The Optimal Layer of User-Specific Reconfigurable Intelligent Surfaces Structure for Uplink Communication System

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Abstract. Reconfigurable intelligent surfaces (RIS) can be utilized for enhancing the communication quality, and are regarded as a promising six-generation (6G) technique. Especially, the RIS generally is deployed as a reflector or an intelligent transmission terminal. Most of the existing works have focused on the reflective RIS. In contrast, the recently emerged user-specific RIS (US-RIS) can improve performance for users at a low cost. Unlike reflective RIS, US-RIS can control the phase of the user uplink signal when the signal penetrates US-RIS. The purpose of this paper is to investigate the energy efficient of multi-layer US-RIS-aided uplink communication system with quality of service to find the optimal layer of US-RIS. To this end, we formula a joint optimization problem over several transmit beamforming vectors. An optimal energy efficient design which is based on alternating update and successive convex approximation (SCA) is proposed. Simulation results reveal that the number of elements has an impact on energy efficiency, which affects the optimal layer.

Keywords: RIS · US-RIS · SCA · Alternating optimization

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1 Introduction

The Fifth-generation (5G) communication is expected to reach its limits in 2030 [1–3] due to the never-ending growth of global mobile data traffic. Although the research and development are still in the early stage, many new mobile communication technologies will appear in the future six-generation (6G) [4,5].

Reconfigurable intelligent surface (RIS) is a revolutionary technology in the field of wireless communication and one of the most important technologies in the future 6G related technologies [6,7].

Recently the emergence of metamaterials has spawned cutting-edge technology, RIS [8]. A planar array of some passive elements can form a RIS, where the input signal is imparted at the desired phase angle by each element independently [9]. To adapt to the dynamically changing wireless propagation environment, the reflected (or transmitted) signal can be reconfigured to propagate in its desired direction by properly adjusting the phase shifts of all elements, and the reflection factor (or loss factor) of each element can be reconfigured [10]. The advantages of RISs have been demonstrated in these actual wireless communication models [11]. Compared to traditional networks without RIS, RIS-aided networks can improve energy efficiency and capacity [12,13]. According to the different ways of changing the propagation direction of the input signal [14], RIS can be roughly divided into two types: reflective type [15,16] and transmissive type [17]. Precisely, the reflective type RIS reflects the input signal in the desired direction. The signal can also penetrate through the transmissive type RIS, and by changing the phase, the signal is transmitted in the desired direction. The concept of user-specific reconfigurable intelligent surfaces (US-RIS) is first proposed by [18]. In the communication system, RIS is traditionally used between the base station (BS) and users, or deployed on the BS. Compared with traditional RIS application scenarios, US-RIS is a hardware technology that beamforming the signals that penetrate them and is used to build large-scale arrays on the user side.

In this paper, we use alternating update and SCA methods to solve the optimal energy efficiency of the US-RIS-aided uplink communication system. Thereby the optimal layer of US-RIS is found. Simulation results demonstrate that the UE's internal circuit consumption and the number of elements can affect the energy efficiency, and the optimal layer changes accordingly.

2 System Model

In Fig. 1, a US-RIS-aided uplink communication system is considered. The system has one UE equipped with M transmit antennas and one BS with N receive antennas. The US-RIS consists of L layers and each layer has K_l passive elements, $l = [1, 2, \cdots, L]$.

The phase shift (PS) matrix of US-RIS's l-th layer is defined as

$$\boldsymbol{\Theta}_l = \mathrm{diag}(\boldsymbol{\theta}_l) = \mathrm{diag}[(\theta_{l,1}, \cdots, \theta_{l,K_l})^T], \tag{1}$$

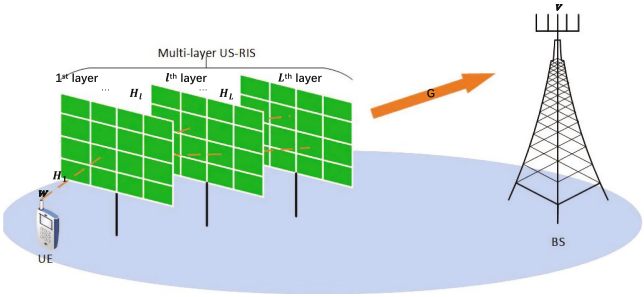

Fig. 1. System model

where, $\theta_{l,k} = e^{j\varphi}$ is k-th element's phase shift of the l-th layer and $\varphi \in [-\pi, \pi]$. Let $s \in \mathbb{C}$ denote the transmit signal for uplink transmission with $\mathbb{E}\{\mid s \mid^2\} = 1$. The received vector $\mathbf{y} \in \mathbb{C}^{N\times 1}$ at the BS can be written as

$$\mathbf{y} = \mathbf{G}^H \left(\prod_{l=1}^{L} \kappa \mathbf{\Theta}_l \mathbf{H}_l \right) \mathbf{w} s + \mathbf{n}, \tag{2}$$

where $\mathbf{G} \in \mathbb{C}^{K_L \times N}$ denotes the channel between the l-th layer of US-RIS and BS. $\mathbf{H}_1 \in \mathbb{C}^{K_1 \times M}$ denotes the channel between US-RIS's 1-st layer and UE. $\mathbf{H}_l \in \mathbb{C}^{K_l \times K_l}, l = [2, \cdots, L]$ denotes the channel between the $(l-1)$-th layer and the l-th layer of US-RIS. In addition, κ is the loss coefficient when the signal transmit through every layer. $\mathbf{w} \in \mathbb{C}^{M\times 1}$ is the uplink beamforming (ULB) vector. $\mathbf{n}$ is a Gaussian White noise vector with zero mean and $\sigma^2 \mathbf{I}_N$ variance matrix. Therefore, the transmission signal which is combined by the BS can be expressed as

$$z = \mathbf{v}^H \mathbf{G}^H \left(\prod_{l=1}^{L} \kappa \mathbf{\Theta}_l \mathbf{H}_l \right) \mathbf{w} s + \mathbf{v}^H \mathbf{n}, \tag{3}$$

where $z = \mathbf{v}^H \mathbf{y}$. The normalized receiving combining (RC) vector $\mathbf{v} \in \mathbb{C}^{N\times 1}$ is used here. Then, SNR is expressed as the following form:

$$SNR = \frac{\mid \mathbf{v}^H \mathbf{G}^H (\prod_{l=1}^{L} \kappa \mathbf{\Theta}_l \mathbf{H}_l) \mathbf{w} \mid^2}{\|\mathbf{v}^H\|_2^2 \sigma^2}. \tag{4}$$

Thus, the achieved data rate is

$$R = \log_2 \left(1 + \frac{\mid \mathbf{v}^H \mathbf{G}^H (\prod_{l=1}^{L} \kappa \mathbf{\Theta}_l \mathbf{H}_l) \mathbf{w} \mid^2}{\|\mathbf{v}^H\|_2^2 \sigma^2} \right). \tag{5}$$

Note that the rate in (5) is affected by the RC vector $\mathbf{v}$, US-RIS PS matrices $\boldsymbol{\Theta}_1, \cdots, \boldsymbol{\Theta}_l$, ULB vector $\mathbf{w}$. Hence, the problem of energy efficient can be formulatedz as

$$\max_{\mathbf{v},\boldsymbol{\Theta}_1,\cdots,\boldsymbol{\Theta}_L,\mathbf{w}} \frac{R}{\|\mathbf{w}\|_2^2 + P_i}, \tag{6a}$$

$$\text{s.t.} \quad 0 \leq \|\mathbf{w}\|_2^2 \leq P_{max}, \tag{6b}$$

$$R \geq r_{min}, \tag{6c}$$

$$|\theta_{l,k}| = 1, \tag{6d}$$

where P_i is the internal power circuit consumption of UE. (6b) is the power constraint of UE. (6c) is the constraint to ensure the minimum rate at the receiving end, namely, quality of service (QoS). (6d) is the range of phase shift of the k-th element of the l-th layer.

Algorithm 1. Alternating Update with SCA

Input: Channel matrices $\mathbf{G}$ and $\mathbf{H}_1, \cdots, \mathbf{H}_L$; loss factor κ; $t = 1$; maximum transmit power P_{max} and internal power circuit consumption P_i.

Output: Maximized energy efficient τ.

1: **while** τ does not converge **do**
2: Update $\mathbf{v}^{opt}$ by (11);
3: Update $\boldsymbol{\Theta}_1^{opt}, \cdots, \boldsymbol{\Theta}_L^{opt}$ by (15);
4: Update $\mathbf{w}^{(t)}$ and $\tau^{(t)}$ by solve problem (28);
5: Set $t = t + 1$;
6: **end while**
7: **return** $\mathbf{v}^{opt}$, $\boldsymbol{\Theta}_1^{opt}, \cdots, \boldsymbol{\Theta}_L^{opt}$ and $\mathbf{w}^{(t)}$.

3 The Optimal Energy Efficient Design

To address the formulate non-convex problem, we design an algorithm which can efficiently solve the problem. We want to find the maximum energy efficient of US-RIS-aided uplink communication system according to the beamforming. The proposed algorithm is used to settle the joint optimization problem (6). Given the input channel matrices $\mathbf{H}_1, \cdots, \mathbf{H}_L$, $\mathbf{G}$ and loss factor κ. By alternately solve the subproblem, the $\mathbf{v}^{opt}$ is the first update with Rayleigh quotient problem, and then $\boldsymbol{\Theta}_1^{opt}, \cdots, \boldsymbol{\Theta}_L^{opt}$ is update. Further we use successive convex approximation(SCA) method to solve $\mathbf{w}$.

3.1 Receiving Combining Vector Design

With other variables fixed, problem (6) can be transformed into the following equivalent form:

$$\begin{aligned}&\max_{\mathbf{v},\|\mathbf{v}\|_2^2=1} \frac{|\ \mathbf{v}^H\mathbf{G}^H(\prod_{l=1}^{L}\kappa\boldsymbol{\Theta}_l\mathbf{H}_l)\mathbf{w}\ |^2}{\|\mathbf{v}^H\|_2^2\sigma^2}\\ &= \max_{\mathbf{v},\|\mathbf{v}\|_2^2=1} \frac{\mathbf{v}^H\mathbf{G}^H(\prod_{l=1}^{L}\kappa_l\boldsymbol{\Theta}_l\mathbf{H}_l)\mathbf{w}\mathbf{w}^H(\prod_{l=1}^{L}\kappa_l\boldsymbol{\Theta}_l\boldsymbol{H}_l)^H\mathbf{G}\mathbf{v}}{\|\mathbf{v}^H\|_2^2\sigma^2}.\end{aligned} \tag{7}$$

Let $\mathbf{U} = \mathbf{G}^H(\prod_{l=1}^{L}\kappa_l\boldsymbol{\Theta}_l\mathbf{H}_l)\mathbf{w}\mathbf{w}^H(\prod_{l=1}^{L}\kappa_l\boldsymbol{\Theta}_l\mathbf{H}_l)^H\mathbf{G}$. Obviously, $\mathbf{U}$ is a Hermitian matrix, and equation (7) can be written as

$$\max_{\mathbf{v}} \ \frac{\mathbf{v}^H\mathbf{U}\mathbf{v}}{\|\mathbf{v}^H\|_2^2\sigma^2}, \tag{8a}$$

$$\text{s.t.} \quad \|\mathbf{v}\|_2^2 = 1, \tag{8b}$$

At this point, the problem is transformed into the Rayleigh quotient problem. And (8) can be formulated to

$$R(\mathbf{U},\mathbf{v}) = \frac{\mathbf{v}^H\mathbf{U}\mathbf{v}}{\mathbf{v}^H\mathbf{v}}. \tag{9}$$

The generalized Rayleigh quotient function (9) is satisfied the relationship as follows

$$\lambda_{min} \le \frac{\mathbf{v}^H\mathbf{U}\mathbf{v}}{\mathbf{v}^H\mathbf{v}} \le \lambda_{max}, \tag{10}$$

where λ_{max} is the maximum eigenvalue of matrix $\mathbf{U}$ and λ_{min} is the minimum eigenvalue of matrix $\mathbf{U}$. So, the $\mathbf{v}^{opt}$ can be expressed as

$$\mathbf{v}^{opt} = \lambda_{max}(\mathbf{U}). \tag{11}$$

3.2 Phase Shift Matrix Design

With other variables fixed, and only considering $\boldsymbol{\Theta}_l$, problem (6) can be equivalently written as

$$\max_{\boldsymbol{\Theta}_1,\cdots,\boldsymbol{\Theta}_L} R, \tag{12a}$$

$$\text{s.t.} \quad R \ge r_{min}, \tag{12b}$$

$$|\theta_{l,k}| = 1. \tag{12c}$$

We can define

$$\boldsymbol{\psi}_{(i,j)} = \prod_{l=i}^{j}\kappa\boldsymbol{\Theta}_l\mathbf{H}_l, \quad (i \in L, \quad j \in L). \tag{13}$$

The SNR can be equivalently written as

$$\begin{aligned} SNR &= \frac{\mid \mathbf{v}^H \mathbf{G}^H \boldsymbol{\psi}_{(l+1,L)} \boldsymbol{\psi}_{(1,l)} \mathbf{w} \mid^2}{\|\mathbf{v}^H\|_2^2 \sigma^2} \\ &= \frac{\mid \mathbf{v}^H \mathbf{G}^H \boldsymbol{\psi}_{(l+1,L)} \mathrm{diag}(\mathbf{H}_l \boldsymbol{\psi}_{(1,l-1)} \mathbf{w}) \boldsymbol{\theta}_l \mid^2}{\|\mathbf{v}^H\|_2^2 \sigma^2}. \end{aligned} \tag{14}$$

Then, with the constraint (12b) and (12c), the optimal phase can be written by

$$\boldsymbol{\theta}_l^{opt} = \begin{cases} \exp\left(j \arg\left(\mathrm{diag}\left(\mathbf{H}_l \boldsymbol{\psi}_{(1,l-1)} \mathbf{w}\right)^H \boldsymbol{\psi}_{(l+1,L)}^H \mathbf{G} \mathbf{v}\right)\right), R \geq r_{min} \\ \text{No solution}, R < r_{min} \end{cases} \tag{15}$$

3.3 Uplink Beamforming Vector Design

To make the problem (6) convex, we use a slack variable τ to transform (6) equivalently as follows

$$\max_{\mathbf{w},\tau} \ \tau, \tag{16a}$$

$$\text{s.t.} \quad \frac{R}{\|\mathbf{w}\|_2^2 + P_i} \geq \tau, \tag{16b}$$

$$0 \leq \|\mathbf{w}\|_2^2 \leq P_{max}, \tag{16c}$$

$$R \geq r_{min}. \tag{16d}$$

Since (16b) is non-convex, we introduce a slack variable α to make the constraint (16b) convex. Therefore, the power constraint can be expressed as

$$\|\mathbf{w}\|_2^2 + P_i \leq \alpha, \tag{17}$$

and constraint (16b) transform into the following form

$$R \geq \tau\alpha. \tag{18}$$

But the power constraint (18) is still non-convex, use a new variable β to relax (18), which is written as

$$\log_2(\beta) \geq \tau\alpha, \tag{19a}$$

$$1 + SNR \geq \beta. \tag{19b}$$

Then, we use another variable γ to make constraint (19a) convex, which can be expressed as

$$\gamma \geq \tau\alpha, \tag{20a}$$

$$\beta \geq 2^{\gamma}. \tag{20b}$$

The relationship between these series of slack variables can be described as

$$\log_2(1+SNR) \geq \log_2(\beta) \geq \gamma \geq \tau\alpha, \tag{21}$$

Due to the fractional form of SNR, a variable Ω can be introduced. Thus, (19b) can be equivalently written as

$$\mid \mathbf{v}^H \mathbf{G}^H (\prod_{l=1}^{L} \kappa \mathbf{\Theta}_l \mathbf{H}_l) \mathbf{w} \mid^2 \geq (\beta - 1)\Omega, \tag{22a}$$

$$\|\mathbf{v}^H\|_2^2 \sigma^2 \leq \Omega. \tag{22b}$$

In addition, we use a slack variable δ, (19a) can be expressed as

$$\delta^2 \geq (\beta - 1)\Omega, \tag{23a}$$

$$\mid \mathbf{v}^H \mathbf{G}^H (\prod_{l=1}^{L} \kappa \mathbf{\Theta}_l \mathbf{H}_l) \mathbf{w} \mid^2 \geq \delta^2. \tag{23b}$$

(19a) and (23a) are non-convex, we sue the first-order Taylor to approximate non-convex constraints. These constraints can be expressed as

$$\gamma \geq \tau^{(t)}\alpha^{(t)} + \alpha^{(t)}\left(\tau - \tau^{(t)}\right) + \tau^{(t)}\left(\alpha - \alpha^{(t)}\right), \tag{24}$$

$$2\delta^{(t)}\delta - \left(\delta^{(t)}\right)^2 \geq \left(\beta^{(t)} - 1\right)\Omega^{(t)} + \Omega^{(t)}\left(\beta - \beta^{(t)}\right) + \left(\beta^{(t)} - 1\right)\left(\Omega - \Omega^{(t)}\right), \tag{25}$$

where t represents the t-th iteration. Then the non-convex constraint (16d) can be shown as

$$\frac{\mid \mathbf{v}^H \mathbf{G}^H (\prod_{l=1}^{L} \kappa \mathbf{\Theta}_l \mathbf{H}_l) \mathbf{w} \mid^2}{\|\mathbf{v}^H\|_2^2 \sigma^2} \geq 2^{r_{min}} - 1, \tag{26}$$

where r_{min} is a constant. Therefore, this constraint can be restated as

$$2\delta^{(t)}\delta - \left(\delta^{(t)}\right)^2 \geq (2^{r_{min}} - 1)(\|\mathbf{v}^H\|_2^2 \sigma^2). \tag{27}$$

Constraints (27) is convex. The convex optimization problem can be described in following form:

$$\max_{\mathbf{w},\tau,\alpha,\beta,\gamma,\Omega,\delta} \tau, \tag{28a}$$

$$\text{s.t.} \quad (16c), (17), (20b), (24), (25), (27). \tag{28b}$$

Hence, we can solve the problem using the CVX.

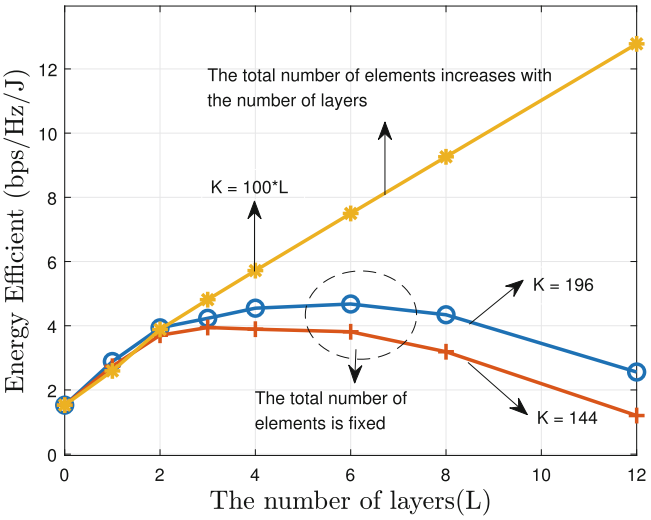

Fig. 2. Energy efficient versus US-RISs' layers

4 Simulation and Discussion

In this section, we conduct some experiments to quantify the energy efficient of the US-RIS-aided uplink communication system after increasing or decreasing the number of layers of US-RIS with and without changing the total number of elements. We then discuss the effect of different internal circuits consumption P_i on energy efficiency. Let λ represent the wavelength of the uplink signal. The side length of each element is $\frac{\lambda}{2}$, and each element is tightly pressed together without spacing. We assume that user having 2 transmitting antennas, and the BS having recieving 8 antennas. The distance between each antenna is $\frac{\lambda}{2}$. We assume that the distance between UE and the first layer of US-RIS is 0.02 m, and the distance between UE and BS is 20 m. Among them, the distance between each layer of US-RIS's layers is 0.02 m. The frequency of uplink transmission signal is configured to 2.5 GHz. The loss coefficient is set to 0.8. The variance of noise is set to $\sigma^2 = -60$ dB. Furthermore, we assume that the uplink communication system knows perfect channel state information (CSI). We initialize the phases of all RIS to random phase values in the feasible set. Thus, we can find the optimal layer according to different conditions.

As shown in Fig. 2, energy efficiency is related to the number of transmissive elements. The total numbers of elements are set as $K = 196$ and $K = 144$. P_i is set to -30 dB and P_{max} is set to 3 dB. The case that the total number of elements increases with the number of layers are considered. In Fig. 2, we can observe that the energy efficiency of the number of elements increasing with the number of layers is significantly better than that of the number of fixed elements for $L \geq 3$. For $L = 12$, the gap from the fixed element number of $K = 192$ to the total number without limited is 10.23 bps/Hz/J. In addition, we can find

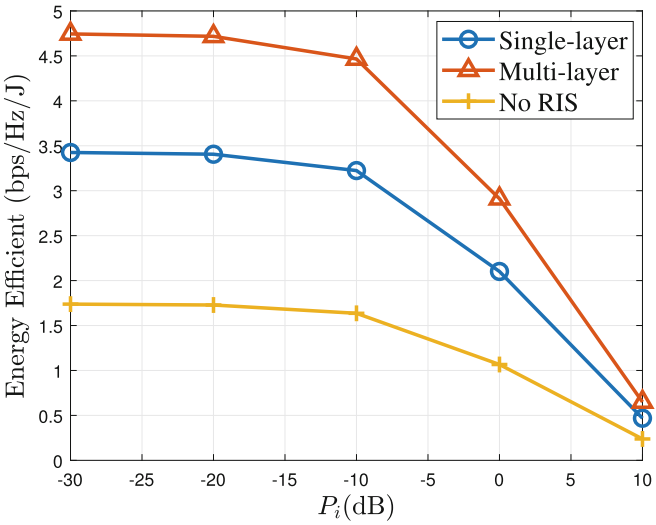

Fig. 3. Energy efficient versus P_i

the optimal number of layers. For $K = 196$, the optimal layer is $L = 6$, and its energy efficient is 4.68 bps/Hz/J. For $K = 144$ the optimal layer is $L = 2$, and its energy efficient is 3.95 bps/Hz/J. An increase in the number of elements can be found to increase the energy efficiency of the system. With a fixed total number of elements, it can also be observed that the number of elements affects the optimal layer for US-RIS.

Figure 3 reveals that energy efficiency is affected by internal circuit consumption. The multi-layer and single-layer cases of US-RIS of the uplink communication system are compared, and the curve of No RIS is used as a baseline. The number of element is set to 192. P_i is set from -30 dB to 10 dB. P_{max} is set to 2 dB. The three curves for single layer, multi-layer and no RIS can see that the energy efficiency decreases with the increase of the P_i. For P_i from -30 dB to 0 dB, the energy efficiency drops more slowly. For P_i from -10 dB to 10 dB, the energy efficiency drops drastically. The efficiency is close to 0 for $P_i = 10$ dB. Energy efficiency decreases as P_i increases. After P_i is more than P_{max}, the energy efficiency decreases slowly and approaches zero.

Figure 4 depicts the convergence of the proposed algorithm under existing simulation conditions. Case of No-RIS as a comparison, the results clearly show that the proposed algorithm for multi-layer US-RIS converges at the fourth iteration. And the proposed algorithm for sigle-layer US-RIS converges at the first iteration.

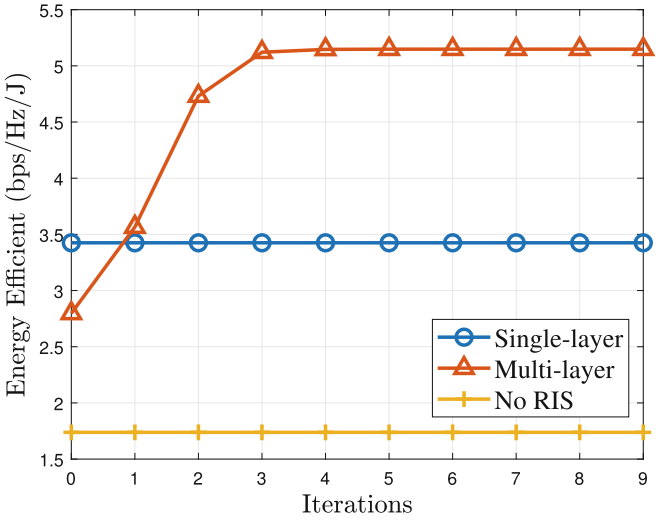

Fig. 4. Energy efficient against iterations

5 Conclusion

In this paper, we formulated a non-convex problem. To address this problem, we subsequently devised an algorithm using alternating update and SCA methods. This problem is divided into three sub-problems and solved separately. To solve the energy efficiency of the system, we alternating update the solutions of the three subproblems. Finally, the optimal layer of US-RIS is found by energy efficiency. The simulation results show that the optimal layer of US-RIS has been found. The optimal layer is affected by the addition or subtraction of elements, and increasing the number of layers does not necessarily lead to an increase in energy efficiency.

References

1. Yu, L., et al.: Sparse code multiple access for 6G wireless communication networks: recent advances and future directions. IEEE Commun. Stan. Mag. **5**(2), 92–99 (2021)
2. Cai, D., Ding, Z., Fan, P., Yang, Z.: On the performance of NOMA with hybrid ARQ. IEEE Trans. Veh. Technol. **67**(10), 10033–10038 (2018)
3. Pham, Q.V., et al.: A survey of multi-access edge computing in 5G and beyond: fundamentals, technology integration, and state-of-the-art. IEEE Access **8**, 116974–117017 (2020)
4. Tariq, F., Khandaker, M.R.A., Wong, K.-K., Imran, M.A., Bennis, M., Debbah, M.: A speculative study on 6G. IEEE Wireless Commun. **27**(4), 118–125 (2020)
5. Cai, D., Xu, Y., Fang, F., Ding, Z., Fan, P.: On the impact of time-correlated fading for downlink NOMA. IEEE Trans. Commun. **67**(6), 4491–4504 (2019)

6. Dang, S., Amin, O., Shihada, B., Alouini, M.S.: What should 6G be? Nat. Electron. **3**(1), 20–29 (2020)
7. Jiao, S., Fang, F., Zhou, X., Zhang, H.: Joint beamforming and phase shift design in downlink UAV networks with IRS-assisted NOMA. J. Commun. Inf. Netw. **5**(2), 138–149 (2020)
8. ElMossallamy, M.A., Zhang, H., Song, L., Seddik, K.G., Han, Z., Li, G.Y.: Reconfigurable intelligent surfaces for wireless communications: principles, challenges, and opportunities. IEEE Trans. Cognit. Commun. Netw. **6**(3), 990–1002 (2020)
9. Wu, Q., Zhang, R.: Towards smart and reconfigurable environment: intelligent reflecting surface aided wireless network. IEEE Commun. Mag. **58**(1), 106–112 (2019)
10. Pan, C., et al.: Reconfigurable intelligent surfaces for 6G systems: principles, applications, and research directions. IEEE Commun. Mag. **59**(6), 14–20 (2021)
11. Dai, L., et al.: Reconfigurable intelligent surface-based wireless communications: antenna design, prototyping, and experimental results. IEEE Access **8**, 45913–45923 (2020)
12. Zhang, Z., Dai, L.: A joint precoding framework for wideband reconfigurable intelligent surface-aided cell-free network. IEEE Trans. Signal Process. **69**, 4085–4101 (2021)
13. Huang, C., Zappone, A., Alexandropoulos, G.C., Debbah, M., Yuen, C.: Reconfigurable intelligent surfaces for energy efficiency in wireless communication. IEEE Trans. Wireless Commun. **18**(8), 4157–4170 (2019)
14. Zeng, S., et al.: Reconfigurable intelligent surfaces in 6G: reflective, transmissive, or both? IEEE Commun. Lett. **25**(6), 2063–2067 (2021)
15. Basar, E., Di Renzo, M., De Rosny, J., Debbah, M., Alouini, M.S., Zhang, R.: Wireless communications through reconfigurable intelligent surfaces. IEEE Access **7**, 116753–116773 (2019)
16. Wang, T., Fang, F., Ding, Z.: An SCA and relaxation based energy efficiency optimization for multi-user RIS-assisted NOMA networks. IEEE Trans. Veh. Technol. (2022)
17. Li, Y., et al.: Transmission-type 2-bit programmable metasurface for single-sensor and single-frequency microwave imaging. Sci. Rep. **6**(1), 1–8 (2016)
18. Liu, K., Zhang, Z., Dai, L., Hanzo, L.: Compact user-specific reconfigurable intelligent surfaces for uplink transmission. IEEE Trans. Commun. **70**(1), 680–692 (2021)