Research Article

Performance Analysis of Reconfigurable Intelligent Surface-Aided Full-Duplex Cooperative NOMA System

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The outage performance of a reconfigurable intelligent surface- (RIS-) aided full-duplex cooperative nonorthogonal multiple access (NOMA) system is studied in this paper. Based on the statistical characteristics of the signal-to-noise ratio of the reflection channel from the access point via RIS to the near user, and the cooperative channel from the near user to the far NOMA user, the outage probability of both the near and far users is derived. Through the comparison with the outage performance of conventional cooperative NOMA without employing RIS, the superiority of the proposed scheme is demonstrated. Finally, the correctness of the analytical results is validated with simulation.

1. Introduction

As a revolutionizing technology for future wireless communications, reconfigurable intelligent surfaces (RISs) have gained tremendous attention recently due to their ability to reconfigure wireless propagation environments [1, 2]. RISs consist of passive metasurfaces which can change and reflect the direction of the incident signal to an expected destination under a smart controller. RISs can operate in a nearly passive full-duplex mode without resulting in self-interference [3]. RISs can replace radio frequency (RF) chains as a novel modulator, leading RISs-aided wireless systems to be low in cost and energy consumption. To satisfy different requirements, RISs-aided wireless systems have been combined with other advanced technologies, such as an unmanned aerial vehicle (UAV) [4], visible light communication (VLC) [5], physical layer security [6], multiuser communication [7, 8], multiantenna communication [9], and nonorthogonal multiple access (NOMA) [10, 11] to enhance system performance.

The integration of RIS into NOMA leads to a novel vision of a network with the features of high cost efficiency, superior spectrum/energy efficiency, and wide area coverage. Great effort has been put into the study of RIS-NOMA. In particu-

lar, Ref. [12] investigated the transmit power minimization via joint designing power allocation of the access point (AP) and the phase shifts of RISs. Ref. [13] studied the impact of the random discrete and coherent phase shifts on the reliability of the RIS-NOMA system. Ref. [14] investigated the user pairing for a RIS-aided NOMA system and made a comparison with a series of RIS-assisted orthogonal multiple access systems.

However, little has been focused on the integration of RIS into cooperative NOMA. Cooperative NOMA [15, 16], based on prior information available in NOMA and cooperation among users, can further improve system performance and extend communication coverage. Motivated by the advantages of IRS and cooperative NOMA, in this work, we study the outage performance of the RISs-aided full-duplex cooperative NOMA system. Note that prior work [17] has studied the RIS-aided user-cooperation relay NOMA system. However, it was carried out from an optimization perspective and formulated a total transmission power minimization problem subject to the RIS's passive beamforming and the power control of both the AP and the user relay.

In this work, we investigate the outage performance of the RISs-aided full-duplex cooperative NOMA system from

FIGURE 1: System model of the RIS-aided full-duplex downlink cooperative NOMA communication system.

TABLE 1: System parameters.

Parameters	Descriptions
f_i	Gain of the channel from the AP to the i th element of the RIS
g_i	Gain of the channel from the i th element of the RIS to U1
λ_i	Reflectance factor of the i th element of the RIS
h_1	Gain of the reflection channel from the AP via RIS to U1
$h_{1,1}$	Gain of the residual self-interference channel from U1 to U1
$h_{1,2}$	Gain of the NOMA cooperative channel from U1 to U2
l	Propagation distance from the AP to the RIS
d	Propagation distance from the RIS to U1
μ_i	Amplitude of the Rayleigh fading of f_i
ν_i	Amplitude of the Rayleigh fading of g_i
ϕ_i	Phase of the Rayleigh fading of f_i
θ_i	Phase of the Rayleigh fading of g_i
φ_i	Reconfigurable phase of the i th element of the RIS
ε	Path-loss index

a probability perspective and through the comparison with the outage performance of conventional cooperative NOMA without employing RIS demonstrate the superiority of the proposed system. Finally, the correctness of the analytical results is validated with simulation.

2. System and Channel Model

The considered RISs-aided full-duplex downlink cooperative NOMA system model is shown in Figure 1, which includes an AP and a RIS consisting of N elements and two prepared NOMA users (U1 and U2). The assumption for considering two cooperative NOMA users is the same as [16]. The direct link between the AP and NOMA users does not exist due to obstacle objects or heavy shadowing, and only the reflected signal from the RIS can be received by NOMA users. We call U1 the near user who is near to the RIS, and U2 the far user. According to the user-relay cooperative NOMA principle, U1 can obtain the prior information of U2 via successive interference cancellation (SIC) [18]. Thus, U1 acts as a relay

to forward the information to U2. Here, a full-duplex relay is utilized by U1 performing receiving information and relay transmission simultaneously. The proposed model can be applied to improve the performance of the cell edge users in multicell cellular systems or enhance the reliability of a device-to-device (D2D) communication system. It should be noted that if the direct link is available then more power will be received for both U1 and U2; thus, the system performance will be improved given the residual self-interference. Therefore, the performance achieved for the proposed system is a lower limit.

For the proposed RIS-aided full-duplex downlink cooperative NOMA system, the gain h_1 of the reflection channel from the AP via RIS to U1 can be given as $h_1 = \sum_{i=1}^N f_i \lambda_i g_i$, where f_i and g_i are, respectively, the gain of the channel from the AP to the i th ($i = 1, \dots, N$) element of the RIS and from the i th element of the RIS to U1, given by $f_i = l^{-\varepsilon/2} \mu_i \exp(-j\phi_i)$ and $g_i = d^{-\varepsilon/2} \nu_i \exp(-j\theta_i)$. The l and d are the propagation distances from the AP to the RIS and from the RIS to U1, respectively. The ε is the path-loss index, being a constant in

(a)

(b)

FIGURE 2: Continued.

FIGURE 2: The far user's outage probability comparison between the RIS-aided full-duplex cooperative NOMA system and the cooperative NOMA system without RIS for various values of N under $\gamma_s = 0$ dB: (a) $w_1 = 0.1$, $R_{th} = 0.2$ b/s/Hz; (b) $w_1 = 0.4$, $R_{th} = 0.2$ b/s/Hz; (c) $w_1 = 0.1$, $R_{th} = 1$ b/s/Hz.

this paper. μ_i and ϕ_i represent the amplitude and phase of f_i , respectively, and ν_i and θ_i denote the amplitude and phase of g_i , respectively. μ_i and ν_i are assumed to follow Rayleigh distribution, and ϕ_i and θ_i can be estimated. How to get ϕ_i and θ_i is beyond the scope of this paper and can be referenced from [2]. The reflectance factor of the i th ($i = 1, \dots, N$) element of the RIS is $\lambda_i = \exp(j\phi_i)$, where the reconfigurable phase ϕ_i of the RIS can be deployed as $\phi_i = \phi_i + \theta_i$ in order to make the signal-to-noise ratio (SNR) of the near user U1 maximum [3]. The system parameters employed in this work are included in Table 1.

Hence, the gain h_1 of the reflection channel can be simplified as

$$h_1 = (ld)^{-\epsilon/2} \sum_{i=1}^N \mu_i \nu_i. \quad (1)$$

For the RIS-aided full-duplex cooperative NOMA system, the near user U1 performs SIC and forwards the detected information to the far user U2 at the time of receiving the signal from RIS; meanwhile, U1 suffers residual self-interference. Thus, the received signal y_1 by U1 can be written as

$$y_1 = h_1 \sqrt{P_s}(w_1 s_1 + w_2 s_2) + h_{1,1} \sqrt{P_1} x + n_1, \quad (2)$$

where P_s is the transmit power of the AP; the information signal s_m intended for the m th NOMA user, $m \in \{1, 2\}$, is allocated power with a coefficient of w_m that satisfies $w_1 <$

w_2 and $w_1^2 + w_2^2 = 1$. The gain of the residual self-interference channel from U1 to U1 is $h_{1,1}$. U1 transmits with power P_1 , and the self-interference signal x satisfies $E[|x|^2] = 1$, where $E(\cdot)$ is the expectation operation. n_1 is the additive white Gaussian noise (AWGN) with zero mean and variance N_1 .

The received signal y_2 by U2 is given by

$$y_2 = h_{1,2} \sqrt{P_1} s_2 + n_2, \quad (3)$$

where $h_{1,2}$ is the gain of the NOMA cooperative channel from U1 to U2. n_2 is the AWGN of this channel with zero mean and variance N_2 .

Employing SIC technology, the near user U1 first decodes the information of the far user U2 and then subtracts it from the received signal in order to recover its own information. Thus, the signal-to-interference-plus-noise ratio (SINR) at U1 to detect information s_2 of U2 can be expressed as $Q_{1,2} = P_s w_2^2 |h_1|^2 / (P_s w_1^2 |h_1|^2 + P_1 |h_{1,1}|^2 + N_1)$. Let the SNR of the reflection channel from the AP via RIS to U1 be $\gamma_1 = P_s |h_1|^2 / N_1$, and the SNR of the residual self-interference channel from U1 to U1 be $\gamma_s = P_1 |h_{1,1}|^2 / N_1$, then the received SINR at U1 to detect information s_2 of U2 can be finally expressed as

$$Q_{1,2} = \frac{w_2^2 \gamma_1}{w_1^2 \gamma_1 + \gamma_s + 1}. \quad (4)$$

(a)

(b)

FIGURE 3: Continued.

FIGURE 3: The far user's outage probability comparison between the RIS-aided cooperative NOMA system and the cooperative NOMA system without RIS for various values of residual self-interference γ_S under $N = 12$: (a) $w_1 = 0.1$, $R_{th} = 0.2$ b/s/Hz; (b) $w_1 = 0.4$, $R_{th} = 0.2$ b/s/Hz; (c) $w_1 = 0.1$, $R_{th} = 1$ b/s/Hz.

The received SINR at U1 to detect its own information s_1 can be expressed as

$$Q_{1,1} = \frac{P_s w_1^2 |h_1|^2}{P_1 |h_{1,1}|^2 + N_1} = \frac{w_1^2 \gamma_1}{\gamma_S + 1}. \quad (5)$$

On condition that U1 can detect information s_2 of U2, the received SNR at U2 to detect its own information s_2 can be given by

$$\gamma_2 = \frac{P_1 |h_{1,2}|^2}{N_2}. \quad (6)$$

3. Statistical Characteristics of SNR

In order to get the performance of the RIS-aided full-duplex cooperative NOMA system, it is necessary to determine the statistical characteristics of γ_1 , γ_2 , and γ_S .

For the SNR of the reflection channel from the AP via RIS to U1, $\gamma_1 = \bar{\gamma}_1 X^2$, where $\bar{\gamma}_1$ is the average SNR given by $\bar{\gamma}_1 = P_s (ld)^{-\epsilon} / N_1$, and $X = \sum_{i=1}^N X_i = \sum_{i=1}^N \mu_i \nu_i$. From [19], we know that if channel amplitude μ_i and ν_i is an independently identically Rayleigh distributed random variable with mean $\sqrt{\pi}/2$ and variance $(1 - \pi/4)$, then X^2 obeys squared K_G distribution, and the probability density function (PDF) of γ_1

can be written as

$$f_{\gamma_1}(r) = \frac{2\Lambda^{a+b}}{\Gamma(a)\Gamma(b)} r^{(a+b)/2-1} K_{a-b}(2\Lambda\sqrt{r}), \quad (7)$$

and the cumulative distribution function (CDF) of γ_1 can be given by

$$F_{\gamma_1}(r) = \int_0^r f_{\gamma_1}(u) du = \frac{1}{\Gamma(a)\Gamma(b)} G_{1,3}^{2,1} \left[\Lambda^2 r |_{a,b,0}^1 \right], \quad (8)$$

where $G_{q_1, q_2}^{q_3, q_4}(\cdot)$ is Meijer's G-function [20] (Eq.(9.301)) with q_1, q_2, q_3, q_4 being the parameters; $K_n(\cdot)$ is the modified n th order Bessel function of the second kind [20] (Eq.(8.432)); $\Gamma(\cdot)$ is the gamma function [20] (Eq.(8.310.1)); Λ has relation to both the K_G distribution parameters and the 2nd order moment of X , which is expressed by $\Lambda = \sqrt{ab/\bar{\gamma}_1 \beta_X(2)}$, where a and b are the K_G distribution parameters and $\beta_X(2)$ is the 2nd order moment of X . Each of X 's j th order moment is given by

$$\beta_X(j) = \sum_{j_1=0}^j \sum_{j_2=0}^{j_1} \cdots \sum_{j_{N-1}=0}^{j_{N-2}} \binom{j}{j_1} \binom{j_1}{j_2} \cdots \binom{j_{N-2}}{j_{N-1}} \cdot \beta_{X_1}(j-j_1) \beta_{X_2}(j_1-j_2) \cdots \beta_{X_N}(j_{N-1}), \quad (9)$$

where $\beta_{X_i}(j) = [\Gamma(1 + j/2)]^2$. With the 2nd order, 4th order, and 6th order moments of X , we can finally get a and b by utilizing Eqs. (14)-(18) of [21].

(a)

(b)

FIGURE 4: Continued.

FIGURE 4: The near user's outage probability comparison between the RIS-aided full-duplex cooperative NOMA system and the cooperative NOMA system without RIS for various values of N under $\gamma_S = 0$ dB: (a) $w_1 = 0.2$, $R_{th} = 0.2$ b/s/Hz; (b) $w_1 = 0.4$, $R_{th} = 0.2$ b/s/Hz; (c) $w_1 = 0.4$, $R_{th} = 0.4$ b/s/Hz.

For the cooperative NOMA channel from U1 to U2, considering that $h_{1,2}$ follows Rayleigh fading, $\gamma_2 \sim \text{Exp}(1/\bar{\gamma}_2)$ always holds, where $\bar{\gamma}_2 = E[|h_{1,2}|^2]P_1/N_2$.

For simplicity, the SNR γ_S of the residual self-interference channel from U1 to U1 is a constant in this paper.

4. Performance Analysis

When the achievable data rate of a wireless link is below the target rate, an outage occurs. In the following, we first obtain the outage probability (OP) of the RIS-aided full-duplex cooperative NOMA system; for the comparison, we also get the OP of the cooperative NOMA system without employing RIS.

4.1. OP of the RIS-Aided Full-Duplex Cooperative NOMA System. Outage experienced by the near user U1 follows two situations. One is U1 cannot detect s_2 of U2 resulting in the break of SIC. The other is U1 can detect s_2 of U2 but U1's overall received SINR cannot support the target rate. Therefore, the OP of the near user U1 can be written as

$$P_{1,\text{out}} = \Pr\left(\frac{1}{2} \log(1 + Q_{1,2}) < R_{th0}\right) + \Pr\left(\frac{1}{2} \log(1 + Q_{1,2}) > R_{th0}, \frac{1}{2} \log(1 + Q_{1,1}) < R_{th1}\right), \quad (10)$$

where the target rate R_{th0} is to limit the data rate achieved by

the reflection channel from the AP via RIS to U1 for decoding the information of U2, and the target rate R_{th1} is employed by U1 to detect its own information.

Similarly, the outage experienced by the far user U2 also follows two situations. One is U1 cannot detect s_2 of U2 causing U2 not receiving information at all. The other is U1 can detect and forward s_2 of U2 but U2's overall received SINR cannot support the target rate R_{th2} . Therefore, the OP of the far user U2 can be written as

$$P_{2,\text{out}} = \Pr\left(\frac{1}{2} \log(1 + Q_{1,2}) < R_{th0}\right) + \Pr\left(\frac{1}{2} \log(1 + Q_{1,2}) > R_{th0}, \frac{1}{2} \log(1 + Q_2) < R_{th2}\right). \quad (11)$$

In the following, the OP of the near user U1 and far user U2 will be calculated, respectively.

Let $\tau_0 = 2^{2R_{th0}} - 1$, $\tau_1 = 2^{2R_{th1}} - 1$, $\tau_2 = 2^{2R_{th2}} - 1$. The OP of U1 for the RIS-aided full-duplex cooperative NOMA system can be written as

$$\begin{aligned} P_{1,\text{out}} &= \Pr(Q_{1,2} < \tau_0) + \Pr(Q_{1,2} > \tau_0, Q_{1,1} < \tau_1) \\ &= \Pr(Q_{1,2} < \tau_0) + \Pr(Q_{1,2} > \tau_0) \Pr(Q_{1,1} < \tau_1) \\ &= \Pr(Q_{1,2} < \tau_0) + [1 - \Pr(Q_{1,2} < \tau_0)] \Pr(Q_{1,1} < \tau_1). \end{aligned} \quad (12)$$

Obviously, it is necessary to first determine $\Pr(Q_{1,2} < \tau_0)$

(a)

(b)

FIGURE 5: Continued.

FIGURE 5: The near user's outage probability comparison between the RIS-aided cooperative NOMA system and the cooperative NOMA system without RIS for various values of residual self-interference γ_s under $N = 12$: (a) $w_1 = 0.2$, $R_{th} = 0.2$ b/s/Hz; (b) $w_1 = 0.4$, $R_{th} = 0.2$ b/s/Hz; (c) $w_1 = 0.4$, $R_{th} = 0.4$ b/s/Hz.

and $\Pr(Q_{1,1} < \tau_1)$ before obtaining $P_{1,out}$. Since $\lim_{\gamma_1 \rightarrow \infty} Q_{1,2} = \lim_{\gamma_1 \rightarrow \infty} w_2^2 \gamma_1 / (w_1^2 \gamma_1 + \gamma_s + 1) = w_2^2 / w_1^2$, if $\tau_0 \geq w_2^2 / w_1^2$, then $\Pr(Q_{1,2} < \tau_0) = 1$ holds. If $0 < \tau_0 < w_2^2 / w_1^2$, then $\Pr(Q_{1,2} < \tau_0) = \Pr(\gamma_1 < \tau_0(\gamma_s + 1) / (w_2^2 - \tau_0 w_1^2)) = F_{\gamma_1}(\tau_0(\gamma_s + 1) / (w_2^2 - \tau_0 w_1^2))$ can be obtained, where $w_2^2 > \tau_0 w_1^2$ should be always satisfied according to the NOMA protocol. In brief, $\Pr(Q_{1,2} < \tau_0)$ can be given by

$$\Pr(Q_{1,2} < \tau_0) = \begin{cases} 1, & \tau_0 \geq \frac{w_2^2}{w_1^2}, \\ F_{\gamma_1}\left(\frac{\tau_0(\gamma_s + 1)}{w_2^2 - \tau_0 w_1^2}\right), & 0 < \tau_0 < \frac{w_2^2}{w_1^2}. \end{cases} \quad (13)$$

Similarly, $\Pr(Q_{1,1} < \tau_1)$ can be given by

$$\Pr(Q_{1,1} < \tau_1) = \Pr\left(\gamma_1 < \frac{\tau_1(\gamma_s + 1)}{w_1^2}\right) = F_{\gamma_1}\left(\frac{\tau_1(\gamma_s + 1)}{w_1^2}\right). \quad (14)$$

Hence, the OP of U1 for the RIS-aided full-duplex coop-

erative NOMA system can be written as

$$P_{1,out} = \begin{cases} 1, & \tau_0 \geq \frac{w_2^2}{w_1^2}, \\ F_{\gamma_1}\left(\frac{\tau_0(\gamma_s + 1)}{w_2^2 - \tau_0 w_1^2}\right) + \left[1 - F_{\gamma_1}\left(\frac{\tau_0(\gamma_s + 1)}{w_2^2 - \tau_0 w_1^2}\right)\right] F_{\gamma_1}\left(\frac{\tau_1(\gamma_s + 1)}{w_1^2}\right), & 0 < \tau_0 < \frac{w_2^2}{w_1^2}. \end{cases} \quad (15)$$

Since $\Pr(Q_2 < \tau_2) = \int_0^{\tau_2} (1/\bar{\gamma}_2) e^{-(u/\bar{\gamma}_2)} du = 1 - e^{-\tau_2/\bar{\gamma}_2}$, the OP of U2 for the RIS-aided full-duplex cooperative NOMA system can be given by

$$P_{2,out} = \begin{cases} 1, & \tau_0 \geq \frac{w_2^2}{w_1^2}, \\ F_{\gamma_1}\left(\frac{\tau_0(\gamma_s + 1)}{w_2^2 - \tau_0 w_1^2}\right) + \left[1 - F_{\gamma_1}\left(\frac{\tau_0(\gamma_s + 1)}{w_2^2 - \tau_0 w_1^2}\right)\right] \left[1 - \exp\left(-\frac{\tau_2}{\bar{\gamma}_2}\right)\right], & 0 < \tau_0 < \frac{w_2^2}{w_1^2}. \end{cases} \quad (16)$$

4.2. OP of the Cooperative NOMA System without RIS. For the comparison, we derive the OP of the cooperative NOMA system without employing RIS, where the AP directly transmit the superimposed signal to U1, and at the time of receiving the signal, U1 performs SIC and forwards to U2; meanwhile, U1 suffers residual self-interference. Note that there is no link from the AP to U2. The SNR of the channel from the AP to U1 is $\gamma'_1 = P_s |h'_1|^2 / N_1$, where h'_1 is the gain of the channel from the AP to U1. Considering that this

channel follows Rayleigh distribution, $\gamma'_1 \sim \text{Exp}(1/\overline{\gamma'_1})$ holds and $\overline{\gamma'_1}$ is the average SNR which can be expressed with $\overline{\gamma'_1}$

$= E[|h'_1|^2]P_s/N_1$. Thus, for the cooperative NOMA system without RIS, the OP of U1 is given by

$$P'_{1,\text{out}} = \begin{cases} 1, & \tau_0 \geq \frac{w_2^2}{w_1^2}, \\ \exp\left(-\frac{\tau_0(\gamma_S+1)}{(w_2^2-\tau_0 w_1^2)\overline{\gamma'_1}}\right) \left[1 - \exp\left(-\frac{\tau_1(\gamma_S+1)}{w_1^2 \overline{\gamma'_1}}\right)\right] + 1 - \exp\left(-\frac{\tau_0(\gamma_S+1)}{(w_2^2-\tau_0 w_1^2)\overline{\gamma'_1}}\right), & 0 < \tau_0 < \frac{w_2^2}{w_1^2}, \end{cases} \quad (17)$$

and the OP of U2 is given by

$$P'_{2,\text{out}} = \begin{cases} 1, & \tau_0 \geq \frac{w_2^2}{w_1^2}, \\ \exp\left(-\frac{\tau_0(\gamma_S+1)}{(w_2^2-\tau_0 w_1^2)\overline{\gamma'_1}}\right) \left[1 - \exp\left(-\frac{\tau_2}{\overline{\gamma'_2}}\right)\right] + 1 - \exp\left(-\frac{\tau_0(\gamma_S+1)}{(w_2^2-\tau_0 w_1^2)\overline{\gamma'_1}}\right), & 0 < \tau_0 < \frac{w_2^2}{w_1^2}. \end{cases} \quad (18)$$

5. Numerical Results and Discussions

The numerical results for the OP of the RIS-aided full-duplex cooperative NOMA system are presented in this section for a range of parameter values, including the element number N of the metasurface, the NOMA power allocation coefficient w_1 , residual self-interference γ_S , the target rate $R_{\text{th}0}$ supported by the channel from the AP via RIS to near user U1 for decoding the information of the far user U2, and the target rate $R_{\text{th}1}$ and $R_{\text{th}2}$ at which information can be detected by U1 and U2, respectively. To investigate the RIS benefits, we compare the outage performance of the RIS-aided full-duplex cooperative NOMA system with that of the cooperative NOMA system without employing RIS. Finally, the Monte-Carlo simulation is employed to verify all the numerical results.

We consider a given user pair (U1, U2) in cooperative NOMA transmission during the simulation process, and the propagation distance from the AP to the RIS is $l = 20$ m, and the propagation distance from the RIS to U1 is $d = 6$ m. The transmission SNR P_s/N_1 varies between 0 dB and 20 dB. For simplicity, we set $R_{\text{th}0} = R_{\text{th}1} = R_{\text{th}2} = R_{\text{th}}$.

The OP of the far user U2 in the RIS-aided full-duplex cooperative NOMA system and the cooperative NOMA system without employing RIS are shown in Figure 2 for various values of the element number N under $\gamma_S = 0$ dB. We can know that no matter how the power allocation coefficient and target rate are, the OP performance of U2 in the RIS-aided cooperative NOMA system is always superior to that of the cooperative NOMA system without deploying RIS, which demonstrates that precisely controlling the propagation of the signal through the RIS can greatly improve the

system performance. We can know from Figure 2 that the simulation results are always consistent with the analytical results. As far as the RIS-aided cooperative NOMA system, we change N from 8 to 12. The OP performance improves with increasing N . For a certain N , increasing the transmission SNR can make the OP performance improved. Comparing Figure 2(a) with Figure 2(c), if given the power allocation coefficient to U1, i.e., $w_1 = 0.1$, increasing R_{th} from 0.2 b/s/Hz to 1 b/s/Hz will make the OP of the far user increase. This means increasing the outage threshold will make the OP performance degraded. Comparing Figure 2(a) with Figure 2(b), we know if given R_{th} and transmission SNR, the OP performance of the far user gets deteriorated by increasing w_1 . This conclusion agrees with the results of [16], and the reason is that increasing the power allocation efficient w_1 of the near user will make lower power allocated to the far user and further causing the received SNR of the far user decreased. As shown in Figure 2, if given the outage performance and the noise variance N_1 , the transmission power needed by the cooperative NOMA system without RIS is higher than that with RIS, which is consistent with the results of [14, 17].

The OP of the far user U2 in the RIS-aided full-duplex cooperative NOMA system and the cooperative NOMA system without deploying RIS are shown in Figure 3 for various values of self-interference γ_S under $N = 12$. Again, we can know that no matter how the power allocation coefficient and target rate are, the OP performance of the RIS-aided full-duplex cooperative NOMA system is always superior to that of the system without employing RIS. With the increasing of the residual self-interference, the OP performance gets deteriorated for both kinds of systems, meaning that the gain

from the cooperation transmission is decreased by increasing the residual self-interference. As shown in Figure 3, if given the outage performance and the noise variance N_1 , the transmission power needed by the RIS-aided cooperative NOMA system increases with the residual self-interference, which is consistent with the results of [17].

We also compare the outage performance of the near user U1 in the RIS-aided full-duplex cooperative NOMA system and the cooperative NOMA system without RIS under a series of parameters, as shown in Figures 4 and 5. For U1, the OP performance of the RIS-aided cooperative NOMA system is always superior to that of the cooperative NOMA system without RIS regardless of the power allocation coefficient and target data rate. Increasing the residual self-interference will make U1's OP performance get degraded for these two kinds of systems. Comparing Figure 4(a) with Figure 4(b), we know that given R_{th} and transmission SNR, the OP performance of the near user gets better by increasing w_1 . This is because more power is allocated to the near user. Comparing Figure 4(b) with Figure 2(b), we can know that under the same conditions, the outage performance of U1 is always inferior to that of U2 for both kinds of systems. The same conclusion can be derived through the comparison of Figure 5(b) with Figure 3(b). For example, when transmission SNR is 10 dB, the outage performance of U1 for the RIS-aided system with $N = 8$ in Figure 4(b) is 0.71 while the outage performance of U2 for the RIS-aided system with $N = 8$ in Figure 2(b) is about 0.06; the outage performance of U1 for the system without employing RIS in Figure 4(b) is around 0.99 while the outage performance of U2 for the system without employing RIS in Figure 2(b) is about 0.66. The reason for that is that the NOMA power allocation factor plays an extremely important role in improving the system performance, where the power allocation coefficient allocated to U1 is $w_1 = 0.4$ while to U2 is $w_2 = \sqrt{1 - w_1^2} = 0.84$, and w_1 is lower than w_2 .

6. Conclusion

In this paper, the OP of the RIS-aided full-duplex cooperative NOMA system is investigated. On deriving the PDF and CDF of the SNR of the reflection channel and the cooperative channel, the OP of both the near and far NOMA users is obtained. For the comparison, the OP of the conventional cooperative NOMA without RIS is also investigated. The correctness of the analytical results is verified via Monte-Carlo simulation. Simulation results show that no matter how the power allocation coefficient and target rate are, the OP performance in the RIS-aided cooperative NOMA system is always superior to that of the system without deploying RIS. With the increasing of the self-interference from full-duplex transmission, the OP performance gets deteriorated for these two systems. Power allocation has great impact on the OP performance of the RIS-aided full-duplex cooperative NOMA system, if given target rate and transmission SNR, the OP performance of the far user gets deteriorated while that of the near user gets better with increasing the power allocation coefficient to the near user. For the RIS-aided

cooperative NOMA system, the OP performance improves with increasing the element number of the metasurface.

Data Availability

All information is within the paper.

Conflicts of Interest

No competing interests exist concerning this study.

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