Reflecting Intelligent Surface Aided Downlink Transmission in Ultra-Dense LEO Satellite Networks

Xin Zhang*, Ting Ma*, Xiaohan Qin*, Yilei Wang*, Haibo Zhou*
*School of Electronic Science and Engineering, Nanjing University, Nanjing, China, 210023
Email: zanxin@smail.nju.edu.cn, majiawan27@163.com, xhderemail@smail.nju.edu.cn,
yileiwang@smail.nju.edu.cn, haibozhou@nju.edu.cn

2023 IEEE 23rd International Conference on Communication Technology (ICCT) | 979-8-3503-2595-9/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICCT59356.2023.10419516

***Abstract*—Reconfigurable intelligent surface (RIS) can co-transmit with ultra-dense low-earth-orbit (LEO) satellites to improve the spectral efficiency and energy utilization of the entire satellite network. In this paper, we study RIS-aided downlink communication system for multi-user in urban scenarios in ultra-dense LEO satellite networks (UDLNs). We set up an optimization model which aims to maximize the sum rate of users in UDLN under the power constraints of LEO satellites. To tackle the intricacies of the sum rate maximization challenge, we employ alternative optimization (AO) to decouple the initial problem into three subproblems including beamforming, user association, and RIS phase shift optimization. We then employ successive convex approximation (SCA) to render the nonconvex subproblems into convex which can be easily solved. Consequently, an iterative algorithm is proposed to converge to the stationary point of the original optimization. Simulation results demonstrate that our algorithm attains optimal sum rates in comparison to other baseline algorithms.**

***Index Terms*—Ultra-dense LEO satellite network, reconfigurable intelligent surface (RIS), sum rate maximization, alternative optimization.**

I. INTRODUCTION

In recent years, ultra dense low-earth-orbit (LEO) satellite networks (UDLNs) emerges as a promising paradigm for the space segment to be integrated with terrestrial networks [1]. UDLN has shown enormous potential not only in achieving seamless global coverage for remote regions, but also in providing massive and high-capacity access for hotspots [2]. However, in urban scenarios, high-rise skyscrapers will block the line-of-sight (LOS) paths from LEO satellites to terrestrial mobile users and reduce the coverage area of LEO satellites, leading to poor LEO satellite availability in street [3]. To overcome the LOS limitation by LEO satellites for street-level communications in urban scenarios, a key conceptual solution is to deploy reconfigurable intelligent surface (RIS) [4]. RIS consists of massive low-cost reflection components, which is capable to reflect incoming signals with adaptable phase shifts and change signal propagation path bypass the obstacles [5]. By installing RIS on the outer wall of the high-rise skyscrapers, the efficient street-level communication service can be realized through the reflection of the building.

Introducing RIS to UDLN in urban areas can significantly enhance signal coverage, improve signal quality and reduce the power consumption of satellite networks, which is of remarkable application prospects. But still, there are many challenges for RIS to be applied in UDLN, such as power limitations of LEO satellites, difficulty of beam tracking due to high-speed moving satellites, and rate constraints of different users. To maximize the data rate of single user, Zheng *et al.* [6] proposed semidefinite relaxation algorithm based optimal beamforming and phase shifting design for double RIS. Deng *et al.* [7] designed RIS-aided multi-satellite communication scheme including rate maximization via holographic beamforming and LEO satellite tracking in the uplink scenario of single user and multiple satellites. However, most of existing researches on RIS-aided LEO communication systems pay more attention to single user without considering the multi-user scenarios. Besides, to obtain the overall network gain provided by multi user scenarios, it is of critical importance to investigate the phase optimization problem for the spatial interference suppression among the multiple users and the cooperation between different elements of the RIS. Therefore, how to design an efficient and applicable algorithm for multi user scenarios in UDLN to jointly optimize the beamforming and RIS phase shift remains a challenging issue.

Motivated by the above deliberation, in this paper, we investigate RIS-aided downlink communication system for the urban scenarios of multi-user in UDLN. Our objective is to optimize the sum rate of users while adhering to the power constraints of the LEO satellites. The main contributions of this paper are highlighted as follows:

- We formulate RIS aided ultra-dense LEO satellite downlink communication system in urban scenarios for multiple users. Optimization model which maximizes the sum rate of UDLN satisfying the power constraint of LEO satellites is set up in this paper.
- We decouple the origin problem of maximizing the sum rate into three separate subproblems and jointly solve beamforming, user association and RIS phase shift problems through alternative optimization (AO).
- The simulation outcomes demonstrate that our algorithm achieves the optimal sum rate compared with baseline algorithms, and thereby significantly improve the performance of UDLN.

The rest of this paper are structured as follows. Section II delineates the system model and presents the problem formulation for RIS aided downlink data transmission in UDLNs. Sections III introduces algorithm aimed at resolving the formulated optimization problem. Section IV provides illustrative outcomes that validate the effectiveness of the proposed algorithm. Conclusions are provided in Section V.

II. SYSTEM MODEL

In this section, we formulate RIS aided ultra-dense LEO satellite downlink communication model for sum rate maximization in urban scenarios.

A. Scenario Description

Mobile users in urban streets experience pronounced urban canyon effects, while signals transmitted from LEO satellites must cover extensive distances to reach these users. To optimize the performance of UDLN, as shown in Fig. 1, we consider a downlink communication system with aid of RIS in urban scenario of UDLN, which consists of L multi-antenna ultra dense LEO satellites denoted by $\mathcal{L} = \{1, 2, \dots, L\}$, K users denoted by $\mathcal{K} = \{1, 2, \dots, K\}$ each equipped with single antenna and a RIS.

Each LEO satellite employs a uniform planar array (UPA) comprising $M_S = M_{S,x} \times M_{S,y}$ antennas, with $M_{S,x}$ and $M_{S,y}$ representing the antenna numbers along the x and y axes, respectively. Simultaneously, the reconfigurable intelligent surface (RIS) comprises $M_R = M_{R,x} \times M_{R,y}$ reflecting elements, uniformly distributed along the x and y axes. Here, $M_{R,x}$ and $M_{R,y}$ signify the count of reflecting elements along the respective axes. The UPA array response vector $\mathbf{v}_S \in \mathbb{C}^{M_S \times 1}$ [8] is deduced as

$$\mathbf{v}_S = \mathbf{v}_S^x \otimes \mathbf{v}_S^y, \tag{1}$$

where $\otimes$ represents the Kronecker product of two vectors, $\mathbf{v}_S^x \in \mathbb{C}^{M_{S,x} \times 1}$ and $\mathbf{v}_S^y \in \mathbb{C}^{M_{S,y} \times 1}$ stand for x and y axes response vectors respectively.

B. Channel Model

Due to the obstacles like high buildings and trees, the direct links between LEO satellite and user are usually blocked. Let $\mathbf{g}_{m,k} \in \mathbb{C}^{M_S \times 1}$ represent the channel vector of the direct link from LEO satellite m to the user k. According to the channel characteristic of satellite to ground, the channel between LEO satellite m to the user k can be expressed as

$$\mathbf{g}_{m,k} = \frac{\sqrt{G_S G_u} c}{4\pi f_c d_{m,k}} \delta_{m,k}^S e^{-\frac{j2\pi}{\lambda} d_{m,k}} \mathbf{v}_S^T, \tag{2}$$

where G_S and G_u denote the antenna gain of LEO satellite and user, respectively. c represents the speed of light, f_c stands for the subcarrier frequency, and $d_{m,k}$ signifies the distance between LEO satellite m and user k, $\delta_{m,k}^S$ denote channel factor denoting Rayleigh fading model with factor σ_{Ray}^2 which is widely utilized in non line-of-sight (NLOS) propagations.

Let $\mathbf{H}_{m,R} \in \mathbb{C}^{M_S \times M_R}$ denote the channel matrix of the link from LEO satellite m to the RIS, which is expressed as

$$\mathbf{H}_{m,R} = \frac{\sqrt{G_S} c}{4\pi f_c d_{m,R}} \delta_{m,R} e^{-\frac{j2\pi}{\lambda} d_{m,R}} \mathbf{v}_R \mathbf{v}_S^T, \tag{3}$$

where $d_{m,R}$ is the distance between LEO m and RIS, $\delta_{m,R}$ is the channel factor of Rician fading model.

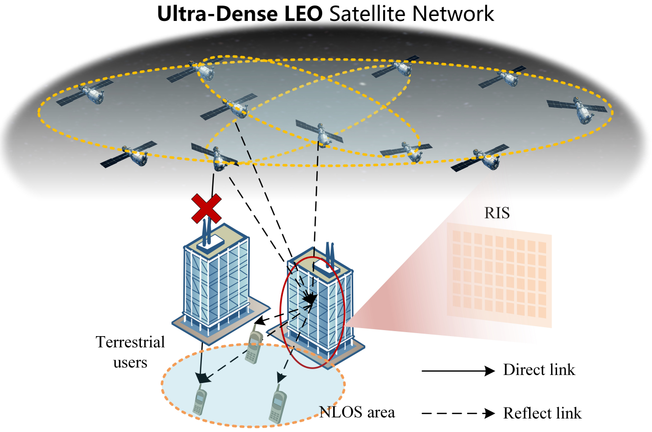

Fig. 1. RIS aided ultra-dense LEO satellite downlink communication in urban scenarios.

Let $\mathbf{l}_{R,k} \in \mathbb{C}^{M_R \times 1}$ denote the channel vector of the direct link from the RIS to the user k. Similarly, $\mathbf{l}_{R,k}$ is modeled as

$$\mathbf{l}_{R,k} = \frac{\sqrt{G_S G_u} c}{4\pi f_c d_{R,k}} \delta_{R,k} e^{-\frac{j2\pi}{\lambda} d_{R,k}} \mathbf{v}_R^T \tag{4}$$

where $\delta_{R,k}$ is the channel factor denoting Rician fading.

The link between LEO and user consists of two parts including direct link (LEO-user) and reflect link (LEO-RIS-user). The overall channel matrix from LEO m to user k is

$$\mathbf{h}_{m,k} = \mathbf{g}_{m,k} + \mathbf{l}_{R,k} \mathbf{\Theta} \mathbf{H}_{m,R}, \tag{5}$$

where $\mathbf{\Theta}$ corresponds to the diagonal matrix of RIS phase. $\Theta_i = e^{j\theta_i}$ indicates the phase shift of the i-th RIS element, where $\theta_i \in [0, 2\pi)$ is the phase angle.

C. Problem Formulation

The transmitted signal of LEO m is derived as

$$\mathbf{y}_m = \sum_{k=1}^{k=K} x_{m,k} s_{m,k} \mathbf{w}_{m,k} \tag{6}$$

where $s_{m,k}$ denotes the signal from LEO m user k and $E\left(\left|s_{m,k}\right|^2\right) = 1$. Meanwhile, $x_{m,k} \in \{0, 1\}$ denotes user satellite association $x_{m,k} = 1$ means user k is access to LEO satellite m, otherwise not. The data rate between LEO satellite m and user k is denoted as

$$R_{m,k} = \log_2 \left(\frac{\left|\mathbf{h}_{m,k} \mathbf{w}_{m,k}\right|^2 x_{m,k}}{\sum_{m'=1}^{L} \sum_{k' \neq k} \left|\mathbf{h}_{m,k} \mathbf{w}_{m',k'}\right|^2 x_{m',k'} + \sigma^2} + 1 \right). \tag{7}$$

This paper focuses on enhancing the downlink sum rate in the given context by jointly optimizing beamforming for each LEO satellites, the association of terrestrial users with LEO satellites, and the phase shifts matrix of RIS. The optimization goal is constrained by various factors, encompassing signal-to-interference-plus-noise ratio (SINR) restrictions for users, the boundaries of transmit power for each LEO satellite, and the limitations associated with user-to-satellite associations. Therefore, the mathematical formulation of the problem can be expressed as follows:

$$\text{(P)}: \quad \max_{\mathbf{w}_{m,k}, x_{m,k}, \boldsymbol{\Theta}} \quad \sum_{m=1}^{L}\sum_{k=1}^{K} R_{m,k} \tag{8}$$

$$\text{s.t.} \quad \sum_{k=1}^{K} x_{m,k} |\mathbf{w}_{m,k}|^2 \le P_0 \quad \forall m \in \mathcal{L}, \tag{8a}$$

$$\sum_{m=1}^{L} R_{m,k} \ge r_0 \quad \forall k \in \mathcal{K}, \tag{8b}$$

$$\sum_{m=1}^{L} x_{m,k} = 1 \quad \forall k \in \mathcal{K}, \tag{8c}$$

$$x_{m,k} \in \{0,1\} \quad \forall m \in \mathcal{L}, k \in \mathcal{K}, \tag{8d}$$

$$|\boldsymbol{\Theta}_{n,n}|^2 = 1 \quad \forall 1 \le n \le M_R, \tag{8e}$$

$$\boldsymbol{\Theta}_{n,j} = 0 \quad \forall j \neq n, 1 \le n, j \le M_R. \tag{8f}$$

where P_0 signifies the maximum allowable transmit power for each LEO satellite, while $r_0 > 0$ represents the minimum requisite transmit rate for each user. The constraint on the power of each LEO satellite is depicted in the formulation (8a). The transmit rate constraint is presented in constraint (8b). Each user k can only access one LEO satellite m within its reach at each time as shown in constraints (8c) and (8d). The phase constraints of each RIS element are shown in constraints (8e) and (8f).

III. ALGORITHM DESIGN

In this section, we propose AO based joint beamforming, user association and RIS phase shift (ABUR) algorithm. The transmit beamforming at LEO satellites, user association and RIS phase shifts are optimized iteratively and alternately until convergence is attained.

A. Beamforming Optimization

By fixing the user association variables $x_{m,k}$ and RIS phase shift Θ, original (P) is transferred into subproblem of beamforming optimization which is denoted as

$$\text{(P1)}: \quad \max_{\mathbf{w}_{m,k}} \quad \sum_{m=1}^{L}\sum_{k=1}^{K} R_{m,k} \tag{9}$$

$$\text{s.t.} \quad \sum_{k=1}^{K} x_{m,k} |\mathbf{w}_{m,k}|^2 \le P_0 \quad \forall m \in \mathcal{L}, k \in \mathcal{K}, \tag{9a}$$

$$\sum_{m=1}^{L} R_{m,k} \ge r_0 \quad \forall k \in \mathcal{K}, \tag{9b}$$

where $\mathbf{w}_{m,k} \in \mathbb{C}^{M_S \times 1} (1 \le m \le L, 1 \le n \le K)$ represents the optimization beamforming variable. We first introduce auxiliary variable $t_{m,k} (1 \le m \le L, 1 \le k \le K)$, the original beamforming subproblem is equivalent to

$$\max_{\mathbf{w}_{m,k}, t_{m,k}} \quad \sum_{m=1}^{L}\sum_{k=1}^{K} \log_2 t_{m,k} \tag{10}$$

$$\text{s.t.} \sum_{m=1}^{L} t_{m,k} \ge 2^{r_0} \quad \forall k \in \mathcal{K}, \tag{10a}$$

$$\sum_{k=1}^{K} x_{m,k} |\mathbf{w}_{m,k}|^2 \le P_0 \quad \forall m \in \mathcal{L}, \tag{10b}$$

$$t_{m,k} \le \frac{|\mathbf{h}_{m,k}\mathbf{w}_{m,k}|^2}{\sum_{m'=1}^{L}\sum_{k' \neq k} x_{m',k'} |\mathbf{h}_{m,k}\mathbf{w}_{m',k'}|^2 + \sigma^2} + 1$$
$$\forall m \in \mathcal{L}, k \in \mathcal{K}. \tag{10c}$$

Combining constraint (10a) with the nonconvex fractional equation constraint (10c), the constraints (10a) and (10c) in (10) can be written as (11) and (12) by introducing additional slack variables variable β_k [9].

$$\sum_{m=1}^{L} x_{m,k} |\mathbf{h}_{m,k}\mathbf{w}_{m,k}| \ge \beta_k \sqrt{t_k - 1}, \tag{11}$$

$$\sum_{m=1}^{L} x_{m,k} \sum_{k' \neq k} |\mathbf{h}_{m,k}\mathbf{w}_{m',k'}|^2 + \sigma^2 \le \beta_k^2, \tag{12}$$

where $\beta_k > 0$ and constraint (11) is nonconvex which has convex upper bound

$$f(\beta_k, t_k; \psi_k) = \frac{\psi_k}{2}\beta_k^2 + \frac{t_k - 1}{2\psi_k}. \tag{13}$$

Using Successive Convex Approximation (SCA) [10], we iteratively solve these convex subproblems and updating the problem variables. In each iteration, the problem (P1) is transferred into (P1$'$) as

$$\left(\text{P1}'\right): \max_{\mathbf{w}_{m,k}, t_{m,k}, \beta_{m,k}} \quad \sum_{m=1}^{L}\sum_{k=1}^{K} \log_2 t_{m,k} \tag{14}$$

$$\text{s.t.} \sum_{m=1}^{L} x_{m,k} |\mathbf{h}_{m,k}\mathbf{w}_{m,k}| \ge \frac{\psi_k}{2}\beta_k^2 + \frac{t_k - 1}{2\psi_k} \quad \forall k \in \mathcal{K}, \tag{14a}$$

$$\sum_{m=1}^{L}\sum_{k' \neq k} x_{m,k} |\mathbf{h}_{m,k}\mathbf{w}_{m',k'}|^2 + \sigma^2 \le \beta_k^2 \quad \forall k \in \mathcal{K}, \tag{14b}$$

$$\sum_{k=1}^{K} x_{m,k} |\mathbf{w}_{m,k}|^2 \le P_0 \quad \forall m \in \mathcal{L}, \tag{14c}$$

$$t_k \ge 2^{r_0} \quad \forall k \in \mathcal{K}, \tag{14d}$$

$$\psi_k = \sqrt{t_k^{(i)} - 1} / \beta_k^{(i)} \quad \forall k \in \mathcal{K}, \tag{14e}$$

$$t_k \ge 1 \quad \forall k \in \mathcal{K}, \tag{14f}$$

$$\beta_k > 0 \quad \forall k \in \mathcal{K}, \tag{14g}$$

where $\mathbf{w}_{m,k} \in \mathbb{C}^{M_S \times 1}$, $t_k \in \mathbb{R}$, $\beta_k \in \mathbb{R}$. (P1$'$) is convex and can be solved.

B. User-LEO Association

To obtain a feasible user-LEO association scheme, we fix the beamforming vector $\mathbf{w}_{m,k}$ of each user and RIS phase shift $\mathbf{\Theta}$, and the original (P) can be transformed into the subproblem of user-LEO association optimization which is denoted as

$$\text{(P2)}: \quad \max_{x_{m,k}} \quad \sum_{m=1}^{L}\sum_{k=1}^{K} R_{m,k} \tag{15}$$

$$\text{s.t.} \quad \sum_{k=1}^{K} x_{m,k} \left|\mathbf{w}_{m,k}\right|^2 \leq P_0 \quad \forall m \in \mathcal{L}, \tag{15a}$$

$$\sum_{m=1}^{L} R_{m,k} \geq r_0 \quad \forall k \in \mathcal{K}, \tag{15b}$$

$$\sum_{m=1}^{L} x_{m,k} = 1 \quad \forall k \in \mathcal{K}, \tag{15c}$$

$$x_{m,k} \in \{0,1\} \quad \forall m \in \mathcal{L}, k \in \mathcal{K}. \tag{15d}$$

(P2) is an integer programming problem characterized by a non-convex objective function which can be converted into a many-to-one matching problem.

We adopt a greedy method to optimize the matching scheme where each terrestrial user is matched with the most preferred LEO satellite and add each association between user and LEO satellite into the set. Specifically, each unmatched user k proposes to LEO m_k^* to match with satisfying

$$m_k^* = \arg\max_{m \in [1,L]} R_{m,k} \quad \forall k \in \mathcal{K}, \tag{16}$$

and the user-LEO association $x_{m,k} = 1$ when $m = m_k^*$.

C. RIS Phase Optimization

For the optimization of RIS shift phase problem, we fix the user-LEO association variables $x_{m,k}$ and beamforming vector $\mathbf{w}_{m,k}$ of each user to decompose the original optimization problem (P) into the following subproblem.

$$\text{(P3)}: \quad \max_{\mathbf{\Theta}} \quad \sum_{m=1}^{L}\sum_{k=1}^{K} R_{m,k} \tag{17}$$

$$\text{s.t.} \quad \sum_{m=1}^{L} R_{m,k} \geq r_0 \quad \forall k \in \mathcal{K}, \tag{17a}$$

$$\left|\mathbf{\Theta}_{n,n}\right|^2 = 1 \quad \forall 1 \leq n \leq M_R, \tag{17b}$$

$$\mathbf{\Theta}_{n,j} = 0 \quad \forall j \neq n, 1 \leq n,j \leq M_R. \tag{17c}$$

For simplicity of notation, the equivalent vectors for the reflect link $\mathbf{a}_{k,j}$ and the direct link $\mathbf{b}_{k,j}$ are defined as

$$\mathbf{a}_{k,j} = \sum_{m=1}^{L} \text{diag}\left(\mathbf{l}_{R,k}\right) \mathbf{H}_m x_{m,R} \cdot \sum_{m'=1}^{L} \mathbf{w}_{m',j} x_{m',j}, \tag{18}$$

$$\mathbf{b}_{k,j} = \sum_{m=1}^{L} \mathbf{g}_{m,k} x_{m,k} \cdot \sum_{m'=1}^{L} \mathbf{w}_{m',j} x_{m',j}. \tag{19}$$

Consequently, the transmission rate of the user k can be derived as

$$R_k = B \log\left(1 + \frac{\left|\mathbf{b}_{k,k} + \mathbf{v}^H \mathbf{a}_{k,k}\right|^2}{\sum_{j \neq k} \left|\mathbf{b}_{k,j} + \mathbf{v}^H \mathbf{a}_{k,j}\right|^2 + \sigma^2}\right). \tag{20}$$

We then introduce the following auxiliary variables t_n, $\mathbf{R}_{k,j}$ and $\mathbf{V}$ [11]

$$t_k = 1 + \frac{\left|\mathbf{b}_{k,k} + \mathbf{v}^H \mathbf{a}_{k,k}\right|^2}{\sum_{j \neq k} \left|\mathbf{b}_{k,j} + \mathbf{v}^H \mathbf{a}_{k,j}\right|^2 + \sigma^2}, \tag{21}$$

$$\mathbf{R}_{k,j} = \begin{bmatrix} \mathbf{a}_{k,j}\mathbf{a}_{k,j}^H & \mathbf{a}_{k,j}\mathbf{b}_{k,j}^H \\ \mathbf{a}_{k,j}^H \mathbf{b}_{k,j} & 0 \end{bmatrix}, \tag{22}$$

$$\mathbf{V} = \begin{bmatrix} \mathbf{v}\mathbf{v}^H & \mathbf{v}^H \\ \mathbf{v} & 1 \end{bmatrix}, \tag{23}$$

where $\mathbf{v}$ represents the vector consisting of the diagonal elements of the RIS phase matrix $\mathbf{\Theta}$. Furthermore, for $\mathbf{V}$ to adhere to the constraints that $\mathbf{V}$ is a semi positive definite matrix with rank one. We choose to relax the rank constraint which is nonconvex. To address this, a similar approach as employed in solving (P1) is used, involving the introduction of supplementary slack variables denoted as β_n. As a result, the problem presented in (24) is transformed into a series of subproblems (P3$'$), which is convex and can be easily addressed.

$$\text{(P3}'\text{)}: \quad \max_{t_k, \mathbf{V}} \quad \sum_{k=1}^{K} \log_2 t_k \tag{24}$$

$$\text{s.t.}\,\text{tr}\left(\mathbf{R}_{k,k}\mathbf{V}\right) + \left|\mathbf{b}_{k,k}\right|^2 \geq \frac{\psi_k}{2}\beta_k^2 + \frac{1}{2\psi_k}\left(t_k - 1\right)^2 \quad \forall k \in \mathcal{K}, \tag{24a}$$

$$\sigma^2 + \sum_{j \neq k}\left(\text{tr}\left(\mathbf{R}_{k,j}\mathbf{V}\right) + \left|\mathbf{b}_{k,j}\right|^2\right) \leq \beta_k \quad \forall k \in \mathcal{K}, \tag{24b}$$

$$\mathbf{V}_{n,n} = 1 \quad \forall 1 \leq n \leq M_R, \tag{24c}$$

$$\mathbf{V} \succeq 0, \tag{24d}$$

$$\psi_k = \left(t_k^{(i-1)} - 1\right) / \beta_k^{(i-1)} \quad \forall k \in \mathcal{K}. \tag{24e}$$

Upon solving $\mathbf{V}$, the RIS phase matrix can be derived through eigenvalue decomposition of $\mathbf{V}$. The diagonal elements $\mathbf{v}$ of the $\mathbf{\Theta}$ can be generated by $\mathbf{v} = \boldsymbol{U}\sqrt{\boldsymbol{D}}$, where $\boldsymbol{D}$ is the eigenvalue matrix of $\mathbf{V}$ and $\boldsymbol{U}$ is the combination of corresponding right eigenvectors.

D. Alternative Optimization

To achieve optimal performance through an efficient approach, we employ the ABUR algorithm, elucidated in **Algorithm 1**. We decouple the initial problem into distinct subproblems (P1) and (P2), as elaborated in the preceding subsections, each addressing specific optimization variables and resolved iteratively. Particularly, we first initialize the variables $\mathbf{x}(0), \mathbf{w}(0), \mathbf{\Theta}(0)$ of the algorithm. And then in the i-th iteration, we calculate $\mathbf{w}(i)$, $\mathbf{x}(i)$ and $\mathbf{\Theta}(i)$ by solving subproblems based on $\mathbf{w}(i-1)$, $\mathbf{x}(i-1)$ and $\mathbf{\Theta}(i-1)$ in previous iteration. This iterative process continues until

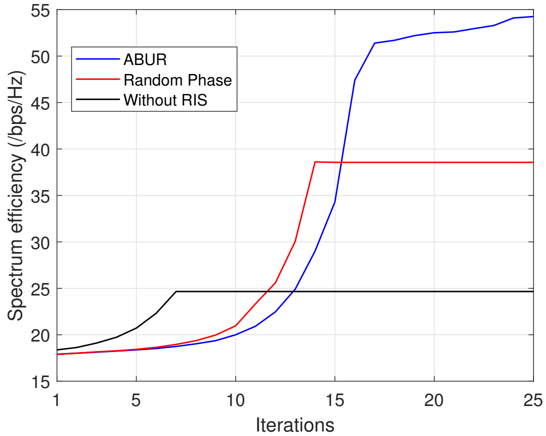

Fig. 2. Convergence rate of sum rate in different algorithms, $K = 32$ and $P_0 = 35$ dBm for all.

Algorithm 1 AO-based joint beamforming, user-LEO association and RIS shift algorithm (ABUR).

```
Input: Initial variables $\mathbf{x}(0), \mathbf{w}(0), \mathbf{\Theta}(0)$, threshold $\varepsilon$.
Output: Optimal $\mathbf{x}^*, \mathbf{w}^*, \mathbf{\Theta}^*$.
1: Calculate the sum rate $R_{total}(0)$ based on $\Psi(0)$, $\mathbf{w}_{m,k}(0)$, and $\mathbf{\Theta}(0)$.
2: $i = 1$.
3: For given $x_{m,k}(i)$ and $\mathbf{\Theta}(i-1)$, calculate $\mathbf{w}_{m,k}(i)$ by solving subproblem (P1').
4: For given $\mathbf{\Theta}(i-1)$ and $\mathbf{w}_{m,k}(i)$, calculate $x_{m,k}(i)$.
5: $m^n(i) = \arg\max_{m\in[1,L]} R_{m,k}$.
6: $x_{m^n(i),n}(i) = 1$.
7: For given $x_{m,k}(i)$ and $\mathbf{w}_{m,k}(i)$, calculate $\mathbf{\Theta}(i)$ by solving subproblem (P3').
8: Calculate the sum rate $R_{total}(i)$ based on $x_{m,k}(i)$, $\mathbf{w}_{m,k}(i)$, and $\mathbf{\Theta}(i)$.
9: if $|R_{total}(i) - R_{total}(i-1)| < \varepsilon$ then
10:     $x_{m,k}(i)^* = x_{m,k}(i)$.
11:     $\mathbf{w}^* = \mathbf{w}(i)$.
12:     $\mathbf{\Theta}^* = \mathbf{\Theta}(i+1)$.
13: else
14:     $i = i + 1$, repeat step 2 to 4.
15: end if
```

specific convergence criteria are met, and the ABUR algorithm has provable convergence under some conditions.

IV. NUMERICAL SIMULATIONS

In this section, we assess the performance of ABUR algorithm using the simulation parameters outlined in TABLE I. To substantiate the efficacy of ABUR algorithm, we compare its performance against two baseline scenarios:

- **Without RIS**: Let the number of RIS element be 0.
- **Random Phase**: The value of RIS phase matrix $\mathbf{\Theta}$ is randomly assigned.

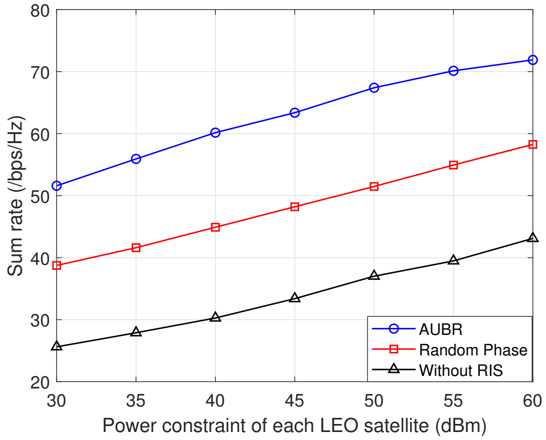

Fig. 3. The sum rate versus power constraint of each LEO satellite when $K = 32$ and $M_R = 16$.

In this 2 baseline scenarios, user-LEO association and beamforming are solved by greedy algorithm and SCA respectively.

All simulation curves are derived from the average of 100 independent channel small-scale fading instances. Numerical illustrations are included to confirm the efficacy of the introduced algorithms. Our analysis is conducted within a 3D coordinate framework, wherein the UPAs of both LEO satellites and the RIS are situated within the x-z plane.

TABLE I
SIMULATION PARAMETERS

Parameters	Value
Rician factor of LOS channel	15 dB
Rayleigh factor of NLOS channel	0.2
Frequency of carrier	20 GHz
Gaussian white noise	-174 dBm/Hz
Orbit height of LEOs	550∼1100 km [12]
Number of LEOs	11927 [12]
Number of LEO satellite antennas	4*4
Antenna Gains	17dBi

Figure 2 illustrates the convergence behavior of ABUR algorithm., random phase and data transmission without RIS. As the iterations increase, the sum rate of UDLN increase. When the iteration count approaches 25, the cumulative rate yielded by ABUR stabilizes, underscoring its robust convergence behavior.

Fig. 3 shows the sum rate versus power constraint of LEO satellite when $K = 32$ and $M_R = 16$. The total sum rate of UDLN shows a linear relationship with the power constraint of each LEO satellite in all three algorithms. The proposed RIS aided ultra-dense LEO satellite downlink communication system performs better than the random phase scenario, due to the fact that random phase may increase the interference between users and thus reduces the sum rate. RIS can significantly increase the sum rate compared to the transmission without RIS because of the presence of LOS paths and the reduction of interference between users by RIS phase shift.

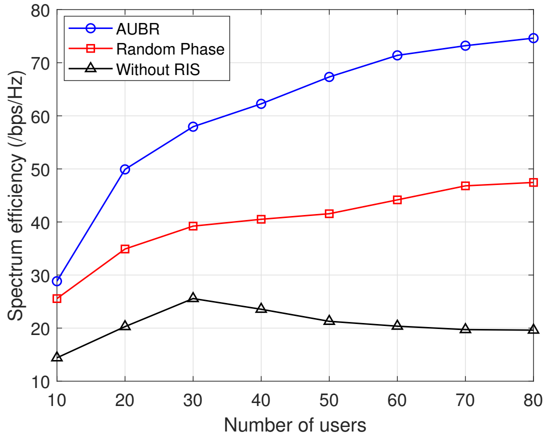

Fig. 4. The sum rate versus the number of users when $M_R = 64$ and $P_0 = 32$ dBm

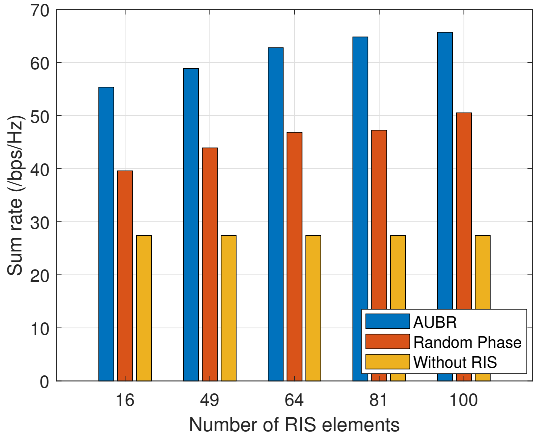

Fig. 5. The sum rate versus number of RIS elements when $K = 32$ and $P_0 = 35$dBm.

Fig. 4 shows the relationship between sum rate and the number of users when $M_R = 64$ and $P_0 = 32$ dBm. The sum rate of random phase escalates as user numbers rise, attributed to the fact that random phase may increase the interference between users in multi-user scenarios thereby decreasing the sum rate of the network. The proposed ABUR algortihm can remarkably enhances the sum rate of UDLN when the number of users are increased compared with random phase.

Fig. 5 shows the relationship between sum rate and the number of RIS elements with M_R ranging from 16 to 100 when $K = 35$ and $P_0 = 32$ dBm. The increase in the number of RIS elements improves the overall downlink sum rate of UDLN for both random phase and ABUR algorithms. The growth rate is gradually regionally flat with the increase of RIS elements for proposed ABUR algorithm. Meanwhile, the optimal RIS phase algorithm improves the sum rate of UDLN at a greater rate than the random phase algorithm.

V. CONCLUSION

In this paper, we have investigated RIS-aided downlink transmission of UDLNs in urban scenarios. We have set up optimization model to maximize the sum rate of UDLN considering the power constraints of LEO satellites. Then we have proposed ABUR algorithm through alternative optimization to solve the sum rate maximization problem. Simulation results have demonstrated that our approach achieves the optimal sum rate in comparison to baseline algorithms, leading to a substantial enhancement in UDLN performance. In the future, we will further investigate RIS application in performing distributed channel estimation in UDLNs considering imperfect channel information.

ACKNOWLEDGEMENT

This work was supported in part by the National Key R&D Program of China under Grant 2020YFB1806104, in part by the Natural Science Fund for Distinguished Young Scholars of Jiangsu Province under Grant BK20220067, in part by the National Natural Science Foundation Original Exploration Project of China under Grant 62250004, in part by the National Natural Science Foundation of China under Grant 62271244.

REFERENCES

[1] X. Qin, T. Ma, Z. Tang, X. Zhang, H. Zhou, and L. Zhao, "Service-aware resource orchestration in ultra-dense LEO satellite-terrestrial integrated 6G: A service function chain approach," *IEEE Transactions on Wireless Communications*, pp. 1–1, 2023.

[2] X. Zhang, B. Qian, X. Qin, T. Ma, J. Chen, H. Zhou, and X. S. Shen, "Cybertwin-assisted mode selection in ultra-dense LEO integrated satellite-terrestrial network," *Journal of Communications and Information Networks*, vol. 7, no. 4, pp. 360–374, 2022.

[3] Y. Seyedi, M. Shirazi, A. Moharrer, S. M. Safavi, and H. Amindavar, "Use of shadowing moments to statistically model mobile satellite channels in urban environments," *IEEE Transactions on Wireless Communications*, vol. 12, no. 8, pp. 3760–3769, 2013.

[4] P. Ramezani, B. Lyu, and A. Jamalipour, "Toward RIS-enhanced integrated terrestrial/non-terrestrial connectivity in 6G," *IEEE Network*, pp. 1–9, 2022.

[5] J. Ye, J. Qiao, A. Kammoun, and M.-S. Alouini, "Nonterrestrial communications assisted by reconfigurable intelligent surfaces," *Proceedings of the IEEE*, vol. 110, no. 9, pp. 1423–1465, 2022.

[6] B. Zheng, S. Lin, and R. Zhang, "Intelligent reflecting surface-aided LEO satellite communication: Cooperative passive beamforming and distributed channel estimation," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 10, pp. 3057–3070, 2022.

[7] R. Deng, B. Di, H. Zhang, H. V. Poor, and L. Song, "Holographic MIMO for LEO satellite communications aided by reconfigurable holographic surfaces," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 10, pp. 3071–3085, 2022.

[8] L. You, K.-X. Li, J. Wang, X. Gao, X.-G. Xia, and B. Ottersten, "Massive MIMO transmission for LEO satellite communications," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 8, pp. 1851–1865, 2020.

[9] L.-N. Tran, M. F. Hanif, A. Tolli, and M. Juntti, "Fast converging algorithm for weighted sum rate maximization in multicell MISO downlink," *IEEE Signal Processing Letters*, vol. 19, no. 12, pp. 872–875, 2012.

[10] Z. Tang, K. Yu, G. Yang, L. X. Cai, and H. Zhou, "New bridge to cloud: An ultra-dense LEO assisted green computation offloading approach," *IEEE Transactions on Green Communications and Networking*, vol. 7, no. 2, pp. 552–564, 2023.

[11] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Transactions on Wireless Communications*, vol. 18, no. 11, pp. 5394–5409, 2019.

[12] *SpaceX Non-Geostationary Satellite System*, Washington, DC, USA, 2016.