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Exploiting performance gap among two users in reconfigurable intelligent surfaces-aided wireless systems

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ABSTRACT

In this work, we study the outage performance of a reconfigurable intelligent surfaces (RIS)-aided wireless systems in the presence of non-orthogonal multiple access (NOMA). In particular, different power factors are allocated to users which belong a dedicated group. We derive exact outage probability of two users in a group. Specifically, it is assumed that the RIS is placed between the source and the users and far user has better performance under assistance of RIS. We also provide comparison analysis to investigate the effect of the main parameters on the outage performance of our proposed system, such as the number of tunable elements of the RIS, power allocation factors, target rates and the average signal-to-noise ratio at the base station. If we set small tunable elements for RIS, we can obtain the best performance. By using Monte-Carlo simulation, we verify our analytical results via simulations. Our main results reported in this paper show the positive effect once we deploy RISs for guaranteeing fairness among NOMA users in wireless systems.

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1. INTRODUCTION

Recently, one of attention for beyond 5G systems is reconfigurable intelligent surface (RIS)-aided systems [1]. By exploiting the special structure of multiple low-cost reflecting elements in intelligent reflecting surfaces (IRS)-assisted a planar array, incident signals are processed at such array using passive beamforming. Therefore, each element of IRS can be intelligent controlled associated with the wireless environment to conduct information transmission [2]–[5]. Meng *et al.* [2] considered the situation when a direct link exists between users and the base station (BS) to achieve the weighted sum rate maximization. Considering alternating optimization, the formulated problem is required to evaluate both active and passive beamforming. Nadeem *et al.* [3] considered the situation when the nonexistence of direct link between the BS and users and further studied the optimal data rate of all users to take into account system fairness. Wu and Zhang [4] considered users' individual minimum rate constraints with respect to the power minimization at the BS. The single user case and the multi-user scenarios are joint considered. While in [5], the authors studied the system energy efficiency maximization by proposing two computationally affordable approaches. In addition, they examined gradient descent search, alternating maximization,and sequential fractional programming. Boulogeorgos and Alexiou [6] presented the analytic framework of the RIS assisted systems to indicate main performance metric, namely the ergodic capacity (EC). Moreover, they also presented high-signal-to-noise-ratio and high-number of reflection units (RUs) approximations regarding ergodic capacity. In the work of [7]-[10], other studies confirmed significant improvement of RIS systems.

To further increase spectral efficiency, one of the main objectives of 5G is non-orthogonal multiple access (NOMA) which is one of the promising techniques to address this issue [11]-[13]. Li *et al.* [14] studied a simultaneous wireless information and power transfer NOMA network. In this system, by using a time-switching protocol from the source radio frequency, the relay is energy constrained and harvests energy enabler. The work in [15] full-duplex (FD) cooperative NOMA relaying systems in the existence of in-phase and quadrature-phase imbalance (IQI). To provide more insights, they examined imperfect successive interference cancellation (ipSIC). As main concept, NOMA decides to serve which users following distance difference between users or power allocation to pair the users. The researchers in [16]-[19] studied the NOMA techniques with two scenarios including single-carrier NOMA (SC-NOMA), multi-carrier NOMA (MC-NOMA).

Recent studies [20]-[24] have presented NOMA-RIS systems. In [22], a novel framework is sytudied passive beamforming in the framework of NOMA-RIS. In [23], a single eavesdropper RIS-assisted downlink NOMA system was explored with existence of hardware impairment. The impact of residual hardware impairment (RHI) on the physical layer security and the closed-form formula of the user's secrecy outage probability are derived. However, there is lack of article compare RIS-NOMA and RIS-OMA along with imperfect SIC, which motive us to further investigate system performance metric of RIS-NOMA system. This paper aims to analyse performance of two NOMA users which are benefited from deployment of RIS.

2. SYSTEM MODEL

We consider two-user NOMA downlink relying on RIS as shown in Figure 1. Two kind of users are classified based on their locations, namely near user (NU) and far user (FU). Regarding advances of NOMA, it it is possible to extend the case of multiple users which are serve by the proposed RIS-NOMA downlink transmission scheme, but the best performance for two-user NOMA scheme is reported in the literature. Therefore, we do not consider degraded performance in such system due to deployment of multiple users, which is beyond the scope of this letter. In this circumstance, one could not be transmission from the base station (BS) to mobile users directly due to heavy blockage or obstacle. The BS generates two beamforming vectors together with technique of zero forcing beamforming to serve two NOMA users. By grouping of paired users, RIS-NOMA satisfies different QoS requirements which are suitable to develop multiple services for mobile users in future wireless systems. Under assistance of RIS equipped N reflecting elements. The RIS is also equipped with a controller associated with switching procedure including working modes. In particular, RIS operate in receiving mode for channel estimation and in reflecting mode for data transmission. Since the RIS is a passive reflecting equipment, we adopt a time-division duplexing (TDD) protocol for uplink and downlink transmissions and assume channel reciprocity for achieving the channel information acquisition in the downlink based on the uplink training sequence.

To enable NOMA mode, the superimposed signal $(a_1 s_1 + a_2 s_2)$ transmitting from the BS then is required to serve distant mobile users with the presence of RIS. This study considers NOMA concept to provide user fairness with a_1 and a_2 are power allocation factors for user NU, and FU respectively. Due to less amount of power required to supply for user NU, we have $a_1 < a_2$ and $a_1^2 + a_2^2 = 1$ [25].

We denote $A = \sum_{i=1}^{N} |g_i| |g_{iN}|$, $B = \sum_{i=1}^{N} |g_i| |g_{iF}|$ for ease in further computation. In particular, we can compute the signal to interference plus noise (SINR) for the user NU to decode the FU's signal is expressed by

$$SINR(S_2) = \frac{A^2 a_2^2}{A^2 a_1^2 + \frac{1}{\rho}}, \tag{1}$$

where ρ represents the transmit signal-to-noise ratio (SNR). By performing SIC, the user NU eliminates signal s_2, then it decodes its signal by computing SNR as [26].

$$SNR(S_1) = \frac{A^2 \rho a_1^2}{\kappa \rho |h_I|^2 + 1}, \tag{2}$$

where $\kappa \in [0, 1]$, $\kappa = 0$ perfect successive interference cancellation (pSIC) and $\kappa = 1$ denote the imperfect successive interference cancellation (ipSIC). Assuming that the remaining interference from ipSIC is modeled as the Rayleigh fading and corresponding complex channel coefficient is denoted by $h_I \sim CN(0, \Omega_I)$ in with $CN(a, b)$ complex normal distribution with average a and variance b.

Different from decoding signal at user NU, computing SINR to detect the FU's signal can be given by

$$SINR_{FU} = \frac{B^2 a_2^2}{B^2 a_1^2 + \frac{1}{\rho}}. \tag{3}$$

The probability density function (PDF) of random variable (RV) T can be obtained as the following in [27, Eq. (24)]

$$f_{T^2}(x) = \frac{1}{2b^{a+1}\Gamma(a+1)} x^{\frac{a-1}{2}} \exp\left(-\frac{1}{b}\sqrt{x}\right) \quad , T \in \{A, B\}, \tag{4}$$

where $a = \frac{N\pi^2}{(16-\pi^2)} - 1$ and $b = \frac{8}{\pi} - \frac{\pi}{2}$. Next, the cumulative distribution function (CDF) of Y can be computed as [27, Eq. (25)]

$$F_{T^2}(x) = \frac{1}{\Gamma(a+1)} \gamma\left(a+1, \frac{1}{b}\sqrt{x}\right). \tag{5}$$

where $\gamma(.,.)$ is the lower incomplete Gamma function. With the aid of [28, Eq. (8.350.1)], (7) can be claimed by

$$F_{T^2}(x) = \frac{1}{\Gamma(a+1)} \sum_{l=0}^{\infty} \frac{(-1)^l}{l!(a+l+1)\, b^{a+l+1}} x^{\frac{a+l+1}{2}}. \tag{6}$$

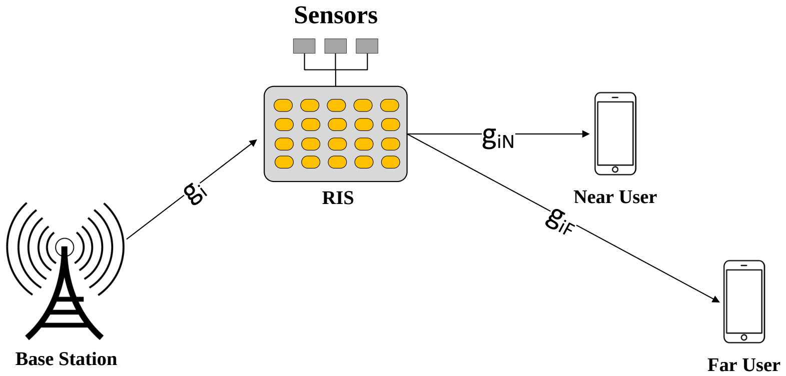

Figure 1. System model

3. PERFORMANCE ANALYSIS

To look at system performance, we intend to derive new closed-form formulas for the outage probability, and performance gap among two NOMA users should be considered for such RIS-aided wireless systems.

3.1. Outage probability at user NU

The outage behavior happens at the user NU once it fails to detect the FU's signal s_2 as well as its own signal s_1.

$$\begin{aligned} P_{NU} =& 1 - \Pr\left(SINR(S_2) > \varepsilon_2, SINR(S_1) > \varepsilon_1\right) \\ =& 1 - \Pr\left(A^2 > \varphi_2, A^2 > \varphi_1\left(\rho|h_I|^2 + 1\right)\right) \end{aligned} \tag{7}$$

where $\varepsilon_1 = 2^{2R_1} - 1$ and $\varepsilon_2 = 2^{2R_2} - 1$ are the threshold of system, R_1 and R_2 are the target rate, $\varphi_2 = \frac{\varepsilon_2}{\rho\left(a_2^2 - a_1^2\varepsilon_2\right)}$ and $\varphi_1 = \frac{\varepsilon_1}{\rho a_1^2}$.

From (9), one can observe $P_{NU} = 0$ when $a_1^2\varepsilon_2 > a_2^2$ and $\varphi_1\left(\rho|h_I|^2 + 1\right) > \varphi_2$. As a result, P_{NU} can be expressed as

$$P_{NU} = 1 - \Pr\left(A^2 > \varphi_1\left(\rho|h_I|^2 + 1\right)\right). \tag{8}$$

Proposition 1:

The closed-form expression of outage probability to detect signal s_2 and s_1 at the NU are given respectively by (9).

$$P_{NU} = \sum_{l=0}^{\infty} \frac{(-1)^l \varphi_1^{\frac{a+l+1}{2}} (\rho\Omega_{h_I})^{\frac{a+l+3}{2}} e^{\frac{1}{\Omega_{h_I}}}}{l!\Omega_{h_I}\Gamma(a+1)(a+l+1)\rho b^{a+l+1}} \Gamma\left(\frac{a+l+3}{2}, \frac{1}{\rho\Omega_{h_I}}\right), \tag{9}$$

where $\Gamma(.)$ is the Gamma function and $\Gamma(.,.)$ is the upper incomplete Gamma function.

Proof:

The outage probability P_{NU} can be further computed by (10).

$$\begin{aligned} P_{NU} =& 1 - \Pr\left(A^2 > \varphi_1\left(\rho|h_I|^2 + 1\right)\right) \\ =& 1 - \int_0^\infty f_{|h_I|^2}(x)\left[1 - F_{A^2}(\varphi_1(\rho x + 1))\right] dx \\ =& 1 - \frac{1}{\Omega_{h_I}} \int_0^\infty e^{-\frac{x}{\Omega_{h_I}}} \left[1 - \sum_{l=0}^{\infty} \frac{(-1)^l \varphi_1^{\frac{a+l+1}{2}}}{l!\Gamma(a+1)(a+l+1) b^{a+l+1}} (\rho x + 1)^{\frac{a+l+1}{2}}\right] dx \\ =& \sum_{l=0}^{\infty} \frac{(-1)^l \varphi_1^{\frac{a+l+1}{2}}}{l!\Omega_{h_I}\Gamma(a+1)(a+l+1) b^{a+l+1}} \int_0^\infty e^{-\frac{x}{\Omega_{h_I}}} (\rho x + 1)^{\frac{a+l+1}{2}} dx \end{aligned} \tag{10}$$

Let $t = \rho x + 1 \to \frac{t-1}{\rho} = x \to \frac{1}{\rho}dt = dx$, P_{NU} can be reformulated by (11).

$$P_{NU} = \sum_{l=0}^{\infty} \frac{(-1)^l \varphi_1^{\frac{a+l+1}{2}} e^{\frac{1}{\rho\Omega_{h_I}}}}{l!\Omega_{h_I}\Gamma(a+1)(a+l+1)\rho b^{a+l+1}} \int_1^\infty e^{-\frac{t}{\rho\Omega_{h_I}}} t^{\frac{a+l+1}{2}} dt. \tag{11}$$

Using [28, Eq. (3.381.3)], (11) can be reformulated by (12).

$$P_{NU} = \sum_{l=0}^{\infty} \frac{(-1)^l \varphi_1^{\frac{a+l+1}{2}} (\rho\Omega_{h_I})^{\frac{a+l+3}{2}} e^{\frac{1}{\Omega_{h_I}}}}{l!\Omega_{h_I}\Gamma(a+1)(a+l+1)\rho b^{a+l+1}} \Gamma\left(\frac{a+l+3}{2}, \frac{1}{\rho\Omega_{h_I}}\right). \tag{12}$$

This completes the proof.

3.2. Outage probability at user FU

Let consider outage probability of user FU as (13).

$$P_{FU} = 1 - \Pr\left(SINR_{FU} > \varepsilon_2\right). \tag{13}$$

Applying (8) of the CDF, P_{FU} is calculated by (14).

$$P_{FU} = 1 - \frac{1}{\Gamma(a+1)} \sum_{l=0}^{\infty} \frac{(-1)^l \varepsilon_2^{\frac{a+l+1}{2}}}{l!(a+l+1) b^{a+l+1}}. \tag{14}$$

4. NUMERICAL RESULTS

In this section, we simulate outage probability based on mathematical derivations and further verify with Monte-Carlo simulation and parameters used are summarized in Table 1. In Figure 2, due to gap among power allocation factors for two users, the performance gap in term of outage performance of user NU and FU at all values of the number of elements in NOMA-RIS system. It is also conclusion that higher number of elements in RIS, the considered system shows superiority in its performance. However, the worse case of ipSIC leads to significant deduction in performance, especially in high SNR regime. Such performance is also similar as Figure 3. In this scenario, different levels of ipSIC (Ω_I /) demonstrates difference in term of outage probability. This figure provide slight improvement when we compare RIS deployed with NOMA and OMA schemes.

Table 1. Table of Parameters for numerical results

Parameters	Results
Monte Carlo simulations repeated	10^6 iterations
The power allocation coefficient	$a_1^2 = 0.1, a_2^2 = 0.9$
The target rate	$R_1 = 3, R_2 = 1.5$ (BPCU)
Mean values of the ipSIC channel power gains	$\Omega_I = 0.001$

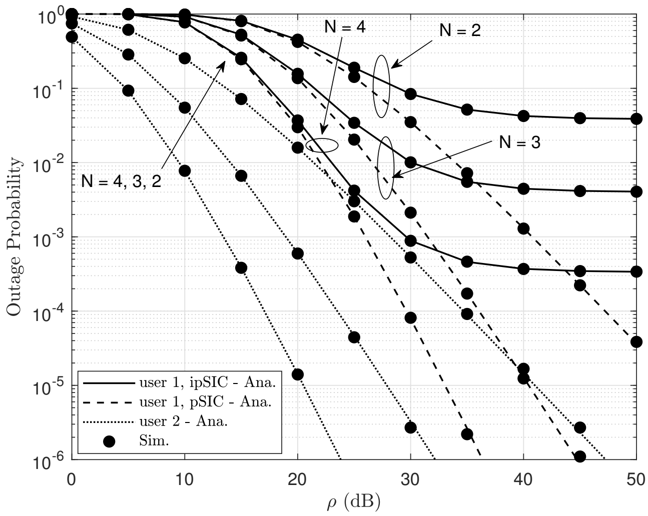

Figure 2. Outage probability versus transmit SNR ρ with varying N

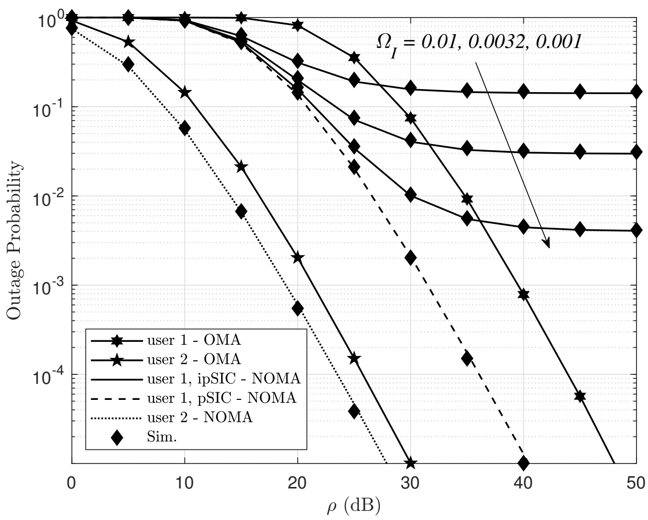

Figure 3. Outage probability versus transmit SNR ρ with varying Ω_I, with $N = 3$

Figure 4 confirms that the optimal outage performance can be achieved when we vary power allocation factor a_1. It can be explained that in (1), (2) and (3), SINRs depend on power allocation factors, and hence outage behavior is decided by such power allocation factors. The difference among performance of two users is explained by this power constraint. Unfortunately, it is likely difficult to find optimal outage probability for user FU. Of course, high SNR at source $\rho = 20dB$ is reported as better case.

Since (7) and (13) contain the target rates, the outage performance is certainly limited by such rate R_1, R_2, shown in Figure 5. Furthermore, the higher target rates exhibit the worse outage performance of two users, shown in Figure 5. By increasing target rate, outage probability will become worse significantly. As can be seen from Figure. 5, when we set $R_1, R_2 = 2.2$, the considered system meets outage event.

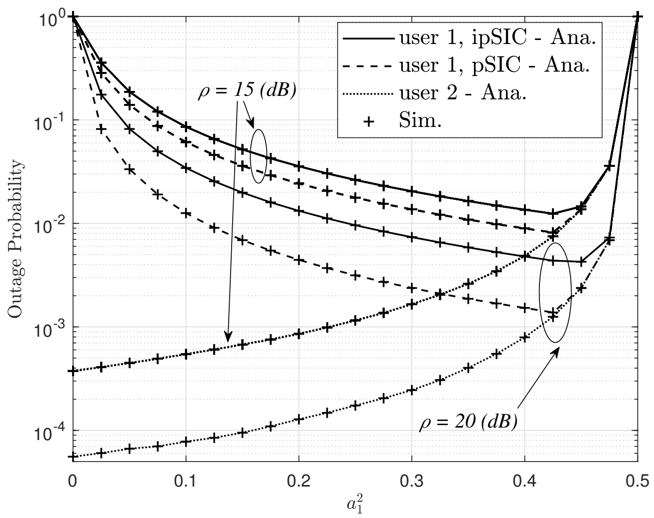

Figure 4. Optimal outage performance of user NU, with $R_1 = 1$, $R_2 = 0.5$, $\Omega_I = 0.01$ and $N = 2$

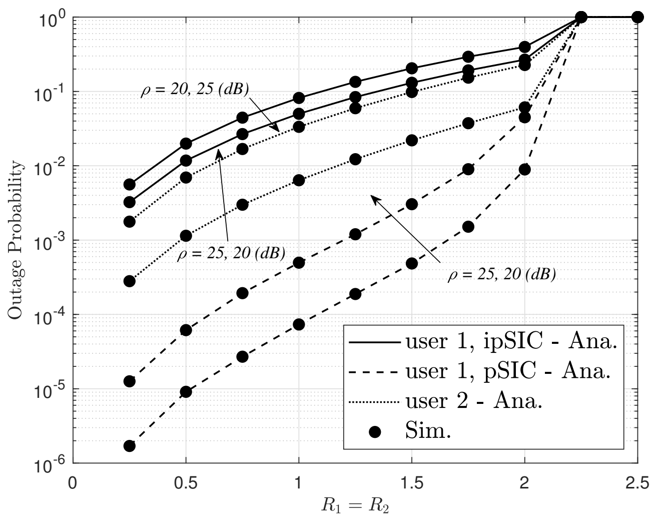

Figure 5. Outage probability versus target rates $R_1 = R_2$, with $N = 2$, $\Omega_I = 0.01$, $a_1^2 = 0.05$ and $a_2^2 = 0.95$

5. CONCLUSION

RIS-NOMA assisted wireless systems have been proposed to provide benefits of NOMA in term of fairness. Considering ideal condition of the optimal phases of the RIS elements over reciprocal channels, it can be achieved the exact outage probability for two users. Our main results indicate the impacts of the number of elements in RIS and power allocations factors on outage performance. Since the exact signal decoding procedure for NOMA scheme is likely difficult to implement in practice, we further consider imperfect SIC in such RIS-NOMA system. Moreover, benefit of NOMA compared with OMA is introduced in such system and this confirms joint deployment of NOMA and RIS introduce promising system for future development. The detailed improvement might be seen just in optimal outage performance of user NU, with $R_1 = 1$, $R_2 = 0.5$, $\Omega_I = 0.01$ and $N = 2$ performance. We can conclude that by joint deployments of NOMA and RIS we introduce promising system for future wireless system.

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