# Robust Resource Allocation in RSMA-Based STAR-RIS-Aided HAP Communication Networks with Imperfect SIC

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***Abstract*—The next generation of wireless communication networks must offer robust connectivity to serve users in remote or disaster-stricken regions where terrestrial infrastructure is unavailable or compromised. High-altitude platforms (HAPs), functioning as non-terrestrial network (NTN) nodes, can rapidly restore coverage and extend service reach by transmitting directly to ground users. To further enhance communication performance, simultaneously transmitting and reflecting reconfigurable intelligent surfaces (STAR-RIS) can be deployed alongside HAPs, intelligently shaping the wireless channel to improve channel reliability. In this work, we investigate a HAP-assisted NTN in which a STAR-RIS aids downlink transmission to multiple ground users under a rate-splitting multiple access (RSMA) protocol with imperfect successive interference cancellation (SIC). The joint design of power allocation at the HAP and STAR-RIS beamforming presents a challenging non-convex problem because of the coupled rate expressions and rank-one constraints on the STAR-RIS matrices. To address this, we introduce auxiliary variables and apply successive convex approximation (SCA) to convexify rate functions, while employing a difference-of-convex (DC) programming approach to handle the rank-one requirement. An alternating optimization framework is then developed to iteratively solve a convex power allocation subproblem and a penalized semi-definite program for STAR-RIS beamforming. Simulation results show the efficacy of the proposed framework, showing excellent performance even under imperfect SIC and with discretized phase shifts at the STAR-RIS.**

## I. Introduction

The terrestrial communication infrastructure has been extensively optimized to ensure efficient and robust services for connected users. However, in remote areas where the low population density makes terrestrial network deployment economically infeasible, or in regions where terrestrial communication systems have been destroyed due to natural disasters, non-terrestrial networks (NTNs) can serve as an alternative or complementary communication solution [1], [2]. Additionally, in urban areas experiencing a temporary surge in user demand, such as during sporting or cultural events, NTNs can help alleviate the burden on existing terrestrial networks by providing a parallel network. High-altitude platforms (HAPs) are an example of NTN nodes that can deliver communication services to users across large areas and have demonstrated excellent performance [3].

In wireless communication systems, spectrum sharing has been shown to enhance spectral efficiency of the network [4], [5]. Motivated by the benefits, the work in [6] optimized user grouping in a Non-orthogonal multiple access (NOMA)-based HAP-assisted communication system to maximize the sum rate. Similarly, [7] focused on power allocation in NOMA-based HAP networks to achieve the same objective. Although NOMA performs well when only two users share a channel, its feasibility diminishes as the number of users grows. This is due to the increased complexity of successive interference cancellation (SIC) and the problem of SIC error propagation [8].

Rate-splitting multiple access (RSMA) has emerged as an attractive solution for spectrum sharing in large communication systems. In RSMA, each user's message is split into two parts: a private message, which is encoded with a user-specific codebook, and a common message, which combines parts of all users' messages and is encoded with a public codebook accessible to all users [9]. Upon reception, all users decode the common message first, extract their portion, and then remove the common message's interference from the received signal. Finally, each user decodes its private message, which only experiences interference from other users' private messages and not from the common message [10]. Consequently, RSMA requires each user to apply SIC only once, regardless of the total number of users. This approach significantly reduces SIC complexity and mitigates the error propagation issues faced by NOMA [11].

Considering RSMA-aided HAP communication networks, the authors in [12] proposed a framework to improve the secrecy of the network, while the work in [13] presented an optimization framework for rate maximization. In the context

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of RSMA-aided HAP communication networks, existing studies have developed optimization frameworks for enhancing secrecy and maximizing rates. However, these works consider perfect SIC, which may not fully reflect the challenges encountered in practical scenarios.

In wireless communication systems, where the distance between transmitter and receiver is large, large-scale fading can significantly degrade the received signal, resulting in poor performance. To handle this concern, reconfigurable intelligent surfaces (RIS), have been introduced. RIS can manipulate the phases of incident signals to improve channel characteristics [14], [15]. In the context of RIS-aided NTNs, the authors in [16] proposed a scheme to maximize the sum rate. Similarly, the authors in [17] proposed a resource allocation framework for maximizing energy efficiency in RSMA-RIS NTNs under perfect SIC assumptions. However, the joint consideration of RSMA and RIS makes the problem highly complex and non-convex. To address this, [17] employed a reinforcement learning-based solution, which requires extensive training and retraining whenever the number of users changes, making it less flexible for dynamic systems.

Furthermore, simple reflective RIS is well-suited for scenarios with fixed receivers, as it can only reflect signals towards the reflective side. For dynamic systems with mobile users, simultaneously transmitting and reflecting (STAR)-RIS is a more suitable candidate since it can serve users on both sides of the incident signal [18]. The authors in [19] optimized STAR-RIS beamforming for energy efficiency maximization in STAR-RIS-aided NOMA systems, while the work in [20] optimized beamforming for sum rate maximization in STAR-RIS-based NTNs. Despite the advantages of STAR-RIS over conventional RIS, it introduces additional complexity due to coupled transmit and reflection beamforming, making the problem more challenging.

The combination of RSMA with STAR-RIS can provide further benefits in HAP networks by enhancing spectral efficiency and mitigating pathloss effects. In this work, we optimize power allocation and STAR-RIS beamforming in a HAP-based communication network under practical imperfect SIC conditions. The optimization problem is formulated subject to the rate requirements of ground users, the power budget at the HAP, and RIS beamforming constraints. Instead of providing an unscalable framework, we propose a scalable technique that accommodates any number of users and RIS elements. The proposed scheme involves transforming the problem into a convex form using mathematical transformations and convex approximations, and then employing convex solvers to obtain the solution.

## II. System model and Problem Formulation

We consider an NTN where a HAP provides service to $K$ ground users in a remote or disaster stricken area, with communication aided by a STAR-RIS containing $N$ elements as shown in Fig. 1. The transmission follows RSMA protocol with imperfect SIC at the receivers. All channels follow Rician fading, where the channel between any two nodes consists

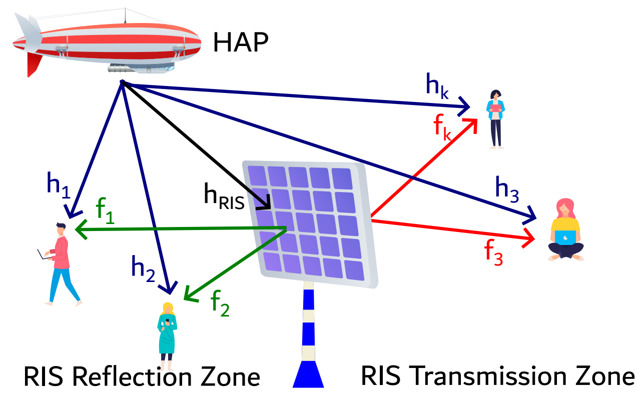


Fig. 1. The figure illustrates a system in which a HAP serves multiple ground users with the assistance of a STAR-RIS deployed to enhance the channel conditions.

of both LoS and NLoS components. Specifically, the Rician channel between nodes $C$ and $D$ is given by:

$$h_{CD} = \Psi \left( \sqrt{\frac{\kappa}{1+\kappa}} h_{CD}^{\mathrm{LoS}} + \sqrt{\frac{1}{1+\kappa}} h_{CD}^{\mathrm{NLoS}} \right) \quad (1)$$

Here, $\Psi$ represents the large-scale fading and is modeled as the inverse squared distance. The parameter $\kappa$ represents the Rician factor. The term $h_{CD}^{\mathrm{LoS}}$ corresponds to the deterministic line-of-sight (LoS) component, which can be computed from the known geometry between the transmitter and receiver. In contrast, the non-line-of-sight (NLoS) component $h_{CD}^{\mathrm{NLoS}}$ follows a circularly symmetric complex normal distribution, i.e., $h_{CD}^{\mathrm{NLoS}} \sim \mathcal{CN}(0,1)$, representing the scattered multipath components with zero mean and unit variance.

The channel from HAP to RIS is denoted as $h_{\mathrm{RIS}} \in \mathbb{C}^{N\times 1}$, the channel from HAP to the $k$th user is $h_k \in \mathbb{C}^{1\times 1}$, and from RIS to the $k$th user is $f_k^H \in \mathbb{C}^{1\times N}$. We consider that $K_T$ users are present in the transmissive region of the RIS and $K_R$ users are in the reflection region such that $K_T + K_R = K$.

The transmission and reflection beamforming vectors of the STAR-RIS are as:

$$c_y = \left[ \sqrt{b_1^y} e^{j\theta_1^y}, \sqrt{b_2^y} e^{j\theta_2^y}, ..., \sqrt{b_N^y} e^{j\theta_N^y} \right], \quad (2)$$

where $y \in \{r,t\}$ indicates whether the signal is reflected or transmitted by the RIS, with $\sqrt{b_n^r} \in [0,1]$, $\sqrt{b_n^t} \in [0,1]$, $\theta_n^r \in [0,2\pi)$, and $\theta_n^t \in [0,2\pi)$. When the surface magnetic and electric impedance of STAR-RIS is adjustable, $\theta_n^r$ and $\theta_n^t$ are independent [21]. However, $\sqrt{b_n^r}$ and $\sqrt{b_n^t}$ must satisfy the energy conservation requirement $b_n^r + b_n^t = 1, \forall n$.

Let $\phi_y = \mathrm{diag}(c_y) \in \mathbb{C}^{N\times N}$. Then the received signal at the $k$th user is:

$$z_k^y = g_k \sqrt{P_k} s_k + \sum_{\substack{i=1 \\ i\neq k}}^{K} g_k \sqrt{P_i} s_i + g_k \sqrt{P_c} s_c + \eta, \quad (3)$$

where $g_k = (h_k + f_k^H \phi_y h_{\text{RIS}})$ with $y \in \{r, t\}$ depending on the user's region, $P_k$ is the power allocated to the $k$th user's private message, $P_c$ is the power allocated to the common message, and $\eta$ denotes AWGN.

Considering imperfect SIC with residual interference factor $\beta \in [0, 1]$, the private rate of the $k$th user is:

$$R_k^p = B \log_2 \left( 1 + \frac{|g_k|^2 P_k}{|g_k|^2 \sum_{\substack{i=1 \\ i \neq k}}^K P_i + \beta |g_k|^2 P_c + \sigma^2} \right), \quad (4)$$

where $\sigma^2$ is the AWGN variance and $B$ denotes the total bandwidth of the system. The common rate is:

$$R^c = \min_k B \log_2 \left( 1 + \frac{|g_k|^2 P_c}{|g_k|^2 \sum_{i=1}^K P_i + \sigma^2} \right). \quad (5)$$

In this work, we aim to optimize the considered system to achieve maximum sum rate. The considered problem is formulated as:

$$\max_{P_k, P_c, \phi_r, \phi_t, r_k} \sum_{k=1}^K R_k^p + r_k, \quad (6)$$

$$\text{s.t.: } R_k^p + r_k \geq R_{\text{min}}, \forall k, \quad (7)$$

$$\sum_{k=1}^K r_k \leq R^c, \quad (8)$$

$$\sum_{k=1}^K P_k + P_c \leq P_{\text{max}}, \quad (9)$$

$$b_n^r + b_n^t = 1, \forall n, \quad (10)$$

$$\theta_n^y \in [0, 2\pi), \forall n, \forall y \in \{r, t\}, \quad (11)$$

where the first constraint ensures that each user's minimum rate requirement $R_{\text{min}}$ is satisfied. The second constraint guarantees that the sum of common message allocations $r_k$ for all users does not exceed the achievable common rate $R^c$. The third constraint enforces the total transmit power budget $P_{\text{max}}$ at the HAP. The fourth constraint maintains the energy conservation principle of the STAR-RIS, requiring $b_n^r + b_n^t = 1$ for each element $n$. The fifth and final constraint restricts the phase shifts $\theta_n^y$ to practical implementation ranges of $[0, 2\pi)$ for both reflection and transmission modes.

## III. Proposed Solution

The considered problem is highly complex and non-convex in nature. To recast the problem into a solvable form, we introduce several auxiliary variables. Let us define $W_k = \text{diag}(f_k^H) h_{\text{RIS}}$, which represents the combined effect of the UAV-to-RIS and the RIS-to-user channel. We then construct the matrix:

$$G_k = \begin{bmatrix} W_k W_k^H & W_k h_k^H \\ W_k^H h_k & 0 \end{bmatrix}, \quad (12)$$

where $h_k$ is the direct channel from the HAP to the $k$-th user. Furthermore, we define the augmented vector and matrix:

$$\overline{c_y} = \begin{bmatrix} c_y \\ 1 \end{bmatrix}, \quad A_y = \overline{c_y} \overline{c_y}^H, \quad (13)$$

with $A_y \succeq 0$ and $\text{rank}(A_y) = 1$ by construction. These variable transformations allow us to reformulate the original problem while maintaining equivalence.

Then, applying the logarithm property $\log(\lambda_1/\lambda_2) = \log(\lambda_1) - \log(\lambda_2)$, we can express the private rate of the $k$th user as:

$$\overline{R}_k^p = B \log_2 \Bigg( P_k(\text{Tr}(G_k A_y) + |h_k|^2) + (\text{Tr}(G_k A_y) + |h_k|^2) \sum_{\substack{i=1 \\ i \neq k}}^K P_i + \beta P_c (\text{Tr}(G_k A_y) + |h_k|^2) + \sigma^2 \Bigg) - B \log_2 \Bigg( \sum_{\substack{i=1 \\ i \neq k}}^K P_i (\text{Tr}(G_k A_y) + |h_k|^2) + \beta P_c (\text{Tr}(G_k A_y) + |h_k|^2) + \sigma^2 \Bigg). \quad (14)$$

Similarly, the common rate expression becomes:

$$\overline{R}^c = \min_k B \log_2 \Bigg( P_c(\text{Tr}(G_k A_y) + |h_k|^2) + (\text{Tr}(G_k A_y) + |h_k|^2) \sum_{i=1}^K P_i + \sigma^2 \Bigg) - B \log_2 \Bigg( (\text{Tr}(G_k A_y) + |h_k|^2) \sum_{i=1}^K P_i + \sigma^2 \Bigg). \quad (15)$$

The transformed optimization problem can now be written as:

$$\max_{P_k, P_c, A_r, A_t, r_k} \sum_{k=1}^K \overline{R}_k^p + r_k, \quad (16)$$

$$\text{s.t.: } \overline{R}_k^p + r_k \geq R_{\text{min}}, \forall k, \quad (17)$$

$$\sum_{k=1}^K r_k \leq \overline{R}^c, \quad (18)$$

$$\sum_{k=1}^K P_k + P_c \leq P_{\text{max}}, \quad (19)$$

$$\text{diag}(A_r + A_t) = \mathbf{1}^N, \forall n, \quad (20)$$

$$A_y \succeq 0, \quad (21)$$

$$\text{rank}(A_y) = 1. \quad (22)$$

The rate expressions still contain non-convex components due to the $-\log$ terms. To address this challenge, we first introduce auxiliary variables $\tau_k$ and $\lambda_k$ that provide upper bounds to the interference-plus-noise terms:

$$\tau_k \geq (\text{Tr}(G_k A_y) + |h_k|^2) \sum_{\substack{i=1 \\ i \neq k}}^K P_i + \beta P_c (\text{Tr}(G_k A_y) + |h_k|^2) + \sigma^2, \forall k, \quad (23)$$

$$\lambda_k \geq (\text{Tr}(G_k A_y) + |h_k|^2) \sum_{i=1}^K P_i + \sigma^2, \forall k. \quad (24)$$

We then employ successive convex approximation (SCA) to transform the rate expressions into convex forms:

$$\hat{R}_k^p = B\log_2\Bigg(P_k(\mathrm{Tr}(G_kA_y)+|h_k|^2)+\sum_{\substack{i=1\\i\neq k}}^{K}P_i(\mathrm{Tr}(G_kA_y) + |h_k|^2)+\beta P_c(\mathrm{Tr}(G_kA_y)+|h_k|^2)+\sigma^2\Bigg)-\Bigg(B\log_2(\overline{\tau}_k) + \frac{B}{\overline{\tau}_k}(\tau_k-\overline{\tau}_k)\Bigg), \quad (25)$$

$$\hat{R}^c = \min_k B\log_2\Bigg(P_c(\mathrm{Tr}(G_kA_y)+|h_k|^2)+(\mathrm{Tr}(G_kA_y)+ |h_k|^2)\sum_{i=1}^{K}P_i+\sigma^2\Bigg)-\Bigg(B\log_2(\overline{\lambda}_k)+\frac{B}{\overline{\lambda}_k}(\lambda_k-\overline{\lambda}_k)\Bigg), \quad (26)$$

where $\overline{\tau}_k$ and $\overline{\lambda}_k$ denote the values of $\tau_k$ and $\lambda_k$ obtained in the previous iteration, respectively.
The power allocation optimization subproblem now becomes convex:

$$\max_{P_k,P_c,r_k,\tau_k,\lambda_k} \sum_{k=1}^{K}\hat{R}_k^p + r_k, \quad (27)$$
$$\text{s.t.: } (17),(18),(19),(23),(24),$$

allowing efficient solution via widely used convex optimization solvers like CVX.

Then, for the RIS beamforming optimization, we face the non-convex rank-1 constraint in (22). We address this through difference-of-convex (DC) programming, exploiting the relationship between the trace and spectral norm:

$$\mathrm{rank}(A_y)=1 \leftrightarrow \mathrm{Tr}(A_y)-\|A_y\|_2=0, \quad (28)$$

where $\mathrm{Tr}(A_y)=\sum_{o=1}^{N+1}\mu_o^y$ represents the sum of all singular values and $\|A_y\|_2=\mu_1^y$ denotes the largest singular value (spectral norm) of $A_y$. Here, $\mu_o^y$ represents the $o$-th largest singular value of $A_y$.

To handle the non-convex spectral norm, we employ Taylor approximation around the solution from the previous iteration ($\hat{A}_y$):

$$\|A_y\|_2 \geq \|\hat{A}_y\|_2+\mathrm{Tr}(\hat{\kappa}_{\max}\hat{\kappa}_{\max}^H(A_y-\hat{A}_y))=\overline{\|A_y\|}_2, \quad (29)$$

where $\hat{\kappa}_{\max}$ is the eigenvector linked to the principal eigenvalue of $\hat{A}_y$. This approximation maintains convexity while ensuring convergence. We incorporate the rank-1 constraint into the objective function as a penalty term. With this, the problem becomes:

$$\max_{A_r,A_t,r_k,\tau_k,\lambda_k}\sum_{k=1}^{K}\hat{R}_k^p+r_k-\Lambda(\mathrm{Tr}(A_r)-\overline{\|A_r\|}_2) - \Lambda(\mathrm{Tr}(A_t)-\overline{\|A_t\|}_2), \quad (30)$$
$$\text{s.t.: } (17),(18),(20),(21),(23),(24),$$

TABLE I
VALUES OF SYSTEM PARAMETERS FOR SIMULATIONS

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $B$ | 1 MHz | $\kappa$ | 3 |
| $\sigma^2$ | $10^{-7}$ | $R_{\min}$ | 50 kbps |
| $\beta$ | 0.1 | $N$ | 16 |
| $K_r$=$K_t$ | 2 | HAP height | 18 Km |

where $\Lambda$ is a large positive penalty parameter that enforces the rank-1 constraint. The resulting problem is a standard semi-definite program (SDP) that can be efficiently solved using MOSEK-enabled CVX solver.

*Alternating optimization:* We solve the problem iteratively by alternating between two subproblems: (1) optimizing power allocation with fixed RIS parameters, and (2) optimizing RIS beamforming using updated power values. Each subproblem's solution feeds into the next iteration, progressively improving the sum-rate until convergence. This approach ensures monotonic improvement while maintaining tractability of the original non-convex problem.

*Computational Complexity:* The power allocation subproblem has a computational complexity of $\mathcal{O}(I_1K^3)$ where $I_1$ denotes the number of iterations required for convergence, while the RIS beamforming SDP solution has a complexity of $\mathcal{O}(I_2N^{3.5})$ where $I_2$ is the number of iterations for convergence [22]. Then, the complexity of the alternating optimization framework can be expressed as $\mathcal{O}(I_3(I_1K^3+I_2N^{3.5}))$, where $I_3$ denotes the iterations needed for the outer alternating optimization loop to converge.

## IV. SIMULATION RESULTS

The system parameters used in the simulations are provided in Table I, unless stated otherwise.

Figure 2 illustrates the impact of changing the available transmission power ($P_{\max}$) at the HAP for the cases of perfect SIC ($\beta=0$) and imperfect SIC with $\beta=0.1$, which corresponds to a 10% residual interference due to SIC errors. While the system with perfect SIC, as anticipated, exhibits significantly superior performance, this scenario is highly idealistic, particularly in practical STAR-RIS-assisted systems where passive elements introduce additional challenges. The results further reveal that even with a significant SIC impairment level of $\beta=0.1$, the system maintains robust performance, and the achievable sum rate consistently improves with increasing transmission power at the HAP.

Figure 3 demonstrates that increasing the number of RIS elements significantly enhances the system performance, as a larger RIS enables more precise beamforming toward the users. With a greater number of elements, the RIS can generate more focused beams, thereby improving the received SINR at the users and achieving higher sum rates even with the same total transmit power at the HAP. As shown in Fig. 3, when the number of RIS elements is increased from 16 to 25, a substantial performance gain of over 25% in the sum rate is observed. Moreover, the RIS equipped with 25 elements consistently outperforms the 16-element RIS across all values

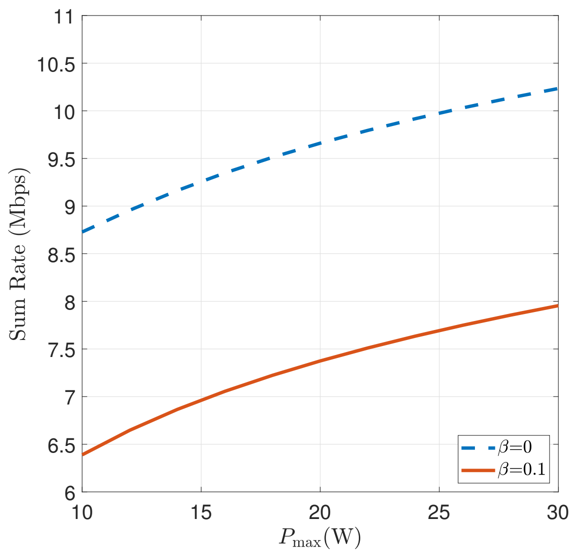


Fig. 2. Impact of varying the available transmission power ($P_{\max}$) at the HAP under perfect and imperfect SIC conditions.

of $P_{\max}$ at the HAP, further highlighting the benefits of scaling the RIS size.

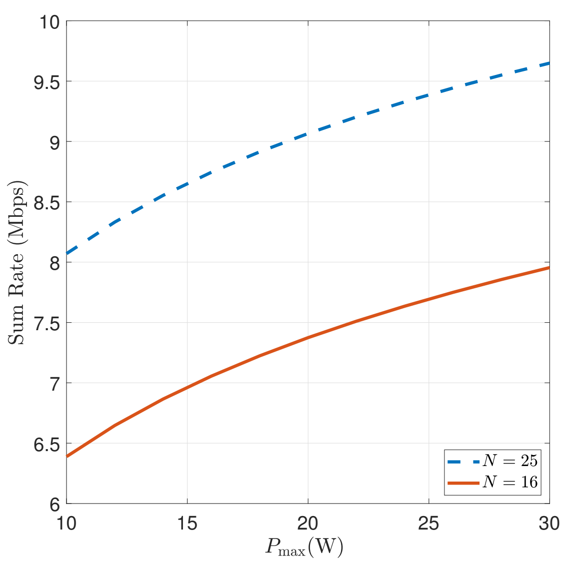


Fig. 3. Impact of increasing the number of RIS elements on the sum rate.

In RSMA systems, the private message of each user experiences interference from the private messages of all other users sharing the same channel, while the common message is additionally interfered by all private messages. Consequently, the overall interference temperature of the system escalates with the number of users. Since STAR-RIS can only perform passive beamforming (manipulating the phases of incident signals while maintaining fixed amplitudes) the power allocation for each user's signal in the superimposed transmission remains unchanged. As a result, as the number of users increases, a gradual degradation in the system's sum rate is observed, as depicted in Fig. 4. This occurs because when a new user is introduced, a portion of the available power must be allocated to meet its minimum rate requirement, thereby reducing the power available for the user with the best channel conditions. Furthermore, the additional user contributes to higher interference levels, ultimately reducing the overall sum rate of the system.

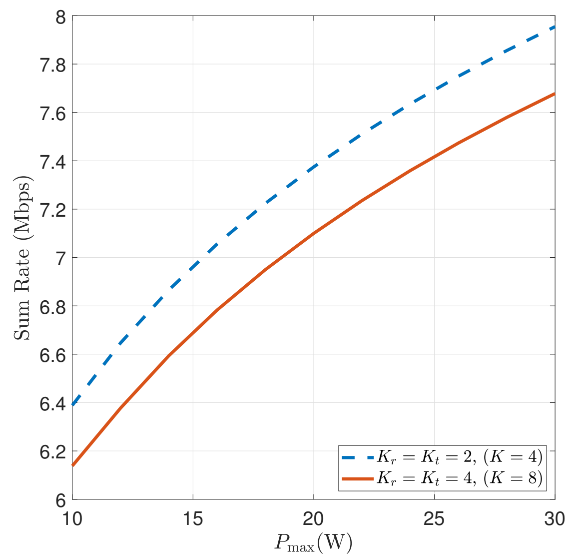


Fig. 4. Impact of increasing the number of users on the sum rate in an RSMA system assisted by STAR-RIS.

In all the previous results, we optimize the RIS beamforming under the assumption of continuous phase shifts, which, while theoretically valid, introduces high computational complexity and may not be feasible in practical implementations. To address this limitation, Fig. 5 evaluates the system performance when the continuous phase shifts obtained from the optimal solution are quantized into 4 discrete levels. The results demonstrate that phase discretization leads to a significant degradation in the achievable system rate. Specifically, the continuous phase shift solution consistently outperforms its discrete counterpart across all values of $P_{\max}$, underscoring the fundamental tradeoff between complexity and performance in RIS-assisted systems.

## V. Conclusion

In this work, we developed a robust and scalable resource allocation framework for maximizing the sum rate in an RSMA-based STAR-RIS-assisted HAP communication network under imperfect SIC conditions. The proposed approach transformed the original challenging non-convex problem, characterized by coupled rate expressions and rank-one constraints into a convex problem using SCA, DC programming, and other mathematical transformations. An alternating optimization algorithm

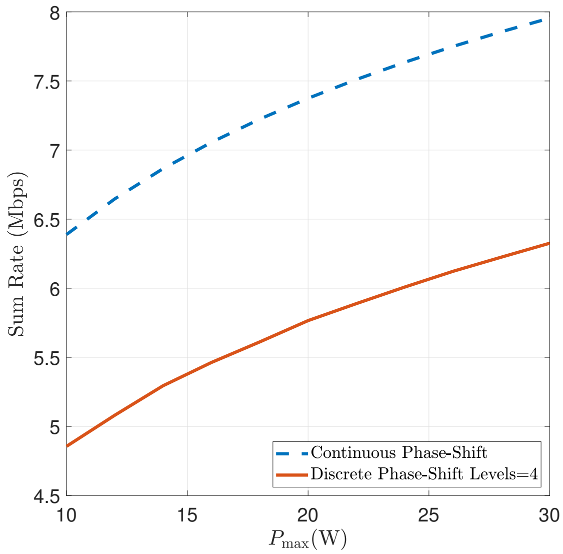


Fig. 5. Comparison of system performance with continuous and quantized (4-level) RIS phase shifts.

was proposed to jointly handle power allocation and STAR-RIS beamforming in an iterative manner, ensuring monotonic improvement of the objective. Results validated the efficacy of the proposed framework, showing robust performance under imperfect SIC and confirming scalability with the number of users and RIS elements. Moreover, the results highlighted the tradeoff between the phase shift resolution and system performance, offering insights for practical deployment of STAR-RIS in dynamic HAP-assisted NTNs.

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