STAR-RIS-Enabled NOMA with Signal Constellation Adjustment for 6G LEO Satellite Networks

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***Abstract*—In this paper, we investigate a simultaneous transmitting and reflecting-reconfigurable intelligent surface-enabled non–orthogonal multiple access (STAR-RIS-NOMA) technique for 6G low earth orbit (LEO) satellite networks. In particular, we focus on the problem of similar channel gains of user equipment (UE) when a direct path between LEO and UEs cannot be formed due to the surrounding terrain and buildings. In this paper, we propose a novel signal constellation scaling and rotation for the STAR-RIS-NOMA technique in LEO satellite networks. In addition, we consider a joint maximum likelihood (JML) detector that can achieve optimal performance in terms of bit-error-rates (BER) rather than a sub-optimal successive interference cancellation (SIC) detector. Through extensive simulations, we show that the proposed technique significantly improves the BER performance of LEO satellite networks.**

***Index Terms*—6G mobile communication system, low earth orbit (LEO) satellite networks, non-terrestrial networks (NTN), non-orthogonal multiple access (NOMA), reconfigurable intelligent surface (RIS), bit-error-rates (BER).**

I. Introduction

Recently, low earth orbit (LEO) satellite communication systems have attracted much more attention as promising solutions to achieve wide service coverage and low latency communication [1]. Moreover, thanks to miniaturization of core components, reduced satellite production costs, and standardization of satellite platforms, Implementation and studies for LEO-based communication systems could be further accelerated [2]. However, LEO satellite communication systems have been faced several challenges such as the scarcity of frequency-time resources due to increased demand, severe path loss due to long-distance transmission, and shadowing effects caused by obstacles since LEO satellite constellations operate at an orbit altitude of 550 kilometers [3].

Recent developments in reconfigurable intelligent surfaces (RIS) technology are expected to address these issues such as long-distance transmission and shadowing effects [4]. Specifically, RIS technology efficiently creates an additional communication path between a transmitter and receiver by adjusting the amplitude and phase of an incident wave with a large antenna surface based on a metamaterial. Moreover, the combination of non-orthogonal multiple access (NOMA) and RIS has attracting attention in research for maximizing massive connectivity and spectral efficiency. In [5], [6], several beamforming techniques were presented for energy efficiency and sum rate maximization in LEO-based RIS-NOMA systems. In [7], optimized RIS reflection coefficients were presented to improve the communication performance of RIS-NOMA while considering LEO-assisted non-terrestrial networks (NTN). In recent, a novel simultaneous transmitting and reflecting RIS (STAR-RIS) was proposed to overcome the coverage limitations of the conventional RIS [8]. In [9], the authors rigorously analyzed the outage probability when grafting STAR-RIS and NOMA on the LEO-assisted NTN.

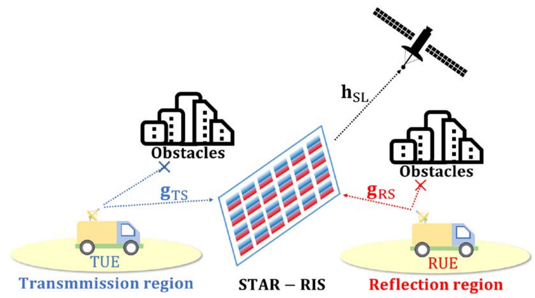

Fig. 1. System model of the LEO satellite communication system assisted by STAR-RIS-NOMA.

However, in high frequency wave propagation, since LEO is relatively at a high altitude, there might not be direct paths between transmitters and a receiver unlike RIS-NOMA for general terrestrial networks. so when detecting received signals without scaling or rotation at the RIS, severe performance degradation can be caused by overlapped constellation due to similar channel gains. Therefore, in this paper, we present the constellation scaling and rotation-based STAR-RIS-NOMA for uplink LEO-enabled NTN. Actually, it has been demonstrated that the constellation scaling and rotation techniques are effective in the uplink NOMA system [10], [11]. However, to the best of our knowledge, constellation scaling and rotation techniques have not been applied to the RIS-NOMA technique for LEO-enabled NTN in the literature. Moreover, we consider a joint maximum likelihood (JML) detector that can achieve optimal communication performance in terms of the bit-error-rates (BER). Through extensive simulations, we verify that our constellation scaling and rotation-based STAR-RIS-NOMA can significantly improve the BER performance.

II. System Model

In this paper, we consider an uplink LEO satellite-enabled STAR-RIS-NOMA network with two user equipments (UEs) as shown in Fig. 1. Herein, the STAR-RIS is equipped with N elements, and both LEO Satellite and all UEs are equipped with a single antenna. It is assumed that Doppler shifts caused by the mobility of LEO satellites and UEs are perfectly compensated and the energy-split (ES) mode of the STAR-RIS where it reflects and transmits signals simultaneously by dividing the incident energy from all elements of STAR-RIS was considered [8]. For ease of explanation, we call the UE in the transmission region as transmit UE (TUE) and the UE in the reflection region as reflect UE (RUE) in this paper. In addition, we also assume that there is no direct path between the LEO satellite and each UE due to surrounding obstacles.

As illustrated in Fig. 1, $\mathbf{h}_{\mathrm{SL}}(\in \mathbb{C}^{N})$, $\mathbf{g}_{\mathrm{TS}}(\in \mathbb{C}^{1\times N})$, and $\mathbf{g}_{\mathrm{RS}}(\in \mathbb{C}^{1\times N})$ denote the wireless channel vector from STAR-RIS to LEO satellite, from TUE to STAR-RIS, and from RUE to STAR-RIS, respectively. Specifically, the $n \in \{1, \cdots, N\}$-th component of $\mathbf{h}_{\mathrm{SL}}$ vector is defined as

$$h_{\mathrm{SL}}^{n} = \sqrt{G_{\mathrm{L}}\left(\frac{c}{4\pi f_{\mathrm{c}} d_{\mathrm{SL}}}\right)^{2}} Q_n, \tag{1}$$

where $G_{\mathrm{L}}, c, f_{\mathrm{c}}$, and d_{SL} are antenna gain of LEO satellite, light velocity, carrier frequency, and transmission distance from STAR-RIS to LEO satellite, respectively. And, we model the wireless channel Q_n as a shadowed Rician fading channel as follows [12]

$$Q_n = Q_{\mathrm{LOS},n} + Q_{\mathrm{NLOS},n}, \tag{2}$$

where $Q_{\mathrm{LOS},n}$ denotes the line-of-sight (LOS) component which is modeled to follow $|Q_{\mathrm{LOS},n}| \sim \text{Nakagami}(m, \omega)$ with a shape parameter of m and a second parameter controlling spread of ω [12], And, $Q_{\mathrm{NLOS},n}$ denotes the non-LOS component which follows a complex Gaussian distribution with zero mean and the variance of b, i.e., $Q_{\mathrm{NLOS},n} \sim \mathcal{CN}(0, b)$. On the other hand, the n-th elements of $\mathbf{g}_{\mathrm{TS}}$ and $\mathbf{g}_{\mathrm{RS}}$ are modeled as Rician fading channels as follows

$$g_{\mathrm{TS}}^{n} = \sqrt{\frac{\kappa_{\mathrm{TS}}}{\kappa_{\mathrm{TS}}+1}} g_{\mathrm{LOS,TS}}^{n} + \sqrt{\frac{1}{\kappa_{\mathrm{TS}}+1}} g_{\mathrm{NLOS,TS}}^{n}, \tag{3}$$

$$g_{\mathrm{RS}}^{n} = \sqrt{\frac{\kappa_{\mathrm{RS}}}{\kappa_{\mathrm{RS}}+1}} g_{\mathrm{LOS,RS}}^{n} + \sqrt{\frac{1}{\kappa_{\mathrm{RS}}+1}} g_{\mathrm{NLOS,RS}}^{n}, \tag{4}$$

where $g_{\mathrm{NLOS,TS}}^{n}$ and $g_{\mathrm{NLOS,RS}}^{n}$ denote the non-LOS components which are modeled to follow $g_{\mathrm{NLOS,TS}}^{n} \sim \mathcal{CN}(0, d_{\mathrm{TS}}^{\alpha})$ and $g_{\mathrm{NLOS,RS}}^{n} \sim \mathcal{CN}(0, d_{\mathrm{RS}}^{\alpha})$, respectively. Herein, d_{TS} and d_{RS} represent the distance from the TUE to the STAR-RIS and from the RUE to the STAR-RIS, respectively, and α means a path loss exponent. Also, $g_{\mathrm{LOS,TS}}^{n}$ and $g_{\mathrm{LOS,RS}}^{n}$ denote LOS components which are deterministic as they can be expressed as path attenuation and phase delay over transmission distance, i.e., $|g_{\mathrm{LOS,TS}}^{n}| = \sqrt{d_{\mathrm{TS}}^{\alpha}}$ and $|g_{\mathrm{LOS,RS}}^{n}| = \sqrt{d_{\mathrm{RS}}^{\alpha}}$. Lastly, κ_{TS} and κ_{RS} are Rician factors for the STAR-RIS and TUE and for the STAR-RIS and RUE, respectively.

From now on, we define the amplitude and phase coefficients of the STAR-RIS for maximizing received signal-to-noise ratio (SNR). First, through (1), (3), and (4), we define the phase information $\angle h_{\mathrm{SL}}^{n}$, $\angle g_{\mathrm{TS}}^{n}$, and $\angle h_{\mathrm{RS}}^{n}$ as $\varphi_{\mathrm{SL}}^{n}(\in [0, 2\pi))$, $\phi_{\mathrm{TS}}^{n}(\in [0, 2\pi))$, and $\phi_{\mathrm{RS}}^{n}(\in [0, 2\pi))$, respectively. It is also assumed that the controller of STAR-RIS knows the perfect channel state information (CSI) as many related studies. Then, the phase shift profile of STAR-RIS for transmission and reflection regions can be defined as diagonal matrices $\mathbf{\Theta}_{\mathrm{T}}(\in \mathbb{C}^{N\times N})$ and $\mathbf{\Theta}_{\mathrm{R}}(\in \mathbb{C}^{N\times N})$, respectively. Thereof, the element in the n-th column of the n-th row, i.e., the diagonal element, can be represented to maximize the received SNR over the transmission and reflection regions as

$$[\mathbf{\Theta}_{\mathrm{T}}]_{n,n} = e^{j\theta_{\mathrm{T}}^{n}} = e^{-j(\varphi_{\mathrm{SL}}^{n}+\phi_{\mathrm{TS}}^{n})}, \tag{5}$$

$$[\mathbf{\Theta}_{\mathrm{R}}]_{n,n} = e^{\theta_{\mathrm{R}}^{n}} = e^{-j(\varphi_{\mathrm{SL}}^{n}+\phi_{\mathrm{RS}}^{n}+\delta)}, \tag{6}$$

where an operator, $[\cdot]_{n,n}$, denotes an element in the n-th column of the n-th row. In (5) and (6), it is designed to match each phase when receiving at the LEO by inverting the phases of the channels from the STAR-RIS to each UE and LEO. In addition, in (6), the δ is related to constellation rotation to maximize the minimum inter-constellation distance. In STAR-RIS, the power splits for transmission and reflection regions are also defined as diagonal matrices $\boldsymbol{\beta}_{\mathrm{T}}(\in \mathbb{C}^{N\times N})$ and $\boldsymbol{\beta}_{\mathrm{R}}(\in \mathbb{C}^{N\times N})$, respectively. In fact, it is correct to obtain the power split ratio for each diagonal element of $\boldsymbol{\beta}_{\mathrm{T}}$ and $\boldsymbol{\beta}_{\mathrm{R}}$, but since the computational complexity is high, the same power split ratio is applied to all elements, i.e., $\boldsymbol{\beta}_{\mathrm{T}} = \beta_{\mathrm{T}} \cdot \mathbf{I}_N$ and $\boldsymbol{\beta}_{\mathrm{R}} = \beta_{\mathrm{R}} \cdot \mathbf{I}_N$ where $\beta_{\mathrm{R}} = 1 - \beta_{\mathrm{T}}$ and $\mathbf{I}_N$ denotes the N-dimensional identity matrix. Then, the power split ratio can be derived as the ratio of channel gains from each UE to LEO in transmission and reflection region as follows

$$\frac{\beta_{\mathrm{T}}|\mathbf{g}_{\mathrm{TS}}\mathbf{\Theta}_{\mathrm{T}}\mathbf{h}_{\mathrm{SL}}|^2}{(1-\beta_{\mathrm{T}})|\mathbf{g}_{\mathrm{RS}}\mathbf{\Theta}_{\mathrm{R}}\mathbf{h}_{\mathrm{SL}}|^2} = R, \tag{7}$$

where R can be adjusted for various purposes. In this paper, R is set to maximize the minimum distance between constellations to improve BER performance. Considering the quadrature phase shift keying (QPSK) modulation, the optimal δ and R for both the JML and SIC detector are known in [11].

Therefore, the received signal at the LEO is given by

$$y = \sqrt{P_{\mathrm{T}}}\beta_{\mathrm{T}}\mathbf{g}_{\mathrm{TS}}\mathbf{\Theta}_{\mathrm{T}}\mathbf{h}_{\mathrm{SL}}x_{\mathrm{T}} + \sqrt{P_{\mathrm{R}}}\beta_{\mathrm{R}}\mathbf{g}_{\mathrm{RS}}\mathbf{\Theta}_{\mathrm{R}}\mathbf{h}_{\mathrm{SL}}x_{\mathrm{R}} + n, \tag{8}$$

where n denotes the additive white Gaussian noise and it is assumed that $n \sim \mathcal{CN}(0, \sigma_n^2)$. Also, let $\Gamma \in \{\mathrm{T}, \mathrm{R}\}$ be a subscript designating the corresponding region, P_Γ and x_Γ mean the transmit power and symbol for UE in Γ region. Finally, we utilize the JML detector to retrieve transmit symbols for transmission and reflection region as

$$\hat{\mathbf{x}} = \underset{x_{\mathrm{T}}, x_{\mathrm{R}} \in \chi}{\arg\min} |y - \beta_{\mathrm{T}}\mathbf{g}_{\mathrm{TS}}\mathbf{\Theta}_{\mathrm{T}}\mathbf{h}_{\mathrm{SL}}x_{\mathrm{T}} - \beta_{\mathrm{R}}\mathbf{g}_{\mathrm{RS}}\mathbf{\Theta}_{\mathrm{R}}\mathbf{h}_{\mathrm{SL}}x_{\mathrm{R}}|^2; \tag{9}$$

where χ denotes the candidate set of modulation symbols.

III. SIMULATION RESULTS

In this section, we show the average BER performance of the STAR-RIS-NOMA when employing constellation scaling and rotation for LEO satellite networks. We considered only two UEs that exclusively exist in the transmission and reflection regions. In addition, it is assumed that there is no direct path from each UE to LEO due to the su rrounding terrain. We set the carrier frequency to 20GHz, the distance from LEO to the STAR-RIS, d_{SL}, to 550km, the number of elements within the STAR-RIS to 500, and the path loss exponent to 2. For channel modeling, we set the antenna gain of LEO to 43dB, Rician factors to $\kappa_{\mathrm{TS}} = \kappa_{\mathrm{RS}} = 10$, and shadowed Rician parameter to $(b, m, \omega) = (19.4, 0.158, 1.29)$ [6]. In addition,

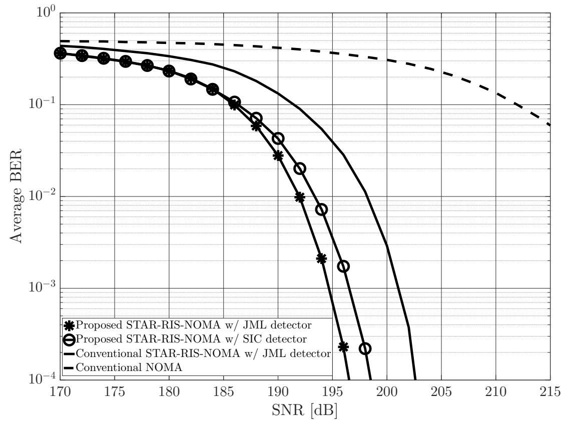

Fig. 2. BER performance of the LEO satellite communication system with STAR-RIS-NOMA when the number of Elements is 500, $(d_{\mathrm{SL}}, d_{\mathrm{TS}}, d_{\mathrm{RS}}) = (550\mathrm{km}, 10\mathrm{m}, 30\mathrm{m})$.

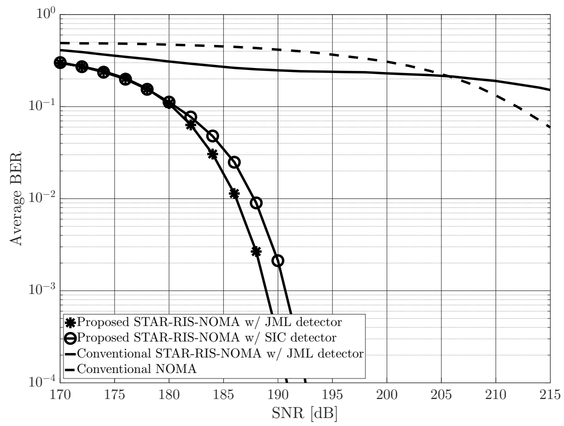

Fig. 3. BER performance of the LEO satellite communication system with STAR-RIS-NOMA when the number of Elements is 500, $(d_{\mathrm{SL}}, d_{\mathrm{TS}}, d_{\mathrm{RS}}) = (550\mathrm{km}, 10\mathrm{m}, 10\mathrm{m})$.

considering QPSK modulation, we set optimal values for R and δ related to constellation scaling and rotation as [11].

Fig. 2 shows the average BER performance according to SNR where the average BER implies the average value of each BER of TUE and RUE. At this time, the distance from TUE to STAR-RIS was set to 10m, and the distance from RUE to STAR-RIS was 30m. In Fig. 2, the proposed STAR-RIS-NOMA refers to a technique that applied constellation scaling and rotation, and conventional STAR-RIS-NOMA refers to a scheme without them. In addition, the conventional NOMA represents the result of applying two-user NOMA assuming that there is a direct path between LEO and all UEs without the aid of the STAR-RIS. In this environment, when LEO receives uplink NOMA data, although the constellations do not overlap or the minimum distance between constellations does not rapidly decrease due to the difference in channel gain, the application of constellation scaling and rotation gives a large gain in the BER performance by considering the optimized power split ratio and rotation angle. Furthermore, it can also be confirmed that the best BER performance is achieved when using the JML detector.

On the other hand, Fig. 3 shows the average BER performance varying SNR when the distance to STAR-RIS was set to 10m for both TUE and RUE. In this case, each signal constellation has a similar channel gain, resulting in overlapping or the minimum distance between constellations greatly reduced. Here, it can be seen that the superior BER performance is obtained by effectively applying constellation scaling and rotation. In other words, it is confirmed that the proposed constellation scaling and rotation-based STAR-RIS-NOMA with the JML detector can significantly improve the BER performance in LEO satellite networks.

IV. Conclusion

In this paper, we proposed the constellation scaling and rotation-based STAR-RIS-NOMA technique with the JML detector for LEO satellite networks. We focused on the performance deterioration that may occur when two UEs have similar channel gains in uplink, and we solved the problem by maximizing both the received SNR and minimum inter-constellation distance. Through extensive computer simulations, we verified that the proposed technique significantly improves the BER performance of the STAR-RIS-NOMA in LEO satellite networks.

Acknowledgment

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