On the Performance Analysis of Full-Duplex Incremental Cooperative NOMA

Eligário Milton da Costa Semedo, Samuel Mafra, Samuel Montejo-Sánchez and Evelio M. G. Fernandez

***Abstract*— A full-duplex incremental cooperative non-orthogonal multiple access (FD-ICN) scheme is proposed for a two user downlink network. Based on a pilot signal from the far user, the base station decides between transmitting in direct transmission mode or using cooperation via the near user. We evaluate the proposed scheme in terms of the pair outage probability, in order to guarantee a feasible service for both users. The results show that the proposed scheme presents better performance in terms of outage probability, when compared with the half-duplex incremental cooperative non-orthogonal multiple access scheme as well as with the conventional cooperative non-orthogonal multiple access schemes.**

***Keywords*— Non-orthogonal multiple access; Incremental; Full-duplex.**

I. INTRODUCTION

In the last years, the demand of services and applications in wireless communications networks has increased considerably. In this context, one of the challenges is to interconnect users and devices anywhere and anytime. The 5G network is a hopeful technology for interconnecting a large number of devices, such as IoT (Internet of Things) devices that will be connected to the internet [1].

On the other hand, the Non-Orthogonal Multiple Access (NOMA) system is considered relevant for the new generations of mobile networks due to its capacity to attend several users at the same time [2]. In recent years, several protocols for NOMA have been proposed to simultaneously transmit signals to the network users, such as the Power Domain NOMA (PD NOMA) [3], Multi-user Share Access (MUSA) [4], Sparse Code Multiple Access (SCMA) [5] and Pattern Division Multiple Access (PDMA) [6]. The NOMA schemes can be divided in two categories: power-domain NOMA and code-domain NOMA [7]. The latter is similar to the code-domain multiple access (CDMA), where the users communicate at the same time and frequency but with different codes. In power-domain NOMA, multiple users are encouraged to communicate at the same frequency and time, but with different power levels. To this end, the base station allocates less power to users with better channel conditions, and these users can decode their own information by applying successive interference cancellations (SIC), offering better performance and spectral efficiency compared to orthogonal multiple access techniques [8].

Cooperative communication has gained a lot of attention in NOMA networks for providing spatial diversity, improving system performance and mitigating the effects of multi-path fading. The communication can occur on either half-duplex or full-duplex modes [9]. Specifically, in half-duplex mode, the cooperative nodes transmit and receive in orthogonal channels, whereas in full-duplex mode the transmission and reception are performed at the same time and at the same frequency band. The half-duplex communication requires the use of additional system resources, while full-duplex communication arises as a viable choice to alleviate this issue. However, although ideal full-duplex relaying can achieve higher capacity than half-duplex relaying [10], its use introduces self-interference that is intrinsic to the full-duplex approach. This self-interference cannot be completely eliminated, but it can be considerably mitigated by using interference cancellation techniques [11]. Although, the full-duplex relays can still achieve high performance, even in the presence of severe interference levels.

Motivated by the important benefits acquired with NOMA and full-duplex techniques, recent works have analyzed the performance of full-duplex cooperative NOMA networks, for instance [12]–[14]. In [12], the authors propose a full-duplex scheme for a downlink NOMA network, where the near user cooperates with the base station by acting as a full-duplex relay for the far user. Moreover, the authors propose an optimal power allocations in order to minimize the outage probability. In [13], a novel cooperative non-orthogonal multiple access scheme is presented with the near user cooperating through a half/full-duplex protocol, but differently of [12], the authors analyze the scenario with a direct link between the base station and the far user. The proposed scheme is analyzed is terms of outage probability, ergodic rate, and energy efficiency.

Recently, the authors of [14] propose a half-duplex Incremental Cooperative NOMA (ICN) protocol for a downlink network. Based on 1-bit feedback from the far user, the source can switch between a direct NOMA transmission mode and a cooperative NOMA transmission mode. If the channel between the source and the far user is in good condition the network will operate the conventional NOMA, otherwise cooperative transmission is activated with the help of the near user. The authors demonstrate that the half-duplex ICN protocol

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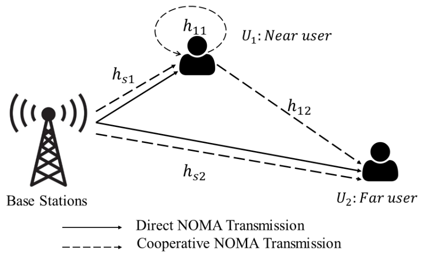

Fig. 1: System Model

outperforms the conventional cooperative NOMA schemes.

Based on the protocol of [14], in this paper we propose an incremental cooperative full-duplex NOMA (FD-ICN) scheme for a two-user downlink network aiming at improving the performance of the cooperative communication system. By using the incremental protocol, it is possible to eliminate the issue of zero diversity for the near user inherent in full-duplex communication. We analyze the proposed scheme in terms of the pair outage probability for different values of residual self-interference, power allocation factor and locations of the near user. The results show that the proposed scheme can outperforms the half-duplex ICN and conventional cooperative NOMA schemes.

The remainder of this paper is organized as follows: Section II introduces the system model. In Section III the proposed FD-ICN is analyzed. In Section IV representative numerical results are provided and insightful discussions are drawn. Finally, Section V concludes the paper.

II. SYSTEM MODEL

We consider a full-duplex downlink network composed of a base station BS, a near full-duplex user U_1 and a far user U_2, as illustrated in Fig. 1.

The quasi-static fading channel between transmitter i and receiver j is denoted by h_{ij}, $i \in \{s, 1\}$, $j \in \{1, 2\}$, where s represents the base station and $\{1, 2\}$ represent the near and far users, respectively. We assume that all channels undergo independent Rayleigh fading, thus $|h_{ij}|^2$ follows an exponential distribution with mean power λ_{ij}. The average fading power is $\lambda_{ij} \triangleq \mathbb{E}\left[|h_{ij}|^2\right] \triangleq d_{ij}^{-\nu}$, where d_{ij} represents the distance between users i and j and ν is the path-loss exponent ($\nu \geq 2$).

We consider the incremental Cooperative NOMA protocol proposed in [14] for a half duplex NOMA network, in which the network can operate in two modes, the direct transmission and cooperative transmission. This choice is based on the quality of the channel h_{s2}. The BS sends a pilot symbol to U_1 and U_2 and, based on the received signal, U_2 estimates h_{s2}. If U_2 judges that the channel is in a good condition, then it sends a positive acknowledgment message (ACK) to both the BS and U_1, and the NOMA direct transmission mode is activated. Conversely, if the channel condition is not favorable, U_2 sends a negative acknowledge (NACK) and the cooperative transmission is activated. In this case, U_1 cooperates with the BS to deliver the message to U_2.

A. Direct Transmission

In direct transmission, the BS sends a superimposed signal to U_1 and U_2. First, U_1 tries to decode the signal of U_2 with the interference of its own signal, then performs SIC to remove the interference and decodes its own signal. The user U_2 decodes its own signal directly considering the interference of the signal of U_1.

At time t, the received signal at U_1 and U_2 can be expressed, respectively, as:

$$y_1[t] = h_{s1}\left(\sqrt{aP}x_1[t] + \sqrt{(1-a)P}x_2[t]\right) + n_1[t], \tag{1}$$

$$y_2[t] = h_{s2}\left(\sqrt{aP}x_1[t] + \sqrt{(1-a)P}x_2[t]\right) + n_2[t], \tag{2}$$

where P is the transmit power, $x_1[t]$ and $x_2[t]$ are the message sent by the source to U_1 and U_2 respectively, a is the power allocation factor, $n_j[t]$ stands for the complex additive white Gaussian noise at node j with variance $\sigma_n^2 = N_0$, where N_0 is the one-sided noise power spectral density. Then $\rho = \frac{P}{N_0}$ is the transmit signal-to-noise ratio (SNR).

The signal-to-interference-plus-noise ratio (SINR) of U_2 decoded by U_j is given by:

$$\gamma_2^j = \frac{(1-a)\rho\,|h_{sj}|^2}{a\rho\,|h_{sj}|^2 + 1}, \tag{3}$$

while, the signal-to-noise ratio (SNR) of U_1 decoded by U_1 after the SIC process is:

$$\gamma_1^1 = a\rho\,|h_{s1}|^2. \tag{4}$$

B. Cooperative transmission

For the cooperative transmission, the communication occurs in two phases, first the base station broadcast the superimposed signal to both users, while in the second phase U_1 retransmits the signal of U_2, if correctly decoded. At the same time, the BS sends a new signal to both users[1]. Finally, U_2 combines both signals using maximal ratio combining (MRC). The residual self-interference is modeled as a fading channel h_{11}, with average fading power λ_{11}.

At time t, the received signal at U_1 and U_2 can be expressed, respectively, as:

$$\begin{aligned} y_1[t] = {} & h_{s1}\left(\sqrt{aP}x_1[t] + \sqrt{(1-a)P}x_2[t]\right) \\ & + h_{11}\sqrt{P}x_{11}[t-\tau] + n_1[t], \end{aligned} \tag{5}$$

$$\begin{aligned} y_2[t] = {} & h_{s2}\left(\sqrt{aP}x_1[t] + \sqrt{(1-a)P}x_2[t]\right) \\ & + h_{12}\left(\sqrt{P}x_2[t-\tau]\right) + n_2[t], \end{aligned} \tag{6}$$

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[1] We consider that U_2 can resolve the signals of BS and U_1, because of the existence of a temporal separation between the signals as cited in [13], [15].

where $x_{11}\left[t-\tau\right]$ is the message sent by U_1 after a processing delay τ.

The signal-to-interference-plus-noise ratio (SINR) of U_2 decoded by U_1 is given by:

$$\gamma_2^{1-FD} = \frac{(1-a)\rho\left|h_{s1}\right|^2}{a\rho\left|h_{s1}\right|^2+\rho\left|h_{11}\right|^2+1}. \tag{7}$$

Then, after the SIC process, U_1 detects its own signal, where the respective SINR is given by:

$$\gamma_1^{1-FD} = \frac{|h_{s1}|^2 a\rho}{|h_{11}|^2\rho+1}. \tag{8}$$

Note that the self-interference at U_1 is taken into account in (8) and (7).

Finally, the SINR at U_2 after performing MRC combining the signals from the direct and cooperative links is given by:

$$\gamma_2^{2-MRC} = \left[h_{12}\right]^2\rho + \frac{|h_2|^2(1-a)\rho}{|h_2|^2 a\rho+1}. \tag{9}$$

III. OUTAGE PERFORMANCE ANALYSIS

In this section, we present the outage probability analysis for the proposed FD-ICN scheme.

A. Outage probability of near user U_1

For the ICN Protocol, the outage probability of U_1 is given by:

$$\begin{aligned} O_1^{FD-ICN} &= 1 - \underbrace{\Pr[\gamma_2^2 \geq \epsilon]\Pr[\gamma_2^1 \geq \epsilon, \gamma_1^1 \geq \epsilon]}_{A} \\ &- \underbrace{\Pr[\gamma_2^2 < \epsilon]\Pr[\gamma_2^{1-FD} \geq \epsilon, \gamma_1^{1-FD} \geq \epsilon]}_{B}, \end{aligned} \tag{10}$$

where $\epsilon = 2^R - 1$ and R is the attempted rate of the users. The term (A) in (10) represents the scenario in which U_2 can decode its own signal, thus BS sends a superimposed signal without the help of U_1. Moreover, U_1 can decode both signals. The term (B) in (10) represents the scenario in which U_2 cannot decode its own signal directly, thus BS sends a superimposed signal and U_1 cooperates with the communication, acting as a relay. In this scenario, U_1 can decode both signals, even in the presence of self-interference.

Let us define each one of the probabilities. The probability that U_2 can decode its own signal is:

$$\Pr\left[\gamma_2^2 \leq \epsilon\right] = \begin{cases} e^{\frac{-\epsilon}{\rho\lambda_{s2}(1-a-a\epsilon)}}, & \text{for } a < \frac{1}{1+\epsilon} \\ 0, & \text{otherwise.} \end{cases} \tag{11}$$

The probability that U_1 can decode both signals in the direct transmission mode is given by

$$\begin{aligned} &\Pr\left[\gamma_2^1 \geq \epsilon, \gamma_1^1 \geq \epsilon\right] \\ &= \Pr\left[|h_{s1}|^2 \geq \frac{\epsilon}{\rho(1-a-\epsilon a)}, |h_{s1}|^2 \geq \frac{\epsilon}{a\rho}\right] \\ &= \begin{cases} e^{\frac{-\epsilon}{\rho\lambda_{s1}a}} & \text{for } 0 < a < \frac{1}{2+\epsilon} \\ e^{\frac{-\epsilon}{\rho\lambda_{s1}(1-a-a\epsilon)}} & \text{for } \frac{1}{2+\epsilon} < a < \frac{1}{1+\epsilon}, \\ 0, \text{otherwise.} \end{cases} \end{aligned} \tag{12}$$

The probability that U_1 can decode both signals in the cooperative transmission mode is [13]:

$$\begin{aligned} &\Pr\left[\gamma_2^{1-FD} \geq \epsilon, \gamma_1^{1-FD} \geq \epsilon\right] \\ &= \Pr\left[|h_{s1}|^2 \geq \frac{\epsilon(1+|h_{11}|^2\rho)}{\rho(1-a-\epsilon a)}, |h_{s1}|^2 \geq \frac{\epsilon(1+|h_{11}|^2\rho)}{a\rho}\right] \\ &= \begin{cases} \frac{\lambda_{s1}}{\lambda_{s1}+\lambda_{11}\frac{\epsilon}{a}} e^{\frac{-\epsilon}{\rho\lambda_{s1}a}} & \text{for } 0 < a < \frac{1}{2+\epsilon} \\ \frac{\lambda_{s1}}{\lambda_{s1}+\lambda_{11}\frac{\epsilon}{(1-a-a\epsilon)}} e^{\frac{-\epsilon}{\rho\lambda_{s1}(1-a-a\epsilon)}} & \text{for } \frac{1}{2+\epsilon} < a < \frac{1}{1+\epsilon}, \\ 0, \text{otherwise.} \end{cases} \end{aligned} \tag{13}$$

Finally, the outage probability of the user U_1 can be written by replacing (11), (12) and (13) in (10).

B. Outage probability of far user U_2

The outage probability of U_2 for the ICN protocol is given by

$$\begin{aligned} O_2^{FD-ICN} &= \underbrace{\Pr\left[\gamma_2^2 < \epsilon\right]\Pr[\gamma_2^{1-FD} < \epsilon]}_{C} \\ &+ \underbrace{\Pr\left[\gamma_2^{1-FD} \geq \epsilon\right]\Pr\left[\gamma_2^2 < \epsilon, \gamma_2^{2-MRC} < \epsilon\right]}_{D}. \end{aligned} \tag{14}$$

The term (C) in (14) represents the probability of both users cannot decode the signal of U_2, while the term (D) in (14) represents the scenario where the cooperative mode is active, U_1 correctly decodes and retransmits the corresponding signal to U_2, however, U_2 cannot decode its own signal by performing MRC.

The probability of U_1 can decode the signal of U_2 in the cooperative transmission mode is given by

$$\begin{aligned} &\Pr\left[\gamma_2^{1-FD} \geq \epsilon\right] \\ &= \Pr\left[|h_{s1}|^2 \geq \frac{\epsilon(1+|h_{11}|^2\rho)}{\rho(1-a-\epsilon a)}\right] \\ &= \begin{cases} \frac{\lambda_{s1}}{\lambda_{s1}+\lambda_{11}\frac{\epsilon}{(1-a-a\epsilon)}} e^{\frac{-\epsilon}{\rho\lambda_{s1}(1-a-a\epsilon)}} & \text{for } a < \frac{1}{1+\epsilon}, \\ 0, \text{otherwise.} \end{cases} \end{aligned} \tag{15}$$

The probability that the cooperative mode is active, however the far user could not correctly decode its own signal after performing MRC is given by (16) [14], where K is a parameter of accuracy, $\varepsilon_k = \cos\left(\frac{2k-1}{2K}\pi\right)$.

Finally, the outage probability of U_2 can be written by replacing (11), (15) and (16) in (14).

C. Pair outage probability

The pair outage probability is an important metric to evaluate the quality of service (QoS) of the network. The pair outage probability is defined as the probability that at least one user could not correctly decode its own signal and it can be written for the FD-ICN scheme as:

$$\begin{aligned} O_{pair}^{FD-ICN} &= 1 - \Pr\left[\gamma_2^2 \geq \epsilon\right]\Pr\left[\gamma_2^1 \geq \epsilon, \gamma_1^1 \geq \epsilon\right] \\ &- \Pr\left[\gamma_2^2 < \epsilon, \gamma_2^{2-MRC} \geq \epsilon\right]\Pr\left[\gamma_2^{1-FD} \leq \epsilon, \gamma_1^{1-FD} \leq \epsilon\right]. \end{aligned} \tag{17}$$

$$\Pr\left[\gamma_2^2 < \epsilon, \gamma_2^{2-MRC} < \epsilon\right] \\ = 1 - e^{\left(-\frac{\epsilon}{\rho\lambda_{s2}(1-a-\epsilon a)}\right)} - \frac{\epsilon}{2\rho\lambda_{s2}(1-a-\epsilon a)} \frac{\pi}{K} \sum_{k=1}^{K} \sqrt{1-\varepsilon_k^2} e^{-\frac{\epsilon - \frac{\epsilon(\varepsilon_k+1)(1-a)}{\epsilon(\varepsilon_k+1)a+2(1-a-\epsilon a)}}{\rho\lambda_{12}}} e^{-\frac{\epsilon(\varepsilon_k+1)}{2\rho\lambda_{s2}(1-a-\epsilon a)}} \tag{16}$$

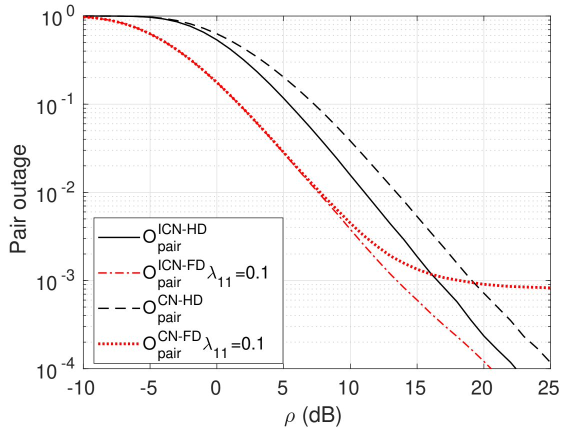


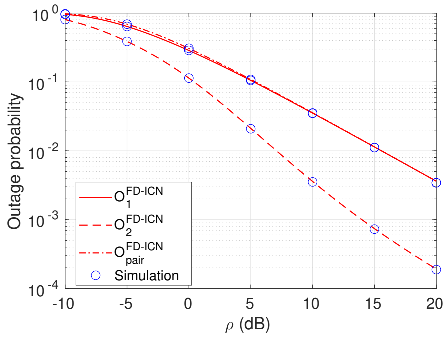
Fig. 2: Pair outage probability for the proposed FD-ICN, HD-ICN and conventional cooperative NOMA schemes as a function of the SNR ρ.

IV. Numerical Results

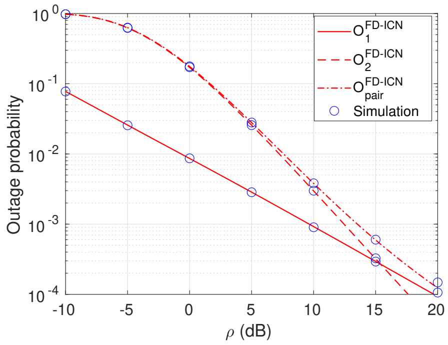
This section presents some numerical results in order to investigate the performance of the proposed full-duplex incremental cooperative NOMA scheme. Moreover, the performance of the proposed scheme is compared to the half-duplex incremental cooperative NOMA scheme analyzed in [14] and conventional cooperative NOMA schemes. In the plots, we assume a path loss exponent $\nu = 4$, $d_{s1} = d_{12} = \frac{1}{2}, d_{s2} = 1, d_{11} = 0.1$, the attempted secondary transmission rate is $R = 1$ bits per channel use (bpcu), $K = 100$ and $N_0 = 1$.

Fig. 2 shows the pair outage probability for the proposed FD-ICN scheme as a function of the SNR ρ for power allocation factor $a = 0.2$ and $\lambda_{11} = 0.1$. The performance of the HD-ICN and conventional cooperative NOMA schemes is also shown. It can be seen that the proposed scheme outperforms the half-duplex NOMA schemes, mainly at lower values of ρ, where the cooperation mode is predominant. By this fact, the conventional full-duplex has a similar performance than that of the incremental protocol. However, the pair outage probability saturates for large values of SNR as a consequence of the self-interference at U_1, which does not occur for the incremental protocol. Finally, the incremental protocols tend to have similar performances for large values of ρ, as the direct mode is activated more frequently.

In Fig. 3, the individual and pair outage probabilities are analyzed as a function of ρ for $d_{s1} \in \{0.2, 0.5\}$, $a = 0.2$ and $\lambda_{11} = 0.1$. The figures show the relevance of the pair outage probability as a metric to evaluate the network performance. In Fig. 3a, U_1 is exactly half the distance between BS and U_2, this is the optimal position for the relay, i.e. U_2 has the best performance. However, U_1 has difficulty decoding its own signal, which is demonstrated by the similarity between the pair outage and the individual outage probability of U_1. Fig. 3b shows the opposite scenario as the near user is closer to the BS, in this context the pair outage probability tends to equal to individual outage probability of U_2 at lower values of ρ.



(a) $d_{s1} = 0.5$



(b) $d_{s1} = 0.2$

Fig. 3: Comparison of individual and pair outage probabilities for the proposed FD-ICN, HD-ICN schemes as a function of the SNR ρ.

Fig. 4 shows the pair outage probability for the proposed FD-ICN and HD-ICN schemes as a function of the power allocation factor a for different values of $\lambda_{11} = \{0.01, 0.1, 1\}$ and $P = 10$ dB. From Fig. 4, it can be noted that the performance of the FD-ICN scheme increases with the effectiveness of the interference cancellation at U_1, which is reflected in low values for λ_{11}. Moreover, for large values of a, there is the occurrence of a step as the cooperation is activated more times. This step is caused by the multiplexing loss of this scheme.

Fig. 5 shows the pair outage probability for the proposed FD-ICN and HD-ICN schemes as a function of the distance between the BS and U_1 (d_{s1}) and considering $a = 2$, $\lambda_{11} = 0.1$ and $P = 10$ dB. It can be noted from the Fig. 5 that the proposed FD-ICN has a better performance when the user U_1 is closer to the BS, as the pair outage is dominated by the

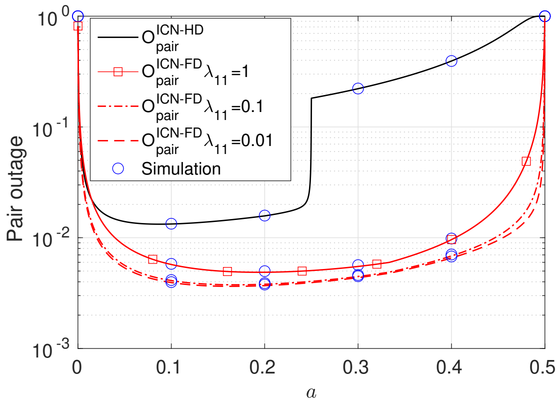


Fig. 4: Pair outage probability for the proposed FD-ICN and HD-ICN schemes as a function of the power allocation factor a.

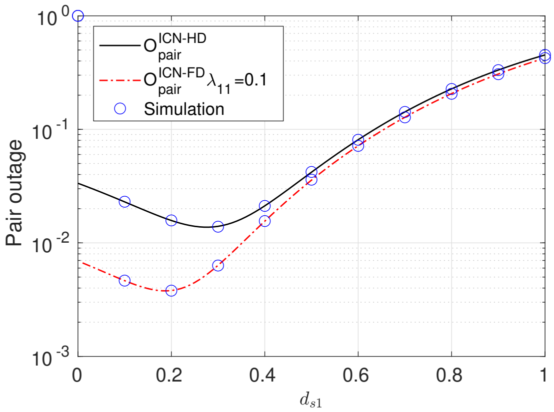


Fig. 5: Pair outage probability for the proposed FD-ICN and HD-ICN schemes as a function of the distance among the base station and U_1 (d_{s1}).

outage of U_2, while for $d_{s1} \geq 0.5$, the performance of both schemes is similar as the fails in the communication of U_1 have more influence in the pair outage probability.

V. CONCLUSIONS

We evaluated the performance of a full-duplex incremental cooperative NOMA scheme. We consider that based on 1-bit feedback of the far user, the system can choose between direct transmission or cooperative transmission, where the near user acts as a full-duplex relay to the far user. The results show that the proposed scheme outperforms, in terms of pair outage probability, the half-duplex incremental cooperative NOMA and conventional cooperative NOMA schemes. As future work, we intend to analyze a scenario when the links can have some line-of-sight through the use of the Nakagami-m fading distribution. Moreover, we intend to analyze a relay selection scheme in the cooperative mode for a scenario with multiple users.

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