Reliability Analysis of CNOMA System Based on STAR-RIS

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***Abstract*—Simultaneously transmitting and reflecting reconfigurable intelligent surface (STAR-RIS) assisted non-orthogonal multiple access (NOMA) system can be widely used to improve the coverage of communications, but the transmitting users have the problems of lower reliability and higher link interruption. To address these problems, a STAR-RIS-assisted cooperative non-orthogonal multiple access (CNOMA) system is proposed in this paper. And the downlink performance of the proposed system with perfect and imperfect successive interference cancellation (SIC) are investigated. Especially the closed-form expressions of outage probability and ergodic rate are derived and verified by Monte-Carlo simulation. The simulation results show that due to the existence of imperfect SIC, the performance of the reflecting user is worse than that of perfect SIC. The proposed STAR-RIS-CNOMA system has a significant performance improvement for the transmitting user compared with that of the traditional STAR-RIS-NOMA system.**

Keywords*—*NOMA, STAR-RIS, SIC, outage probability

I. INTRODUCTION

The demand for high-speed, high-quality communications has spawned the research of the sixth-generation mobile communication technology (6G). Non-orthogonal multiple access (NOMA) has been regarded as a promising multiple access candidate for 6G networks. It uses superposition coding technology at the transmitter and successive interference cancellation (SIC) technology at the receiver to eliminate internal user interference [1]. Based on different application scenarios and requirements, the concept of cooperative NOMA communication was proposed [2]. A strong user with better selection conditions is selected as a relay in the cooperative phase to serve the weak user. In addition, the authors of [3] studied half-duplex and full-duplex CNOMA systems and discussed the performance of the system in terms of outage probability (OP) and ergodic rate. A threshold-based CNOMA model was proposed, which selects CNOMA transmission only when the user's signal-plus-interference-to-noise ratio (SINR) is greater than a predetermined threshold [4].

Reconfigurable intelligent surfaces (RISs) can actively reconfigure the wireless communication environment, coupled with their nearly passive and reflective nature, and have become the focus of research. [5] studied the RIS-assisted CNOMA system, in which the near user acts as a decode-and-forward half-duplex relay to perform device-to-device communication for the far user. However, traditional RIS requires that the transmitting and receiving nodes are located on the same side of the RIS, simultaneously transmitting and reflecting reconfigurable intelligent surface (STAR-RIS) can overcome this limitation [6]. STAR-RIS can provide services to users on both sides of the surface, thereby providing enhanced degrees of freedom for signal propagation [7]. The OP of a STAR-RIS-NOMA network over spatially correlated channels was investigated in [8], and a moment matching method was proposed, which approximates the gain distribution of the composite channel to gamma random variables. In [9], the performance of STAR-RIS-aided communication under energy splitting (ES) and mode switching (MS) protocols was analyzed in Rayleigh fading channels. [10] studied the STAR-RIS-NOMA system, allocating more elements to the reflecting user. The results showed that the performance of the transmission user was much worse than that of the reflection user. The performance of the STAR-RIS-NOMA system over Nakagami-m fading channels has been studied [11], [12]. The authors studied the reliability performance of the STAR-RIS-assisted NOMA network under the Rician channel in [13].

At present, most of the research focuses on the performance analysis of STAR-RIS-NOMA system, but there are few studies on the problem of poor performance of transmitting users. This paper explores a STAR-RIS-CNOMA system in which the transmitting user employs maximum ratio combining (MRC) to receive signals from both the direct and cooperative links, while considering the case of imperfect SIC in practical transmission scenarios. The main contributions of this paper can be summarized as follows:

- A STAR-RIS-assisted CNOMA system is proposed, where the reflecting user R acts as a half-duplex decode-and-forward relay, enhancing the reliability of the transmitting user compared to traditional STAR-RIS-NOMA.
- Using the curve fitting channel model, the cascade channel gain is approximately fitted to the Gamma distribution, and the closed expressions of the OP and ergodic rate of the reflection user and the transmission user under the MS protocol are derived.
- Under the MS protocol, considering the case of perfect SIC and imperfect SIC in actual communication, the influence of different residual interference transfer factors on the performance of reflective users is studied.

II. SYSTEM MODEL

A. Deployment

Fig. 1 considers a STAR-RIS-assisted downlink CNOMA system. The BS is fixed and the direct links from the BS to the users are blocked. Assume that the users are deployed in a circular area with the center point represented by O, user T is located in the transmission area of STAR-RIS, and user R is located in the reflection area of STAR-RIS. By utilizing the MS protocol, STAR-RIS consists of M elements, where M_r elements are used for reflection links

The remaining M_t elements are used for transmission links, and $M_r + M_t = M$. STAR-RIS is located above center O at a height of H meters. The distance between BS and STAR-RIS is d_0, the reflecting and transmitting users are horizontally located at distances d_r and d_t from the center O, respectively.

B. NOMA Protocol

To achieve cooperative communication, downlink transmission is performed in two phases. In the first phase, the BS sends a superimposed signal x to the paired CNOMA users R and T, denoted as $x = \sqrt{a_r P_t} x_r + \sqrt{a_t P_t} x_t$, where P_t represents the transmit power at the BS, x_r and x_t represent the desired signals of user R and user T, a_r and a_t represent the power allocation coefficients of R and T, and $a_r + a_t = 1$. From the perspective of user fairness, the BS allocates more transmit power to the weak user T, i.e., $a_r < a_t$.

In the second phase, to improve the communication quality at T, R resends the signal x_t obtained in the first phase to T. T uses the maximum ratio combining method to receive signals in two phases.

C. Channel Model

In the first phase, the BS to STAR-RIS, STAR-RIS to R, and STAR-RIS to T links are represented as $h = \left[h^1, \cdots, h^M\right]$, $h_r = \left[h_r^1, \cdots, h_r^{M_r}\right]^H$, $h_t = \left[h_t^1, \cdots, h_t^{M_t}\right]^H$. In the second phase, The R to STAR-RIS, STAR-RIS to T, links are represented as $g_r = \left[g_r^1, \cdots, g_r^{M_t}\right]$, $g_t = \left[g_t^1, \cdots, g_t^{M_t}\right]^H$.

This paper considers the optimal phase configuration of STAR-RIS. Therefore, the cascaded channel from the BS to the user R and the user T through STAR-RIS is expressed as $|h_{br}| = |h\Theta_r h_r| = \left|\sum_{i=1}^{M_r} h^i \sqrt{\beta_r^i} e^{j\theta_r^i} h_r^i\right|$, $|h_{bt}| = |h\Theta_{t1} h_t| = \left|\sum_{i=1}^{M_t} h^i \sqrt{\beta_t^i} e^{j\theta_{t1}^i} h_t^i\right|$. The cascaded channel from the user R to the user T through STAR-RIS is expressed as $|g_{rt}| = |g_r \Theta_{t2} g_t| = \left|\sum_{i=1}^{M_t} g_r^i \sqrt{\beta_t^i} e^{j\theta_{t2}^i} g_t^i\right|$. The transmission factor matrix and reflection factor matrix of STAR-RIS are expressed as

$$\Theta_r = diag\left(\sqrt{\beta_1^r} e^{j\theta_1^r}, \sqrt{\beta_2^r} e^{j\theta_2^r}, \cdots, \sqrt{\beta_M^r} e^{j\theta_M^r}\right), \tag{1}$$

$$\Theta_t = diag\left(\sqrt{\beta_1^t} e^{j\theta_1^t}, \sqrt{\beta_2^t} e^{j\theta_2^t}, \cdots, \sqrt{\beta_M^t} e^{j\theta_M^t}\right). \tag{2}$$

It is assumed that all channels in the model follow the Rician distribution and the channel state information (CSI) is perfect. Since the channels of each STAR-RIS element are independent and identically distributed, the skewness characteristic of the Gamma distribution aligns well with the distribution of the channel gain. The MATLAB curve fitting tool can be used to approximate the cascaded channel gain as a Gamma distribution [10]. Under the MS protocol, the probability density function (PDF) and cumulative distribution function (CDF) of $|h_{br}|^2$ can be given by

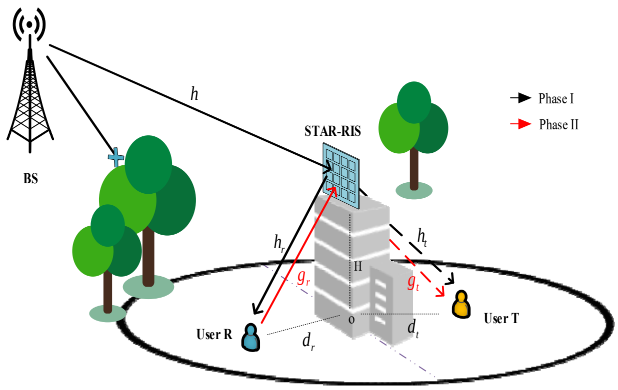

Fig. 1. System model of STAR-RIS assisted CNOMA system

$$f_{|h_{br}|^2}(x) = \frac{x^{k_{br}-1}}{\Gamma(k_{br})(\lambda_{br})^{k_{br}}} \exp\left(-\frac{x}{\lambda_{br}}\right), \tag{3}$$

$$F_{|h_{br}|^2}(x) = \frac{\gamma\left(k_{br}, \frac{x}{\lambda_{br}}\right)}{\Gamma(k_{br})}. \tag{4}$$

The PDF and CDF of $|h_{bt}|^2$ and $|g_{rt}|^2$ are defined in a similar way.

D. Signal Model

For the first phase, the received signals at user R and user T are respectively expressed as

$$y_r = (h\Theta_r h_r)\left(\sqrt{a_r P_t} x_r + \sqrt{a_t P_t} x_t\right) + n_o, \tag{5}$$

$$y_{t1} = (h\Theta_{t1} h_t)\left(\sqrt{a_r P} x_r + \sqrt{a_t P_t} x_t\right) + n_o, \tag{6}$$

where $n_o \sim \mathcal{CN}(0, \sigma^2)$ is the additive white Gaussian noise (AWGN). Θ_{t1} represents the first-phase transmission coefficient matrix of the STAR-RIS-T link.

The SINR of the user R decoding x_t is presented as

$$\gamma_{r \to t} = \frac{a_t P_t d_0^{-\alpha} (H^2 + d_r^2)^{-\frac{\alpha}{2}} |h_{br}|^2}{a_r P_t d_0^{-\alpha} (H^2 + d_r^2)^{-\frac{\alpha}{2}} |h_{br}|^2 + \sigma^2}. \tag{7}$$

The SINR of user R decoding its own signal x_r can be expressed as

$$\gamma_r = \frac{a_r P_t d_0^{-\alpha} (H^2 + d_r^2)^{-\frac{\alpha}{2}} |h_{br}|^2}{\xi a_t P_t d_0^{-\alpha} (H^2 + d_r^2)^{-\frac{\alpha}{2}} |h_{br}|^2 + \sigma^2}, \tag{8}$$

where α is the path loss exponent, ξ represents the residual interference factor of imperfect SIC.

The user T does not rely on SIC and treats the reflected user's signal as interference. Therefore, the SINR of its decoded useful signal is given by

$$\gamma_{t_1} = \frac{a_t P_t d_0^{-\alpha} (H^2 + d_t^2)^{-\frac{\alpha}{2}} |h_{bt}|^2}{a_r P_t d_0^{-\alpha} (H^2 + d_t^2)^{-\frac{\alpha}{2}} |h_{bt}|^2 + \sigma^2}. \tag{9}$$

For the second phase, user R forwards the decoded signal to T, and the received signal at T be defined as

$$y_{t2} = \left(g_r \Theta_{t2} g_t\right) x_t \sqrt{P_n} + n_o, \tag{10}$$

where P_n represents the transmission power at user R, Θ_{t2} represents the second-phase transmission coefficient matrix of the STAR-RIS-T link. The SNR of user T can be expressed as

$$\gamma_{t_2} = \frac{P_n (H^2 + d_r^2)^{-\frac{\alpha}{2}} (H^2 + d_t^2)^{-\frac{\alpha}{2}} \mid g_{rt} \mid^2}{\sigma^2}. \tag{11}$$

III. Outage Probability

A. The Outage Probability of User R

For user R, the interruption may occur when R fails to decode x_r or x_t, or both. Then the OP of user R is defined as

$$\begin{aligned} P_{\text{out}}^r &= \Pr\left\{\gamma_{r\to t} < \gamma_{th}^{SIC}\right\} + \Pr\left\{\gamma_{r\to t} > \gamma_{th}^{SIC}, \gamma_r < \gamma_{th}\right\} \\ &= 1 - \Pr\left\{\gamma_{r\to t} > \gamma_{th}^{SIC}, \gamma_r > \gamma_{th}\right\}, \end{aligned} \tag{12}$$

where $\gamma_{th}^{SIC} = 2^{R_{th}} - 1$ and $\gamma_{th} = 2^{R_{th}} - 1$ represent the threshold for the SIC process and outage threshold, respectively. R_{th} is the upper limit of the rate.

Let, $\rho_1 = \frac{P_t d_0^{-\alpha} (H^2 + d_t^2)^{-\frac{\alpha}{2}}}{\sigma^2}$, $\rho_2 = \frac{P_n (H^2 + d_r^2)^{-\frac{\alpha}{2}} (H^2 + d_t^2)^{-\frac{\alpha}{2}}}{\sigma^2}$, $\rho_3 = \frac{P_t d_0^{-\alpha} (H^2 + d_r^2)^{-\frac{\alpha}{2}}}{\sigma^2}$. The closed-form OP expression of R can be calculated by

$$\begin{aligned} P_{\text{out}}^r &= 1 - \Pr\left\{\frac{a_t \rho_3 \mid h_{br} \mid^2}{a_r \rho_3 \mid h_{br} \mid^2 + 1} > \gamma_{th}^{SIC}, \frac{a_r \rho_3 \mid h_{br} \mid^2}{\varepsilon a_t \rho_3 \mid h_{br} \mid^2 + 1} > \gamma_{th}\right\} \\ &= 1 - \Pr\left\{\mid h_{br} \mid^2 > \gamma_{\max}\right\} \\ &= \frac{\Upsilon(k_{br}, \frac{\gamma_{\max}}{\lambda_{br}})}{\Gamma(k_{br})}, \end{aligned} \tag{13}$$

where $\gamma_{\max} = \{\gamma_1, \gamma_2\}$, $\gamma_1 = \frac{\gamma_{th}^{SIC}}{\rho_3\left(a_t - a_r \gamma_{th}^{SIC}\right)}$, $\gamma_2 = \frac{\gamma_{th}}{\rho_3\left(a_r - \varepsilon a_t \gamma_{th}\right)}$.

B. The Outage Probability of User T

User T uses the MRC method to combine and receive the signals of the two phases, and the total received SINR is $\gamma_t^{MRC} = \gamma_{t_1} + \gamma_{t_2}$ .An interruption occurs when R fails to decode successfully, or when R decodes successfully but the SINR obtained after MRC at T is less than the threshold required by the quality of service. The OP of T is defined as

$$\begin{aligned} P_{\text{out}}^t &= \Pr(\gamma_{r\to t} > \gamma_{\text{th}}^{SIC}, \gamma_t^{MRC} < \gamma_{\text{th}}) \\ &\quad + \Pr(\gamma_{r\to t} < \gamma_{\text{th}}^{SIC}, \gamma_{t_1} < \gamma_{\text{th}}) \\ &= A_1 \times \Pr(\gamma_{r\to t} > \gamma_{\text{th}}^{SIC}) \\ &\quad + (1 - \Pr(\gamma_{r\to t} > \gamma_{\text{th}}^{SIC})) \times \Pr(\gamma_{t_1} < \gamma_{th}) \end{aligned} \tag{14}$$

A_1 can be calculated as

$$\begin{aligned} A_1 &= \Pr(\gamma_t^{MRC} < \gamma_{\text{th}}) = \Pr\left(\frac{a_t \rho_1 \mid h_{bt} \mid^2}{a_r \rho_1 \mid h_{bt} \mid^2 + 1} + \rho_2 \mid g_{rt} \mid^2 < \gamma_{\text{th}}\right) \\ &= \int_0^{\gamma_3} f_{|h_{bt}|^2}(x) F_{|g_{rt}|^2}\left(\frac{\gamma_{\text{th}}}{\rho_2} - \frac{a_t \rho_1 x}{\rho_2 (a_r \rho_1 x + 1)}\right) dx \\ &= \int_0^{\gamma_3} f_{|h_{bt}|^2}(x)\left(1 - \exp\left(-\frac{\phi(x)}{\lambda_{rt}}\right) \sum_{n=0}^{k_{rt}-1} \frac{\left(\frac{\phi(x)}{\lambda_{rt}}\right)^n}{n!}\right) dx \\ &= \frac{\Upsilon(k_{bt}, \frac{\gamma_3}{\lambda_{bt}})}{\Gamma(k_{bt})} - A_2 \end{aligned} \tag{15}$$

A2 can be obtained by Chebyshev Gauss integral. Substituting A_1 into (14), the closed-form OP expression of user T can be obtained as follows.

$$\begin{aligned} P_{\text{out}}^t = &\left\{ \frac{\Upsilon(k_{bt}, \frac{\gamma_3}{\lambda_{bt}})}{\Gamma(k_{bt})} - \frac{\gamma_3}{2} \left(\frac{1}{\lambda_{bt}}\right)^{k_{bt}} \frac{1}{\Gamma(k_{bt})} \sum_{i=1}^{N} \sum_{n=0}^{k_{rt}-1} w_i \sqrt{1 - \varepsilon_i^2} \frac{1}{n!} \right. \\ &\left. \times \left(\frac{\phi(\Omega(\varepsilon_i))}{\lambda_{rt}}\right)^n (\Omega(\varepsilon_i))^{k_{bt}-1} \exp\left[-\left(\frac{\phi(\Omega(\varepsilon_i))}{\lambda_{rt}} + \frac{\Omega(\varepsilon_i)}{\lambda_{bt}}\right)\right] \right\} \\ &\times \left(1 - \frac{\Upsilon(k_{br}, \frac{\gamma_1}{\lambda_{br}})}{\Gamma(k_{br})}\right) + \frac{\Upsilon(k_{br}, \frac{\gamma_1}{\lambda_{br}}) \Upsilon(k_{bt}, \frac{\gamma_1}{\lambda_{bt}})}{\Gamma(k_{br}) \Gamma(k_{bt})}, \end{aligned} \tag{16}$$

where $\gamma_3 = \frac{\gamma_{th}}{\rho_1\left(a_t - a_r \gamma_{th}\right)}$, $\phi(x) = \frac{\gamma_{\text{th}}}{\rho_2} - \frac{a_t \rho_1 x}{\rho_2 (a_r \rho_1 x + 1)}$, $\Omega(\varepsilon_i) = \frac{\gamma_3}{2}(\varepsilon_i + 1)$, $w_i = \pi / N$, $\varepsilon_i = \cos\left((2i-1)\pi / 2N\right)$, and N is a parameter in Chebyshev-Gauss quadrature.

IV. Ergodic Rate

This paper adopts the threshold-based selective cooperative NOMA scheme proposed in [5]. The ergodic rate of user R and T are expressed as

$$R_r = \mathbb{E}\left[\log_2\left(1 + \gamma_r\right)\right], \tag{17}$$

$$\begin{aligned} R_t = &\Pr(\gamma_{r\to t} < \gamma_{\text{th}}^{SIC}) \mathbb{E}\left[\log_2\left(1 + \gamma_{t_1}\right)\right] \\ &+ \Pr(\gamma_{r\to t} \geq \gamma_{\text{th}}^{SIC}) \mathbb{E}\left[\log_2\left(1 + \gamma_t^{MRC}\right)\right]. \end{aligned} \tag{18}$$

A. Ergodic Rate of User R

Considering the actual situation of imperfect SIC, with the aid of [14, eq. (8.352.4)] and [14, eq. (3.353.5.7)], the ergodic rate of user R can be calculated as

$$\begin{aligned} R_r &= \mathbb{E}\left[\log_2\left(1 + \frac{a_r \rho_3 \mid h_{br} \mid^2}{\varepsilon a_t \rho_3 \mid h_{br} \mid^2 + 1}\right)\right] \\ &= \int_0^\infty \log_2(1 + (\varepsilon a_t + a_r)\rho_3 x) f_{|h_{br}|^2}(x) dx \\ &\quad - \int_0^\infty \log_2(1 + \varepsilon a_t \rho_3 x) f_{|h_{br}|^2}(x) dx \\ &= \frac{1}{\ln 2} \sum_{n=0}^{k_{br}-1} \frac{1}{n!\left((\varepsilon a_t + a_r)\rho_3 \lambda_{br}\right)^n} \Big[(-1)^{n-1} \end{aligned}$$

$$\times\exp\left(\frac{1}{(\varepsilon a_t + a_r)\rho_3\lambda_{\rm br}}\right)\mathrm{Ei}\left(-\frac{1}{(\varepsilon a_t + a_r)\rho_3\lambda_{\rm br}}\right)$$
$$+\sum_{m=1}^{n}(-1)^{n-m}(m-1)!\left(\frac{1}{(\varepsilon a_t + a_r)\rho_3\lambda_{\rm br}}\right)^{-m}\Bigg]$$
$$-\frac{1}{\ln 2}\sum_{n=0}^{k_{\rm br}-1}\frac{1}{n!(\varepsilon a_t\rho_3\lambda_{\rm br})^n}\left[(-1)^{n-1}\exp\left(\frac{1}{\varepsilon a_t\rho_3\lambda_{\rm br}}\right)\right.$$
$$\left.\times\mathrm{Ei}\left(-\frac{1}{\varepsilon a_t\rho_3\lambda_{\rm br}}\right)+\sum_{m=1}^{n}(-1)^{n-m}(m-1)!\left(\frac{1}{\varepsilon a_t\rho_3\lambda_{\rm br}}\right)^{-m}\right], \qquad (19)$$

where $Ei(\cdot)$ represents the exponential integral function.

B. Ergodic Rate of User T

Define $\Psi = |h_{bt}|^2 + \rho_1\bar{c}a_r|h_{bt}|^2|g_{rt}|^2 + \bar{c}|g_{rt}|^2$.

Lemma 1. The distribution of Ψ can be derived as [5]

$$\Psi \sim \Gamma(k_{\rm MRC}, \lambda_{\rm MRC}), \qquad (20)$$

where $k_{\rm MRC} = \frac{E_{\rm MRC}^2}{V_{\rm MRC}}$, $\lambda_{\rm MRC} = \frac{V_{\rm MRC}}{E_{\rm MRC}}$, $c = \frac{P_n}{P_t}$, $\bar{c} = \frac{\rho_2}{\rho_1}$,

$E_{\rm MRC} = \mathbb{E}(|h_{bt}|^2)\mathbb{E}(|g_{rt}|^2) = k_{\rm bt}\lambda_{\rm bt} + \rho_1\bar{c}a_r k_{\rm bt}\lambda_{\rm bt}k_{\rm rt}\lambda_{\rm rt} + \bar{c}k_{\rm rt}\lambda_{\rm rt}$,

$V_{\rm MRC} = k_{\rm bt}\lambda_{\rm bt}^2 + \rho_1^2\bar{c}^2 a_r k_{\rm bt}\lambda_{\rm bt}^2 k_{\rm rt}\lambda_{\rm rt}^2(1+k_{\rm bt}+k_{\rm rt}) + \bar{c}^2 k_{\rm rt}\lambda_{\rm rt}^2$.

The ergodic rate of user T can be written as

$$R_t = \frac{\Upsilon(k_{br}, \frac{\gamma_1}{\lambda_{br}})}{\Gamma(k_{br})}\times\left\{\frac{1}{\ln 2}\sum_{n=0}^{k_{\rm bt}-1}\frac{1}{n!}\left(\frac{1}{\rho_1\lambda_{\rm bt}}\right)^n\left[(-1)^{n-1}\exp\left(\frac{1}{\rho_1\lambda_{\rm bt}}\right)\right.\right.$$
$$\left.\left.\times\mathrm{Ei}\left(-\frac{1}{\rho_1\lambda_{\rm bt}}\right)+\sum_{m=1}^{n}(-1)^{n-m}(m-1)!\left(\frac{1}{\rho_1\lambda_{\rm bt}}\right)^{-m}\right]\right\}-\left\{\frac{1}{\ln 2}\right.$$
$$\times\sum_{n=0}^{k_{\rm bt}-1}\frac{1}{n!}\left(\frac{1}{a_r\rho_1\lambda_{\rm bt}}\right)^n\left[(-1)^{n-1}\exp\left(\frac{1}{a_r\rho_1\lambda_{\rm bt}}\right)\mathrm{Ei}\left(-\frac{1}{a_r\rho_1\lambda_{\rm bt}}\right)\right.$$
$$\left.\left.+\sum_{m=1}^{n}(-1)^{n-m}(m-1)!\left(\frac{1}{a_r\rho_1\lambda_{\rm bt}}\right)^{-m}\right]\right\}+\left(1-\frac{\Upsilon(k_{br}, \frac{\gamma_1}{\lambda_{br}})}{\Gamma(k_{br})}\right)\left\{\frac{1}{\ln 2}\right.$$
$$\times\sum_{n=0}^{k_{MRC}-1}\frac{1}{n!}\left(\frac{1}{\lambda_{MRC}}\right)^n\left[(-1)^{n-1}\exp\left(\frac{1}{\lambda_{MRC}}\right)\mathrm{Ei}\left(-\frac{1}{\lambda_{MRC}}\right)\right.$$
$$\left.\left.+\sum_{m=1}^{n}(-1)^{n-m}(m-1)!\left(\frac{1}{\lambda_{MRC}}\right)^{-m}\right]\right\}. \qquad (21)$$

V. Numerical Results

Based on STAR-RIS-CNOMA communication model, the proposed CNOMA is compared with the non-cooperative NOMA as a performance benchmark [10], and the parameters of simulation are given in Table I.

The outage probability of user R and user T with increasing transmit power P_t at the BS and different numbers of STAR-RIS elements is shown in Fig. 2. For user R, when imperfect SIC exists, its outage performance deteriorates because the residual interference from user T affects the valid information of user R during decoding. Additionally, the effect of the number of STAR-RIS elements on OP is also considered. It is obvious that as the number of elements increases, the performance gain is greater. For example, the outage performance of the reflective user R with imperfect SIC when $M = 45$ is better than that of the user with perfect SIC when $M = 30$.

The OP of user R under different ξ values is shown in Fig.3. Under the same transmission power, the larger the ξ value is, the greater the OP of user R is, and the adverse impact of erroneous decoding on user R also increases accordingly.

TABLE I. Simulation Parameters.

Parameter	***Value***
The number of STAR-RIS elements	$M = 30$
Power allocation coefficients	$a_r : a_t = 0.3:0.7$
Ratio of reflecting and transmitting elements	$M_r : M_t = 2:1$
Pass loss exponent	$\alpha = 2.4$
Noise variance	$\sigma^2 = -90$dB
Distance	$\{H, d_0, d_r, d_t\} = \{30, 300, 80, 80\}$
Residual interference factor	$\xi = 0$
Transmit Power of R	$P_n = 10$dB

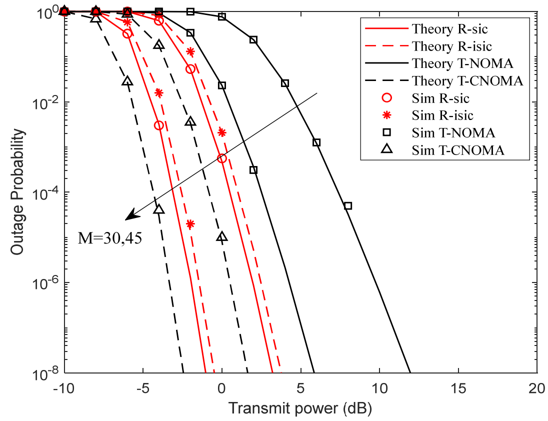

Fig. 2. OP versus the P_t with $M = \{30, 45\}$.

The ergodic rates of user R and user T versus the transmit power at the BS are plotted in Fig. 4. Set $c = 0.2$. The ergodic rate of user T assisted by STAR-RIS-CNOMA is much higher than that of user T assisted by STAR-RIS-NOMA, and the advantages of cooperative transmission are significant.

To illustrate the superiority of STAR-RIS-CNOMA, the sum rate of user R and user T versus different transmit power at the BS and different numbers of STAR-RIS elements are plotted in Fig. 5. M is taken as 30 and 45 respectively. It can be seen that the larger the value of M is, the larger the ergodic rate achieved by the user under the same transmission power, which is due to the large number of STAR-RIS elements providing well integrated signals to enhance the channel quality. Furthermore, the advantages of the STAR-RIS-CNOMA scheme are evident even with imperfect SIC.

Fig. 6 compares the trend of ergodic rate of user R under perfect and imperfect SIC, the larger the ξ value, the smaller the ergodic rate of user R, but it tends to be flat. Therefore, it is very important to consider these factors in actual communication scenarios.

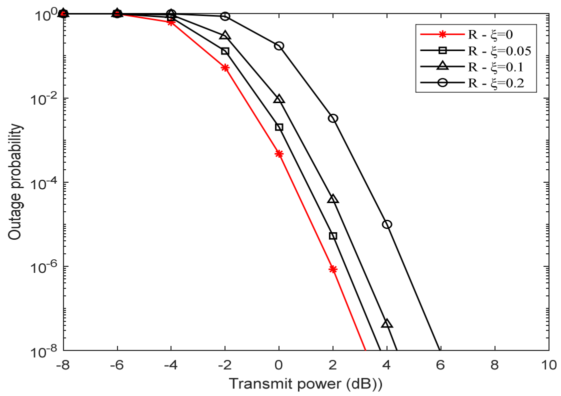

Fig. 3. OP of user R versus P_t with $\xi=\{0,0.05,0.1,0.2\}$.

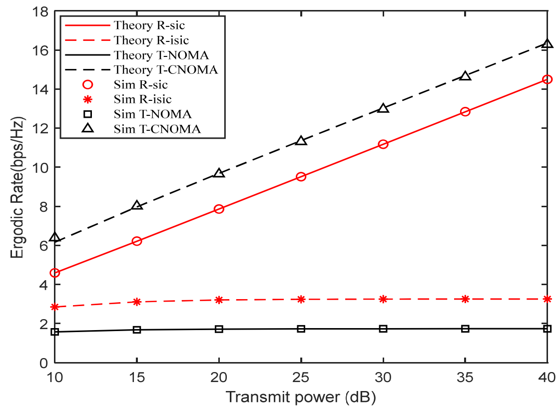

Fig. 4. Ergodic rates of user R and user T versus P_t

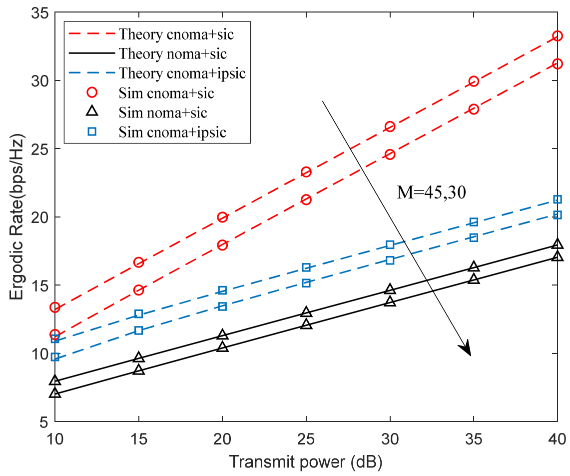

Fig. 5. Sum rate versus P_t with $M=\{30,45\}$.

VI. CONCLUSION

This paper mainly focused on the STAR-RIS-CNOMA system. By fitting the distribution of composite channel power gain to Gamma distribution, theoretical expressions of ergodic rate and OP under perfect SIC and imperfect SIC were derived. Numerical results showed that: 1) the performance of the system could be improved to a certain extent by increasing the number of STAR-RIS elements. 2) imperfect SIC had an adverse effect on the performance of reflecting users. 3) cooperative links significantly enhanced the reliability of transmitting user.

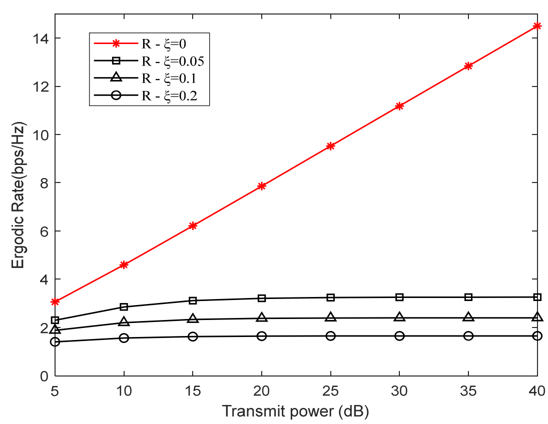

Fig. 6. Ergodic rates of user R versus P_t with $\xi=\{0,0.05,0.1,0.2\}$

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REFERENCES

[1] Z. Ding et al., "Application of Non-Orthogonal Multiple Access in LTE and 5G Networks," in IEEE Communications Magazine, vol. 55, no. 2, pp. 185-191, February 2017.

[2] Z. Ding, M. Peng and H. V. Poor, "Cooperative Non-Orthogonal Multiple Access in 5G Systems," in IEEE Communications Letters, vol. 19, no. 8, pp. 1462-1465, Aug. 2015.

[3] X. Yue, Y. Liu, S. Kang, A. Nallanathan and Z. Ding, "Exploiting Full/Half-Duplex User Relaying in NOMA Systems," in IEEE Transactions on Communications, vol. 66, no. 2, pp. 560-575, Feb. 2018.

[4] F. Kara and H. Kaya, "Threshold-Based Selective Cooperative-NOMA," in IEEE Communications Letters, vol. 23, no. 7, pp. 1263-1266, July 2019.

[5] X. Gu et al., "On the Performance of Cooperative NOMA Downlink: A RIS-Aided D2D Perspective," in IEEE Transactions on Cognitive Communications and Networking, vol. 9, no. 6, pp. 1610-1624, Dec. 2023.

[6] Y. Liu et al., "STAR: Simultaneous Transmission and Reflection for 360° Coverage by Intelligent Surfaces," in IEEE Wireless Communications, vol. 28, no. 6, pp. 102-109, December 2021.

[7] X. Mu, Y. Liu, L. Guo, J. Lin and R. Schober, "Simultaneously Transmitting and Reflecting (STAR) RIS Aided Wireless Communications," in IEEE Transactions on Wireless Communications, vol. 21, no. 5, pp. 3083-3098, May 2022.

[8] T. Wang, M. -A. Badiu, G. Chen and J. P. Coon, "Outage Probability Analysis of STAR-RIS Assisted NOMA Network With Correlated Channels," in IEEE Communications Letters, vol. 26, no. 8, pp. 1774-1778, Aug. 2022.

[9] D. Gunasinghe and G. Amarasuriya, "Performance Analysis of STAR-RIS for Wireless Communication," ICC 2022 - IEEE International Conference on Communications, Seoul, Korea, Republic of, 2022, pp. 3275-3280.

[10] C. Zhang, W. Yi, Y. Liu, Z. Ding and L. Song, "STAR-IOS Aided NOMA Networks: Channel Model Approximation and Performance Analysis," in IEEE Transactions on Wireless Communications, vol. 21, no. 9, pp. 6861-6876, Sept. 2022.

[11] B. Zhao, C. Zhang, W. Yi and Y. Liu, "Ergodic Rate Analysis of STAR-RIS Aided NOMA Systems," in IEEE Communications Letters, vol. 26, no. 10, pp. 2297-2301, Oct. 2022.

[12] M. Aldababsa, A. A. Mwais, and M. Obaid, "Performance of STAR-RIS assisted NOMA networks in Nakagami-m fading channels," Int. J. Electron. Commun., vol. 166, Jul. 2023, Art. no. 154685.

[13] X. Yue, J. Xie, Y. Liu, Z. Han, R. Liu and Z. Ding, "Simultaneously Transmitting and Reflecting Reconfigurable Intelligent Surface Assisted NOMA Networks," in IEEE Transactions on Wireless Communications, vol. 22, no. 1, pp. 189-204, Jan. 2023.

[14] I. S. Gradshteyn and I. M. Ryzhik, Table of Integrals, Series and Products, 7th ed. New York, NY, USA: Academic, 2007.