $P_{1,DF}^{ICN}$ and $P_{2,DF}^{ICN}$ are obtained from (37) and (40), respectively.

4.2. Outage Performance Analysis with CCN Protocol. As a benchmark for the outage behaviors of ICN system, the outage behaviors of the DF-based CCN system are investigated.

4.2.1. Outage Probability of D_1 . According to the description of the CCN system, the expression of the outage probability for D_1 is the same with (36). Hence, the closed-form expression of outage probability for D_1 in the DF-based CCN system is given as

$$P_{1,DF}^{CCN} = 1 - e^{-\theta'/\Omega_{1,b}} - e^{-\theta'/\Omega_{r,1}} + e^{-\theta'/\Omega_{1,b}} e^{-\theta'/\Omega_{r,1}}, \quad (46)$$

where (46) is derived on the condition of $a_2/a_1 > \gamma'_{th2}$, otherwise $P_{1,DF}^{CCN} = 1$.

4.2.2. Outage Probability of D_2 . According to the CCN protocol, the expression of the outage probability for D_2 can be given as

$$P_{2,DF}^{CCN} = \Pr(\gamma_2 < \gamma'_{th2}) \Pr(\gamma_2^{DF} < \gamma'_{th2}). \quad (47)$$

The closed-form expression of outage probability for D_2 in the DF-based CCN system is given as

$$P_{2,DF}^{CCN} = (1 - e^{-\tau'/\Omega_{2,b}})(1 - e^{-\tau'/\Omega_{r,2}}), \quad (48)$$

where (48) is also derived on the condition of $a_2/a_1 > \gamma'_{th2}$, otherwise, $P_{2,DF}^{CCN} = 1$. Similar to AF-based NOMA system, it is obvious that the outage behavior of D_2 for ICN system outperforms CCN system.

4.2.3. Diversity Analysis

(1) *Diversity Order of D_1* . When $\rho \rightarrow \infty$, based on $e^{-x} \approx 1 - x$ ($x \rightarrow 0$), the asymptotic outage probability of D_1 for the DF-based CCN system is given as

$$P_{1,DF}^{CCN,\infty} \approx \frac{\theta'^2}{\Omega_{1,b}\Omega_{r,1}}. \quad (49)$$

Substituting (49) into (23), we can obtain $d_{1,DF}^{CCN} = 2$.

(2) *Diversity Order of D_2* . Similarly, the asymptotic outage probability of D_2 for the DF-based CCN system can be obtained as

$$P_{2,DF}^{CCN,\infty} \approx \frac{\tau'^2}{\Omega_{2,b}\Omega_{r,2}}. \quad (50)$$

Substituting (50) into (23), we can obtain $d_{2,DF}^{CCN} = 2$, where (49) and (50) are also derived on the condition of $a_2/a_1 > \gamma'_{th2}$, otherwise, $P_{2,DF}^{CCN} = 1$. It is obvious that the diversity orders of two users for DF-based ICN and CCN systems are the same as that of the AF-based ICN and CCN systems, respectively.

Remark 14. When $\gamma_{th2} < a_2/a_1 \leq \gamma'_{th2}$, the outage behavior of two users for AF-based ICN system is the same as the DF-based ICN system, as the two users for AF-/DF-based ICN systems works in direct NOMA transmission mode. Furthermore, the outage behavior of two users for ICN system is superior to that of the CCN system when $\gamma_{th2} < a_2/a_1 \leq \gamma'_{th2}$, as the outage probability of two users for CCN system is one under the condition of $\gamma_{th2} < a_2/a_1 \leq \gamma'_{th2}$.

4.2.4. Throughput Analysis. Similarly, the throughput in delay-limited transmission for DF-based system with CCN protocol is given by

$$R_{DF}^{CCN} = (1 - P_{1,DF}^{CCN})R_1 + (1 - P_{2,DF}^{CCN})R_2. \quad (51)$$

where $P_{1,DF}^{CCN}$ and $P_{2,DF}^{CCN}$ are obtained from (46) and (48), respectively.

5. Numerical Results

In this section, simulation results are provided to evaluate the outage performance of users for AF/DF-based NOMA systems. Monte Carlo simulation parameters used in this section are given as follows. The power allocation coefficients [15] of D_1 and D_2 are $a_1 = 0.2$ and $a_2 = 0.8$ (In this paper, the power allocation factor is taken fixed value, optimizing the power allocation factor is capable of further improving the system secrecy performance, which motivates us to investigate optimal power allocation algorithms in our future work.), respectively. Additionally, the target rate [25] of D_1 and D_2 are $R_1 = 1.5$ BPCU and $R_2 = 0.5$ BPCU, respectively, where BPCU is an abbreviation for bit per channel use. We assume $\Omega_{i,j} = (d_{i,j}/d_0)^{-\alpha}$ [34], in which $d_{i,j}$ denotes the distance between i and j , d_0 is a reference distance, and α is a path loss exponent. The parameters correspond to $d_{1,b} = 50$ m, $d_{2,b} = 85$ m, $d_{r,b} = d_{r,1} = d_{r,2} = 63$ m for $d_0 = 40$ m, and $\alpha = 3$. Especially, α is the path loss exponent usually satisfying $2 \leq \alpha \leq 6$. To ensure the validity of numerical results, the numerical results of the outage probability with different path loss exponent are also presented in the following. Apart from the performance of AF/DF-based ICN system, the performance of CCN system is also considered as a benchmark for comparison, where the total communication process is completed in two slots. The BS sends information x_1 and x_2 to relay R in the first slot. In the second slot, R forwards the information x_1 and x_2 to D_1 and D_2 , respectively. The above parameters are set on the general condition of $a_2/a_1 > \gamma'_{th2}$, as the outage probability of the two users for the CCN system is one when $a_2/a_1 \leq \gamma'_{th2}$. The following simulation results are first given on the general condition of $a_2/a_1 > \gamma'_{th2}$.

FIGURE 2: The outage probability versus transmit SNR for AF-based NOMA system with $a_1 = 0.2$, $a_2 = 0.8$, $R_1 = 1.5$ BPCU, $R_2 = 0.5$ BPCU, and $\alpha = 3$.

Figures 2 and 3 plot the outage probability of two users versus SNR for AF-based and DF-based ICN/CCN system, respectively. The black and blue curves represent the outage performance for ICN and CCN systems, respectively. In these two figures, the exact theoretical curves of D_1 and D_2 for AF- and DF-based ICN system are plotted according to (19), (22) and (37), (40), respectively. Obviously, the Monte Carlo simulation verifies the accuracy of our derivation. In addition, the blue curves of D_1 and D_2 for AF- and DF-based CCN system are plotted according to (29), (31) and (46), (48), respectively; which served as a benchmark for comparison. It is shown that the outage performance of D_2 for ICN system outperforms CCN system, which verifies the conclusion in Remark 7. We can observe that D_1 of the ICN system is able to achieve better outage performance in the low SNR region, since the possibility that the relay does not participate in communication is greater in high SNR. Besides, the red simulation curves represent the outage probability of D_1 and D_2 for cooperative NOMA systems, which is also used as a benchmark. We can observe that the outage behaviors of the cooperative NOMA system outperform NOMA systems. Furthermore, the asymptotic outage probability curves of D_1 and D_2 for AF- and DF-based ICN systems are plotted according to (24), (26) and (41), (43), respectively. As can be observed from the figures, the asymptotic curves approximate the exact curves well in the high SNR region.

Figure 4 plots the outage probability of two users versus SNR for ICN systems with different targeted data rates. One can observe that the outage probability of D_1 becomes worse with increasing R_1 . The reason is that the threshold for decoding increases as R_1 increases. However, the outage behaviors of D_1 are hardly affected by R_2 adjustment. This phenomenon can be explained as that D_2 should be quickly connected with a low data rate, while D_1 should be served

FIGURE 3: The outage probability versus transmit SNR for DF-based NOMA system with $a_1 = 0.2$, $a_2 = 0.8$, $R_1 = 1.5$ BPCU, $R_2 = 0.5$ BPCU, and $\alpha = 3$.

FIGURE 4: The outage probability versus transmit SNR for ICN system with different target rates, $a_1 = 0.2$, $a_2 = 0.8$, and $\alpha = 3$.

opportunistically according to the definition of the cooperative NOMA, i.e., D_2 is easy to be successfully decoded. Therefore, the outage performance of D_1 can successfully decode the information of D_2 , and it will not be affected by R_2 adjustment. Besides, the outage behaviors of D_2 deteriorates as R_2 increases, but it does not depend on changes in R_1 , which verifies the derivation in (22) and (40). This is due to the fact that the information of D_1 is not decoded and is regarded as noise when D_2 decoding its own message. Another observa-

FIGURE 5: The outage probability versus transmit SNR for ICN system with different power allocation coefficients, $R_1 = 1.5$ BPCU, $R_2 = 0.5$ BPCU, and $\alpha = 3$.

tion is that the outage performance of D_2 for DF protocol is better than that of AF protocol. Because the signal x_1 , which is considered as noise, is amplified while the AF relay amplifies the useful signal x_2 ; i.e., the enhancement of interference affects the decoding performance of the relay link between relay and D_2 . The reason is that when the useful signal x_2 is amplified by AF relay, the signal x_1 as the noise signal is also amplified; i.e., the interference affects the decoding performance of D_2 with relaying link (the link between R and D_2).

Figure 5 plots the outage probability of two users versus SNR for ICN system with different power allocation coefficients. The black, red, and blue solid curves represent the outage probability of two users with $a_1 = 0.4$, $a_1 = 0.2$, and $a_1 = 0.1$, respectively. The figure shows that the outage behavior of D_1 deteriorates with the decrease of a_1 . Moreover, the outage performance of D_2 is improved with the decrease of a_1 (i.e., the increase of a_2). Obviously, each user's performance will become better as the increase of the transmission power allocated to each user. In summary, the dynamic power allocation factor affects the outage behavior of two users. This phenomenon indicates that it is significant to select beneficial system parameters. Especially in NOMA communication systems, when users are generally classified into the nearby users and distant users by their quality of service, where the nearby users require a high data rate, and the distant users may only require a predetermined low data rate. Without loss of generality, it is best to assign a higher power to the distance user in order to ensure the higher priority (higher communication reliability) of the distance user.

As a further development, Figure 6 plots the outage probability of two users versus SNR for ICN system with different

FIGURE 6: The outage probability versus transmit SNR for ICN system with different path loss exponent, $a_1 = 0.2$, $a_2 = 0.8$, $R_1 = 1.5$ BPCU, and $R_2 = 0.5$ BPCU.

path loss exponent. The black, red, and blue solid curves represent the outage probability of two users with $\alpha = 2$, $\alpha = 3$, and $\alpha = 4$, respectively. It is obvious that the performance of two users for the ICN system is strongly affected by the path loss exponent. As shown in Figure 6, the performance of the ICN system deteriorates as the path loss exponent increases. However, it is worth noting that the curves with different path loss exponent have the same slopes, which verifies the conclusions in Remark 4, Remark 6, Remark 11, and Remark 13, i.e., the diversity orders of D_1 are one, and the diversity orders of D_2 are two under the condition of $a_2/a_1 > \gamma'_{th2}$.

Figure 7 plots the outage probability of two users versus SNR for ICN system with different distance $d_{r,b}$. One can observe that the outage behavior of D_1 is hardly affected by the distance between BS and relay. This is mainly due to the performance of near user D_1 which mainly depends on the direct link (the link between BS and D_1) when $a_2/a_1 > \gamma'_{th2}$. We also can observe that the outage behavior of D_2 for AF relaying case deteriorates as the distance $d_{r,b}$ becomes larger. The reason is that $E\{|h_{r,b}|^2\}$ becomes smaller when the $d_{r,b}$ becomes larger, which leads to the received SINR at D_2 with relaying link decrease in AF relaying case according to (11). In contrast, the performance of D_2 for DF relaying case is almost unchanged, which verifies the derivation in equation (40). The reason is that we have assumed the relay is capable of decoding the two users's information successfully for simplicity.

Figure 8 plots the system throughput versus SNR in delay-limited transmission mode for ICN and CCN systems, which are plotted according to (28), (34), (45), and (51), respectively. We can observe that the throughput of the ICN system is higher than that of the CCN system in low SNR region, since

FIGURE 7: The outage probability versus transmit SNR for ICN system with different distance $d_{r,b}$, $a_1 = 0.2$, $a_2 = 0.8$, $R_1 = 1.5$ BPCU, $R_2 = 0.5$ BPCU, and $\alpha = 3$.

FIGURE 8: The system throughput versus transmit SNR for ICN and CCN systems with $a_1 = 0.2$, $a_2 = 0.8$, $R_1 = 1.5$ BPCU, $R_2 = 0.5$ BPCU, and $\alpha = 3$.

the outage performance of the users for the ICN system is better than that of the CCN system. It is noting that this superiority is more pronounced at low SNR. Another observation is that throughput ceilings exist in the ICN and CCN systems in the high SNR region. The reason is that the outage probability tends zero, and the throughput almost depends on the target data rate in the high SNR region.

The above simulation results are under general condition $a_2/a_1 > \gamma'_{th2}$. To verify the accuracy of the analysis under special condition $\gamma_{th2} < a_2/a_1 \leq \gamma'_{th2}$, the power allocation

FIGURE 9: The outage probability versus transmit SNR for AF-/DF-based ICN and CCN systems with $a_1 = 0.4$, $a_2 = 0.6$, $R_1 = 1.5$ BPCU, $R_2 = 1$ BPCU, and $\alpha = 3$.

coefficients of D_1 and D_2 are reset to $a_1 = 0.4$ and $a_2 = 0.6$, respectively. Simultaneously, the target rates of D_1 and D_2 are reset to $R_1 = 1.5$ BPCU and $R_2 = 1$ BPCU, respectively. The remaining parameters are unchanged. Figure 9 plots the outage probability of two users versus SNR for AF-/DF-based ICN and CCN systems when $\gamma_{th2} < a_2/a_1 \leq \gamma'_{th2}$. As the conclusion in Remark 14, the outage behavior of two users for AF-based ICN system is the same as the DF-based ICN system. The black and red curves represent the outage performance for ICN and CCN systems, respectively. As can be observed from the figures, the Monte Carlo simulation verifies the accuracy of our derivation. One can observe that the asymptotic curves approximate the exact curves well in the high SNR region. It is worth noting that the curves have the same slopes, which verifies the conclusions in Remark 4, Remark 6, Remark 11, and Remark 13, i.e., the diversity order of D_1 for ICN system is one, and the diversity order of D_2 for ICN system under the condition of $\gamma_{th2} < a_2/a_1 \leq \gamma'_{th2}$ is also one. Obviously, when $\gamma_{th2} < a_2/a_1 \leq \gamma'_{th2}$, the outage behavior of two users for ICN system is superior to that of CCN system, as the outage probability of two users for CCN system is one, which verifies the conclusions in Remark 14. Similarly, the system throughput in delay-limited transmission mode for ICN system is also higher than that of the CCN system when $\gamma_{th2} < a_2/a_1 \leq \gamma'_{th2}$. The rest of the performance analysis, which is similar to the performance analysis under general condition $a_2/a_1 > \gamma'_{th2}$, will not be discussed.

6. Conclusion

In this paper, the ICN system has investigated insightfully. The outage behavior of the proposed system has been charac-

terized based on AF and DF relaying, respectively. New closed form expressions of outage probability for two users have been derived. Based on the analytical results, the diversity orders achieved by the nearby and distant users were obtained. Additionally, the performance of the CCN system has also been analyzed, which has been served as a benchmark for the purpose of comparison. Numerical results have verified that the distant user of the ICN system achieved better outage behavior than that of CCN system. The nearby user for the ICN system was capable of achieving better performance than that of CCN system in the low SNR region, and the outage performance of distant user for DF-based ICN system was superior to AF-based ICN system, when the system worked in cooperative NOMA transmission mode. Furthermore, the throughput of the ICN system was higher than that of CCN system in the low SNR region.

Appendix

A. Proof of Theorem 1

The expression (17) can be rewritten as

$$P_{1,AF}^{ICN} = 1 - \underbrace{\Pr(\gamma_2 \geq \gamma_{th2})}_{Q_1} \underbrace{\Pr(\gamma_{1,2} \geq \gamma_{th2}, \gamma_1 \geq \gamma_{th1})}_{Q_2} - \Pr(\gamma_2 < \gamma_{th2})(1 - P_{1,AF}^{CCN}). \quad (A.1)$$

Combining (6) and Q_1 , Q_1 can be rewritten as

$$Q_1 = \Pr\left(\frac{a_2 \rho_s |h_{2,b}|^2}{a_1 \rho_s |h_{2,b}|^2 + 1} \geq \gamma_{th2}\right) = \Pr\left(|h_{2,b}|^2 \geq \frac{\gamma_{th2}}{\rho_s(a_2 - a_1 \gamma_{th2})}\right) = e^{-\tau/\Omega_{2,b}}, \quad (A.2)$$

where $\tau = \gamma_{th2}/(\rho_s(a_2 - a_1 \gamma_{th2}))$ with $a_2 > a_1 \gamma_{th2}$. Note that (A.2) is derived on the condition of $a_2 > a_1 \gamma_{th2}$, otherwise, $Q_1 = 0$.

Similarly, combining (4), (5), and Q_2 , Q_2 can be rewritten as

$$Q_2 = \Pr\left(\frac{a_2 \rho_s |h_{1,b}|^2}{a_1 \rho_s |h_{1,b}|^2 + 1} \geq \gamma_{th2}, a_1 \rho_s |h_{1,b}|^2 \geq \gamma_{th1}\right) = \Pr\left(|h_{1,b}|^2 \geq \frac{\gamma_{th2}}{\rho_s(a_2 - a_1 \gamma_{th2})}, |h_{1,b}|^2 \geq \frac{\gamma_{th1}}{a_1 \rho_s}\right) = e^{-\theta/\Omega_{1,b}}, \quad (A.3)$$

where $\theta = \max(\tau, \sigma)$ and $\sigma = \gamma_{th1}/a_1 \rho_s$ with $a_2 > a_1 \gamma_{th2}$. Note that (A.3) is derived on the condition of $a_2 > a_1 \gamma_{th2}$, otherwise, $Q_2 = 0$.

Then, we derive the closed-form expression of $P_{1,AF}^{CCN}$, i.e., the closed-form expression of (18), which can be rewritten as

$$P_{1,AF}^{CCN} = \left[1 - \underbrace{\Pr \left(\gamma_{1,2} \geq \gamma'_{th2}, \gamma_1 \geq \gamma'_{th1} \right)}_{Q_3} \right] \times \left[1 - \underbrace{\Pr \left(\gamma_{1,2}^{AF} \geq \gamma'_{th2}, \gamma_1^{AF} \geq \gamma'_{th1} \right)}_{Q_4} \right]. \quad (A.4)$$

Combining (4), (5), and Q_3 , applying some algebraic manipulations, Q_3 can be rewritten as

$$\begin{aligned} Q_3 &= \Pr \left(\frac{a_2 \rho_s |h_{1,b}|^2}{a_1 \rho_s |h_{1,b}|^2 + 1} \geq \gamma'_{th2}, a_1 \rho_s |h_{1,b}|^2 \geq \gamma'_{th1} \right) \\ &= \Pr \left(|h_{1,b}|^2 \geq \frac{\gamma'_{th2}}{\rho_s (a_2 - a_1 \gamma'_{th2})}, |h_{1,b}|^2 \geq \frac{\gamma'_{th1}}{a_1 \rho_s} \right) \\ &= e^{-\theta' / \Omega_{1,b}}, \end{aligned} \quad (A.5)$$

where $\theta' = \max(\tau', \sigma')$ and $\tau' = \gamma'_{th2} / (\rho_s (a_2 - a_1 \gamma'_{th2}))$, $\sigma' = \gamma'_{th1} / a_1 \rho_s$ with $a_2 > a_1 \gamma'_{th2}$. Note that (A.3) is derived on the condition of $a_2 > a_1 \gamma'_{th2}$, otherwise, $Q_3 = 0$.

Similarly, Combining (9), (10), and Q_4 , Q_4 can be rewritten as

$$\begin{aligned} Q_4 &= \Pr \left(\frac{a_2 \rho_s |h_{r,b}|^2 |h_{r,1}|^2}{a_1 \rho_s |h_{r,b}|^2 |h_{r,1}|^2 + |h_{r,1}|^2 + |h_{r,b}|^2 + (1/\rho_s)} \geq \gamma'_{th2}, \frac{a_1 \rho_s |h_{r,b}|^2 |h_{r,1}|^2}{|h_{r,1}|^2 + |h_{r,b}|^2 + (1/\rho_s)} \geq \gamma'_{th1} \right) \\ &= \Pr \left(|h_{r,1}|^2 \geq \frac{\theta' (\rho_s |h_{r,b}|^2 + 1)}{\rho_s (|h_{r,b}|^2 - \theta')}, |h_{r,b}|^2 \geq \theta' \right) \\ &= \int_0^\infty \frac{1}{\Omega_{r,b}} e^{-x+\theta' / \Omega_{r,b}} e^{-\theta' (\rho_s (x+\theta') + 1) / x \rho_s \Omega_{r,1}} dx \\ &= e^{-\theta' / \Omega_{r,b} - \theta' / \Omega_{r,1}} \sqrt{\frac{4\theta' (\rho_s \theta' + 1)}{\rho_s \Omega_{r,1} \Omega_{r,b}}} K_1 \left(\sqrt{\frac{4\theta' (\rho_s \theta' + 1)}{\rho_s \Omega_{r,1} \Omega_{r,b}}} \right), \end{aligned} \quad (A.6)$$

where (A.6) is derived according to ([35], Eq.(3.324.1)), it is noting that (A.5) is derived on the condition of $a_2 > a_1 \gamma'_{th2}$, otherwise, $Q_4 = 0$.

Substituting (A.2), (A.3), (A.4), and (A.5) into (A.1), we can obtain (19). The proof is completed.

B. Proof of Theorem 2

We can rewrite (21) as

$$P_{2,AF}^{ICN} = \underbrace{\Pr \left(\gamma_2^{AF} < \gamma'_{th2} \right)}_{\Lambda_1} \underbrace{\Pr \left(\gamma_2 < \gamma_{th2} \right)}_{\Lambda_2}. \quad (B.1)$$

Substituting (11) into Λ_1 , after some algebraic manipulations, Λ_1 can be rewritten as

$$\begin{aligned} \Lambda_1 &= \Pr \left(|h_{r,b}|^2 < \tau' \right) \\ &+ P_r \left(|h_{r,2}|^2 < \frac{\tau' (\rho_s |h_{r,b}|^2 + 1)}{\rho_s (|h_{r,b}|^2 - \tau')}, |h_{r,b}|^2 \geq \tau' \right) \\ &= \left(1 - e^{-\tau' / \Omega_{r,b}} \right) + \int_{\tau'}^\infty \frac{1}{\Omega_{r,b}} e^{-y / \Omega_{r,b}} dy \\ &\quad - \int_{\tau'}^\infty \frac{1}{\Omega_{r,b}} e^{-y / \Omega_{r,b}} e^{-\tau' (\rho_s y + 1) / \rho_s (y - \tau')} \Omega_{r,2} dy \\ &= 1 - e^{-\tau' / \Omega_{r,b}} e^{-\tau' / \Omega_{r,2}} \frac{1}{\Omega_{r,b}} \int_0^\infty e^{-x / \Omega_{r,b}} e^{-\tau' (\rho_s \tau' + 1) / \rho_s x \Omega_{r,2}} dx \\ &= 1 - e^{-\tau' / \Omega_{r,b}} e^{-\tau' / \Omega_{r,2}} \sqrt{\frac{4\tau' (\rho_s \tau' + 1)}{\rho_s \Omega_{r,2} \Omega_{r,b}}} \\ &\quad \times K_1 \left(\sqrt{\frac{4\tau' (\rho_s \tau' + 1)}{\rho_s \Omega_{r,2} \Omega_{r,b}}} \right), \end{aligned} \quad (B.2)$$

where ((B.2) is derived according to ([35], Eq.(3.324.1)), it is noting that (B.2) is derived on the condition of $a_2 > a_1 \gamma'_{th2}$, otherwise, $\Lambda_1 = 1$.

Substituting (6) into Λ_2 , the closed-form expression of Λ_2 can be given as

$$\Lambda_2 = 1 - e^{-\tau / \Omega_{2,b}}. \quad (B.3)$$

Note that (B.3) is derived on the condition of $a_2 > a_1 \gamma_{th2}$, otherwise, $\Lambda_2 = 1$.

Substituting (B.2) and (B.3) into (B.1), we can obtain (22). The proof is completed.

C. Proof of Remark 7

We have obtain the outage probability of D_2 for AF-based ICN system as shown in (21), which can be rewritten as

$$P_{2,AF}^{ICN} = \Pr \left(\gamma_2 < \gamma_{th2} \right) P_r \left(\gamma_2^{AF} < \gamma'_{th2} \right). \quad (C.1)$$

Since $\gamma_{th2} = 2^{R_2} - 1$, $\gamma'_{th2} = 2^{2R_2} - 1$, and $R_2 > 0$, we can obtain

$$\gamma_{th2} < \gamma'_{th2}. \quad (C.2)$$

And we can further obtain that

$$\Pr(\gamma_2 < \gamma_{th2}) < \Pr(\gamma_2 < \gamma'_{th2}). \quad (C.3)$$

According to (C.3), compared to (C.1) and the outage probability $P_{2,AF}^{CCN}$ in (31), we can obtain $P_{2,AF}^{ICN} < P_{2,AF}^{CCN}$. The proof is completed.

Data Availability

If the data are needed during the process of reviewing or publishing, they are provided by the author Zhenling Wang (Email: wangzhenling@shu.edu.cn).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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