RIS Selection and Energy Efficiency Optimization for Irregular Distributed RIS-assisted Communication Systems

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Abstract

In order to improve spectral efficiency and reduce power consumption for reconfigurable intelligent surface (RIS) assisted wireless communication systems, a joint design considering irregular RIS topology, RIS on-off switch, power allocation and phase adjustment is investigated in this paper. Firstly, a multi-dimensional variable joint optimization problem is established under multiple constraints, such as the minimum data requirement and power constraints, with the goal of maximizing the system energy efficiency. However, the proposed optimization problem is hard to be resolved due to its property of nonlinear nonconvex integer programming. Then, to tackle this issue, the problem is decomposed into four sub-problems: topology design, phase shift adjustment, power allocation and switch selection. In terms of topology design, Tabu search algorithm is introduced to select the components that play the main role. For RIS switch selection, greedy algorithm is used to turn off the RISs that play the secondary role. Finally, an iterative optimization algorithm with high data-rate and low power consumption is proposed. The simulation results show that the performance of the irregular RIS aided system with topology design and RIS selection is better than that of the fixed topology and the fix number of RISs. In addition, the proposed joint optimization algorithm can effectively improve the data rate and energy efficiency by changing the propagation environment.

Keywords: Reconfigurable Intelligent Surface (RIS), Switch design, Energy efficiency optimization.

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1. Introduction

With the rapid growth of mobile users and new wireless applications, communication connections are becoming almost ubiquitous. This has led to higher demands on spectral efficiency and connectivity. Driven by these requirements, researchers have begun to develop the sixth generation (6G) wireless communication technology. Compared with 5G, 6G must greatly improve the communication network performance in terms of coverage, capacity, delay, and reliability, which results in extremely challenging energy efficiency and cost design [1-2].

In recent years, reconfigurable intelligent surface (RIS) technology has been considered as a potential candidate for 6G due to its ability to achieve programmable propagation environments with high energy efficiency and low hardware cost. Specifically, RIS is a reflective surface with integrated electronic circuits, which consists of a number of components controlled by programmable varactor diodes. Through intelligent control, RIS has the advantages of changing the propagation environment of electromagnetic waves, enriching the channel scattering conditions, solving signal propagation in the case of obstacles, and improving the safety of electromagnetic wave propagation [3-5]. The existing literature has studied RIS from the aspects of precoding, power allocation, phase shift adjustment and so on. The results show that RIS performs well in improving the spectral efficiency and coverage probability of communication systems. However, for the system model where multiple irregular RISs are deployed around the user, how to plan the RIS deployment, and how to select the appropriate RIS to provide services to the user and optimize the system energy efficiency have not been studied. Therefore, this paper focuses on the energy efficiency optimization problem of this novel system.

1.1 Related works

In order to further improve the performance of RIS-assisted communication systems, a large number of studies have been conducted in the existing literature on adjusting the RIS phase shift, transmission power, and beamforming [6-16]. Literature [6] combines the transmit power of the base station (BS) and phase adjustment to optimize the available rate of RIS-assisted communication system. In [7], the asymptotic performance of large RIS-based antenna array system is studied, the channel hardening effect is analyzed, and the performance bound is derived. [8] proposes a resource allocation algorithm taking into account the passive beamforming and modulation schemes. In [9], authors study the RIS-aided multi-user communication system, and propose corresponding resource allocation algorithms for the single-user scenario and the multi-user scenario respectively. Numerical results show that RIS improves system performance significantly. In [11], authors propose a coverage maximization algorithm and give the optimal RIS layout in closed form by analyzing the relationship between RIS layout and the coverage area of RIS. [15] analyzes the relationship between the performance and the number of RISs in a distributed RIS environment. It shows that although the increase of the number of RISs will improve the system capacity, the beamforming complexity, channel estimation overhead and channel feedback overhead will also be increased correspondingly, so the number of RISs should not be too large. However, the RIS components studied in these literatures are regularly deployed. [16] proposes a novel RIS topology of irregular array in which a given number of RIS elements are irregularly arranged on the surface of RIS. The choice of RIS element arrangement will increase the RIS degree of freedom and spatial diversity, thus improving the system capacity.

1.2 Motivation and contributions

Inspired by the advantages that the irregular configuration of phased array has, this paper studies the RIS on-off selection and energy efficiency optimization problem under the irregular RIS topology, which has not been studied in other literature so far.

Specifically, this paper first establishes a model of multiple irregular RIS-assisted downlink communication systems, and proposes an optimization problem with the objective of maximizing the energy efficiency (EE), which combines multiple-variable optimization such as RIS topology design, RIS switch selection, and power allocation. Since it is difficult to obtain the optimal solution of the joint optimization problem, we then decompose the optimization problem into the following sub-problems: topological structure optimization of RIS, RIS phase shift matrix, power allocation and RIS switch state selection sub-problems, so as to obtain the sub-optimal solution of system energy efficiency. Finally, the superiority of the proposed algorithm is verified by simulation analysis. The main work of this paper is summarized as follows.

1) We propose a distributed irregular RIS-assisted communication system, which can adapt to network requirements by designing RIS element topology structure and dynamically opening or closing RISs. In order to maximize the energy efficiency of the system, we jointly optimize RIS element topology, the phase shift of RIS, transmit power and RIS switching state vector. Under the constraint of user minimum rate, transmit power and RIS phase shift unit modulus, we propose an optimization problem aiming at energy efficiency maximization.

2) To deal with the proposed non-convex optimization problem, we decompose the problem into four sub-problems of low complexity. Then, the optimal solution is obtained by solving the four joint sub-problems iteratively.

3) We apply a modified Tabu search algorithm to obtain the solution of the topology design sub-problem. The phase shift is optimized by SCA, and power allocation in derived in a close form. For RIS switch optimization sub-problem, the greedy algorithm is used to find the optimal solution.

4) To evaluate the performance, we prove the convergence of the proposed algorithm. In addition, the complexity is analyzed theoretically and EE is evaluated by simulations.

2. System Model and Question Description for RIS-assisted Communication Systems

2.1 System Model

This paper investigates a novel downlink system model of multiple irregular RIS-assisted communication systems, as shown in **Fig. 1**. In the system, there is one base station (BS) with M antennas and L irregular RIS evenly distributed d_0 meters away from a single antenna user, among which the N_l reflection elements of the l th irregular RIS are sparsely distributed on the grid points of RIS. The small yellow rectangle of RISs in the figure represents the reflection element that works, and if all elements work, it’s a common regular RIS. Here we focus on how to select RIS when there are many RIS around the user and how to design the topology of the reflecting element on RISs to optimize system energy efficiency.

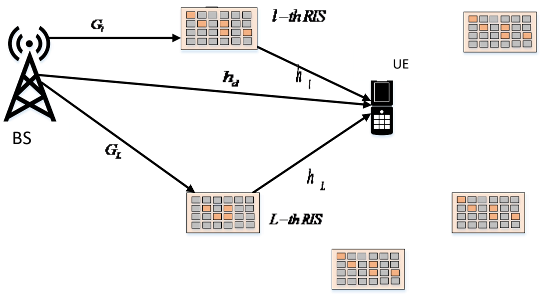


Fig. 1. The downlink of Irregular RIS-aided communication systems
(the on-off status of RIS is controlled by BS)

As shown in **Fig. 1**, the received signals of the user equipment (UE) consists of the signal from direct link and the signals from reflected link. Assuming that the BS has the channel status information of all channels [17-18], the signal received at UE can be expressed as:

$$y = (h_d^H + \sum_{l=1}^{L} x_l h_l^H Z_l\, \Theta_l G_l) ws + \sigma^2 \tag{1}$$

where $w \in \mathbb{C}^M$ represents the transmitted precoding vector from BS, σ^2 is the variance of AWGN, $s \in \mathbb{C}$ is the transmitted signal, $h_l \in \mathbb{C}^{Ns}$ is the channel vector between the irregular RIS l and the UE, $G_l \in \mathbb{C}^{N_S \times M}$ is a $N_S \times M$ channel matrix between BS and the l th RIS, $h_d \in \mathbb{C}^M$ is the channel from BS to UE, $\Theta_l = \text{diag}([\theta_{l,1}, \dots \theta_{l,n} \dots, \theta_{l,N_S}])$ is the phase shift matrix at the lth RIS where $\theta_{l,n} = e^{j\varphi_{l,n}}$ denotes the reflection coefficient of the nth elements of RIS l, $\varphi_{l,n}$ is the phase shift. $\Gamma = \{1, \dots, L\}$ and $\theta_l = [\theta_{l,1}, \dots \theta_{l,n} \dots, \theta_{l,N_S}]^T$ are the index set of RISs and phase shifts of RIS l respectively. $\mathbb{C}$ denotes the set of complex numbers. In order to reduce power consumption, some RISs are not always selected as a serving RIS for the UE. Hence, we introduce the variable $x_l \in \{0,1\}$ here to indicate whether the corresponding RIS is selected. That is to say, x_l=1 indicates that the l th RIS is selected, otherwise, it is not selected. $Z_l = \text{diag}(\mathbf{z}_l)$ represents the topology selection matrix of the lth irregular RIS with $\mathbf{z}_l = [z_{l,1}, \dots z_{l,n} \dots, z_{l,N_S}]^T$. If the RIS element is deployed at the ith grid point of the l irregular RIS, then $z_{l,i} = 1$, otherwise, $z_{l,i} = 0$.

Assuming that the BS adopts the maximum ratio transmission, the data rate and energy efficiency can be expressed respectively as:

$$R_t = Blog_2\left(1 + \frac{p_{down}\left|h_d^H + \sum_{l=1}^{L} x_l h_l^H Z_l diag(\theta_l) G_l\right|^2}{\sigma^2}\right) \tag{2}$$

and

$$\text{EE} = \frac{R_t}{\tau^{-1} p_{down} + P_U + P_{BS} + \sum_{l=1}^{L} x_l N_l P_R} \tag{3}$$

where B is bandwidth, p_{down} the transmission power of the BS. $\rho = \tau^{-1} p_{down} + P_U + P_{BS} + \sum_{l=1}^{L} x_l N_l P_R$ is the power consumption, τ^{-1} is transmitted power amplifier efficiency of BS. P_{BS}, P_U, and P_R are the hardware static power consumption at BS, UE and RIS, respectively.

2.2 Question formulation

Based on the above analysis, we focus our attention on how to maximize the energy efficiency of the system by considering the optimal design of the RIS location, the topology structure of the reflective components, and the phase shift. Hence, the optimization problem is expressed as follows

$$\max_{\boldsymbol{\theta},p_{down},x,Z} EE = \frac{R_t}{\tau^{-1}p_{down}+P_U+P_{BS}+\sum_{l=1}^{L} x_l N_l P_R} \tag{4}$$

s.t.

$$C_1: Blog_2(1+p_{down}\gamma) \geq R_{min},$$
$$C_2: p_{down} \leq P_{max},$$
$$C_3: \varphi_{l,n} \in [0,2\pi];\ l=1,\dots,L; n=1,\dots,N_S$$
$$C_4: x_l \in \{0,1\};\ l=1,\dots,L,$$
$$C_5: z_{l,n}(z_{l,n}-1)=0;\ l=1,\dots,L; n=1,\dots,N_S$$
$$C_6: \sum_n z_{l,n}=1; l=1,\dots,L;$$

where $\boldsymbol{\theta}=[\theta_1,\dots\theta_l\dots,\theta_L], \gamma=\frac{\left|h_d^H+\sum_{l=1}^{L} x_l h_l^H Z_l diag(\theta_l) G_l\right|^2}{\sigma^2}$, C_1 ensures the UE's minimum data rate, C_2 is the transmission power constraint of the BS, C_4 indicates whether RIS l is selected, C_5 and C_6 are sparse deployment constraints of irregular RISs where N diagonal elements of the matrix $\mathbf{Z}$ are assigned 1. Because the constraints C_3, C_4, C_5 and C_6 are non-convex, the optimization problem (4) is hard to solve directly.

3. Energy Efficiency Optimization Strategy

To tackle the above-mentioned issue, we decompose the optimization problem (4) into 4 sub-problems. Specifically, we first optimize topology matrix $\mathbf{Z}$ when the phase shift, power, and on-off variable of RISs are fixed. Then, we employ Taylor expansion to optimize of phase shift and power allocation with other variables fixed. Furthermore, we select APs by greedy algorithm to maximize the EE. Finally, we iteratively update the solutions until convergence.

3.1 RIS reflection element topology optimization based on the modified Tabu search

Tabu search, as a low-complexity strategy for combinatorial optimization problems, has received a lot of attention in numerous areas, such as scheduling, spatial planning, and graph coloring. The Tabu search algorithm starts with an initial solution vector and finds a local neighborhood around it. It selects the best vector among neighboring solutions even if the current solution is the worst. Therefore, it is prone to deviate from the local optimal value. Motivated by the success applications of Tabu search, a modified Tabu search based optimization for the topology of the RIS is proposed. Different from the traditional Tabu search, in the proposed algorithm, RIS elements are not arranged in the two adjacent grid points and the moving distance is adjusted dynamically according to the number of the system parameters, such as reflection elements of RIS, the number of iterations, etc. Before introducing the proposed algorithm, we introduce some definitions.

Definition of moving distance: Define p as the number of 0 and 1 interchanges per time, which will be dynamically adjusted. The larger p is, the faster the exchange is, and the smaller p is, the slower the exchange is. Therefore, if a smaller search range is needed, p is initialized to a smaller number and then adjusted according to the system parameters. Conversely, p is initialized to the larger number.

Definition of Neighborhood: The neighborhood of a given topology vector z_l is defined as a set $N(\mathrm{z}_l)$. If the cardinality of $N(\mathrm{z}_l)$ is Q, it has Q neighboring vectors. Each neighboring vector has 2 p different value from the former one.

Tabu list: Tabu list records the previous solutions and avoids getting stuck in a local optimum. Any solution worse than the elements in the Tabu list will not be adopted. In addition, if the Tabu list is full, the first vector in the list will be removed.

Next, we propose the steps of topology planning based on the modified Tabu list as follows:

Step 1: We initialize the topology of each RIS l as $\mathrm{z}_l^{(0)}$ with randomly select N discontinuous ones, and set the remaining $N_S - N$ elements to 0. Then, the energy efficiency is calculated. To provide better diversity performance, we add all cases with N consecutive ones directly to the Tabu list.

Step 2 starts the iteration.

Step 3: We generate a neighbor list with Q neighbors by exchanging p zeros and p ones to obtain the topology of RIS denoted by $\mathrm{z}_{l,1}^{(i)}, \dots, \mathrm{z}_{l,Q}^{(i)}$. Then, calculate the energy efficiency of all candidates according to equation (3).

Step 4: The candidate with the largest energy efficiency is then selected, i.e., $\mathrm{z}_{l,*}^{(i)} = \underset{q}{\operatorname{argmax}}\left\{EE\left(\mathrm{z}_{l,q}^{(i)}\right)\right\}$, which is saved as a new topology for the next iteration. That is to say, in the neighbor list, we select the topology with the highest energy efficiency as $\mathrm{z}_{l,1}^{(i+1)}$, and add $\mathrm{z}_{l,*}^{(i)}$ to the tabu list to avoid circular search. If the list is full, we delete the earliest Tabu solutions in the current list.

Step 5: The optimization value and Tabu list will be updated accordingly. After reaching the iteration threshold, we can obtain the history optimal topology of RIS.

The aforementioned topology optimization of RIS is briefly described in Algorithm 1.

Algorithm 1 Topology optimization of RIS

Input: M, N, N_S, L, the number of neighbors Q, moving distance p, the number of iterations T, the length of Tabu list.

Output: Topology Z_0

1) Initialize the topology of each RIS $\mathrm{z}_l^{(0)}$, Tabu list (the cases with N consecutive 'one' are added to the initial Tabu list), randomly select N ones that are not adjacent, $N_S - N$ zeors, the number of neighbors Q, and moving distance p.
2) for i=1:T
3) Adjust p adaptively according to i, exchange p zeros and p ones that are not adjacent to change the topology of RIS, and generate a neighbor list $\mathrm{z}_{l,1}^{(i)}, \dots, \mathrm{z}_{l,Q}^{(i)}$.
4) In the neighbor list, select the topology with the highest energy efficiency as $\mathrm{z}_{l,1}^{(i+1)}$.
5) Add $\mathrm{z}_{l,*}^{(i)} = \underset{q}{\operatorname{argmax}}\left\{EE\left(\mathrm{z}_{l,q}^{(i)}\right)\right\}$ to the Tabu list and update the Tabu list.
6) end for
7) Output: The history optimal topology of RIS l.

3.2 Optimization for phase shift and transmit power

By fixing RIS topology and RIS switching variable x, we jointly optimize subproblem of RIS phase coefficient and transmitting power to obtain the suboptimal solution of the objective function. Since the denominator of optimization problem (4) has nothing to do with phase optimization, the phase optimization problem can be transformed into the following problem:

$$\max_{\boldsymbol{\theta}} \left| h_d^H + \sum_{l=1}^{L} x_l h_l^H (\theta_l)^T U_l \right|^2 \tag{5}$$

$$s.t. \varphi_{l,n} \in [0,2\pi];\ l = 1, \ldots, L; n = 1, \ldots, N_S$$

where $(\theta_l)^T U_l = h_l^H Z_l diag(\theta_l) G_l$, $U_l = diag(h_l^H Z_l) G_l$.

In order to make RIS selection variable x, topology variables Z_l and the corresponding phase coefficient separation, we denote $\boldsymbol{U} = [x_1 U_1, \ldots, x_L U_L] \in \mathbb{C}^{Q \times M}$ and $\boldsymbol{v} = [{\theta_1}^*, \ldots, {\theta_L}^*] \in \mathbb{C}^Q$. Then, problem (5) reduces to the optimization problem of variable $\boldsymbol{U}$ and variable $\boldsymbol{v}$:

$$\max_{\boldsymbol{v}} \left| h_d^H + \boldsymbol{U}^H \boldsymbol{v} \right|^2 \tag{6}$$

s.t.,

$$|v_q| = 1; q \in \{1, \ldots, Q\}$$

where $Q = LN_S$.

In order to solve problem (6), the first-order Taylor expansion of its objective function is carried out,

$$\left| h_d^H + \boldsymbol{U}^H \boldsymbol{v} \right|^2 \approx 2R\left((h_d^H + \boldsymbol{U}^H \boldsymbol{v}^{\boldsymbol{n-1}})^H \boldsymbol{U}^H \boldsymbol{v} \right) + \left| h_d^H + \boldsymbol{U}^H \boldsymbol{v}^{\boldsymbol{n-1}} \right|^2 - 2R((h_d^H + \boldsymbol{U}^H \boldsymbol{v}^{\boldsymbol{n-1}})^H \boldsymbol{U}^H \boldsymbol{v}^{\boldsymbol{n-1}}) \tag{7}$$

Then, by relaxing the constraints, problem (6) is transformed into a solvable convex problem according to (7) as follows:

$$\max_{\boldsymbol{v}} 2R\left((h_d^H + \boldsymbol{U}^H \boldsymbol{v}^{\boldsymbol{n-1}})^H \boldsymbol{U}^H \boldsymbol{v} \right) \tag{8}$$

s.t.

$$|v_q| \leq 1; q \in \{1, \ldots, Q\}$$

Therefore, if the following conditions are satisfied:

$$Im\left(\left[(h_d^H + \boldsymbol{U}^H \boldsymbol{v}^{\boldsymbol{n-1}})^H \boldsymbol{U}^H \right]_q \right) [\boldsymbol{v}]_q = 0; q \in \{1, \ldots, Q\}$$

is a real number, and $[\boldsymbol{v}]_q$=1, then $\boldsymbol{v}$ has an optimal solution:

$$\boldsymbol{v} = e^{j \measuredangle \boldsymbol{U}^H (h_d^H + \boldsymbol{U}^H \boldsymbol{v}^{\boldsymbol{n-1}})} \tag{9}$$

Here, $[\cdot]_q$ is the q th element of $[\cdot]$. The target value obtained by the above algorithm is monotone non-decreasing, and the iteratively obtained value $\boldsymbol{v}^n$ converges to the point satisfying the Karush-Kuhn-Tucker (KKT) optimal condition of the original non-convex problem (6).

In order to optimize the power, we substitute the optimized phase (9) into formula (4) and further simplify the optimization problem as follows:

$$\max_{p_1} EE = \frac{Blog_2(1+p_{down}\gamma)}{\tau^{-1}p_{down}+P_U+P_{BS}+\sum_{l=1}^{L} x_l N_l P_R} \tag{10}$$

s.t.

$$C_1: Blog_2(1+p_{down}\gamma) \geq R_{min}$$
$$C_2: p_{down} \leq P_{max}$$

Since the objective function of Equation (10) is upper convex, the point where its derivative equals 0 is the power point that maximizes the objective function. We take the derivative of the objective function of problem (10) with respect to p_{down} as

$$\frac{\partial \frac{Blog_2(1+p_{down}\gamma)}{\tau^{-1}p_{down}+P_U+P_{BS}+\sum_{l=1}^{L} x_l N_l P_R}}{\partial p_{down}} = \frac{B\left(\gamma(\tau^{-1}p_{down}+P_U+P_{BS}+\sum_{l=1}^{L} x_l N_l P_R)-\tau^{-1}\cdot(1+p_{down}\gamma)ln(1+p_{down}\gamma)\right)}{ln2\cdot(1+p_{down}\gamma)(\tau^{-1}p_{down}+P_U+P_{BS}+\sum_{l=1}^{L} x_l N_l P_R)^2} \tag{11}$$

The optimal power can be obtained by solving the following formula

$$\gamma\left(\tau^{-1}p_{down}+P_U+P_{BS}+\textstyle\sum_{l=1}^{L} x_l N_l P_R\right)-\tau^{-1}\cdot(1+p_{down}\gamma)ln(1+p_{down}\gamma)=0 \tag{12}$$

Let $t=1+p_{down}\gamma$, and from (12), we have

$$f(t)=t(lnt-1)=\gamma\tau(P_U+P_{BS}+\textstyle\sum_{l=1}^{L} x_l N_l P_R) \tag{13}$$

From (13), we have

$$p_{down}=\left[f^{-1}\left(\gamma\tau(P_U+P_{BS}+\textstyle\sum_{l=1}^{L} x_l N_l P_R)\right)-1\right]/\gamma \tag{14}$$

where $f^{-1}()$ is the inverse function of $f(t)$.

3.3 RIS selection and switching optimization

After optimizing the topology structure, power and phase shift, the optimization objective function (4) is simplified to

$$\max_{x} EE = \frac{Blog_2\left(1+\frac{p_{down}\left|h_d^H+\sum_{l=1}^{L} x_l h_l^H Z_l diag(\theta_l)G_l\right|^2}{\sigma^2}\right)}{\tau^{-1}p_{down}+P_U+P_{BS}+\sum_{l=1}^{L} x_l N_l P_R} \tag{15}$$

However, (15) is a nonlinear integer problem and can’t be solved directly. Therefore, we adopt greedy algorithm (shown in Algorithm 2) to calculate the corresponding objective function by trying to deactivate each RIS. If the disable of one RIS helps to improve the energy efficiency of the system, it will be closed; otherwise, it will not be closed. The RIS selection and switching optimization steps are described as follows:

Sept 1: We first initialize the switch vector of RISs to $x = (x_1, x_2, \dots, x_L)^T = 1_L$, denote the set of activated RIS as Γ', and calculate the corresponding energy efficiency as

$$EE_0 = \frac{Blog_2(1 + p_{down}\gamma)}{\tau^{-1}p_{down} + P_U + P_{BS} + \sum_{l=1}^{L} N_l P_R}$$

Step 2: We calculate the energy efficiency EE_l by deactivating RIS $l \in \Gamma'$ according to (15)

$$EE_l = \mathrm{EE}|_{x_l=0}$$

Step 3: If switching off RIS l^* makes the system most energy efficient, turn it off. Then, update initial energy efficiency EE_0 and the set Γ' for the next iteration.

Step 4: If switching off RIS does not improve EE, break and output the optimized EE and optimized vector x.

Algorithm 2: RIS selection and switching optimization based on greedy algorithm.

Input: $\boldsymbol{Z}_0$, $\boldsymbol{\theta}$, p_{down}

1) Initialize the switch vector of RISs, i.e. $\boldsymbol{x} = \boldsymbol{1}_L$, denote the initial energy efficiency as EE_0; Denote the set of active RIS as Γ'.
2) **while** the cardinality of Γ' >1 do;
3) **for** each active RIS $l \in \Gamma'$;
4) Deactivate RIS l, i.e. $x_l = 0$, and calculate the energy efficiency EE_l by (15);
5) If $EE_l - EE_0 > \varepsilon > 0$, and $l^* = argmax\{EE_l\}$, let $x_{l*} = 0$. Update the initial energy efficiency EE_0 and the set of active RIS Γ'.
6) **else** $x_{l*} = 1$ and break.
7) **end for;**
8) **end while**
9) Output: The optimized EE and optimized RIS switch vector $\boldsymbol{x}$.

3.4 The framework of the joint optimization algorithm

According to the previous topology optimization, phase and power optimization, and RIS switch optimization, we obtain the overall framework of the algorithm in this paper. The specific optimization scheme is given in Algorithm 3. In this framework, the variables are alternately updated until the convergence of the objective function is achieved. In addition, since the objective function in (4) is increasing at each iteration and the target value is bounded, this ensures the convergence of algorithm 3.

Algorithm 3: The Proposed Joint optimization Framework

Input: Initialize RIS phase element $\boldsymbol{\theta}^{\boldsymbol{0}}$, transmit power p_{down}^0, RIS topology $\boldsymbol{Z}_0$ and RIS switching vector x^0; Set m=1;

Step 1: fix the phase $\boldsymbol{\theta}^{m-1}$, transmit power p_{down}^{m-1}, RIS switching vector x^{m-1}, and optimized RIS topology of the (m-1) th iteration, and optimize the matrix of the mth topology $\boldsymbol{Z}^m$.

Step 2: fix the RIS topology $\boldsymbol{Z}^m$, transmit power p_{down}^{m-1}, and RIS on-off vector x^{m-1}, and optimize the phase element of RIS $\boldsymbol{\theta}^m$.

Step 3：fix the RIS topology $\boldsymbol{Z}^m$, RIS on-off vector x^{m-1}, $\boldsymbol{\theta}^m$, and optimize the transmit power p_{down}^m under the maximum transmit power constraint；
Step 4：fix the RIS topology $\boldsymbol{Z}^m$, the optimized transmit power p_{down}^m, $\boldsymbol{\theta}^m$, and optimize x^m (which indicates whether a RIS is enabled or not);
m=*m*+1;
Repeat the above steps until EE converges;
Output: $\boldsymbol{Z}^{opt}$, p_{down}^{opt}, $\boldsymbol{\theta}^{opt}$, x^{opt} and the optimized EE.

3.5 Complexity analysis

The complexity of Algorithm 3 mainly depends on the updates of the three variables Z, θ, and x. Specifically, according to Algorithm 1, the complexity of updating the topology Z is $O(T_1QL)$. According to (9), the complexity of solving θ is $O(T_2AM)$, where A is the total number of elements of the L RISs. According to Algorithm 2, the complexity of solving x mainly depends on calculating the objective function in (15) and the cardinality of Γ. Hence, the complexity of this part is $O(L(L-1)AM)$, where $O(AM)$ represents the complexity of calculating the EE in (15), and $O(L(L-1))$ is the iteration number of Algorithm 2. T_1 *and* T_2 are the number of iterations for convergence of topology and phase shift optimization, respectively. We ignore the complexity of power allocation since it is a closed-form solution. In summary, the complexity of our proposed algorithm is $O(T_1QL + T_2AM + L(L-1)AM)$. By contrast, the optimization of topology structure by exhaustive method has a higher complexity, i.e., $LC_{N_s}^N = \frac{LN_s!}{N!(N_{s-N})!}$. The complexity of optimization x by exhaustive method is $\sum_{l=1}^{L} C_L^l$.

4. Simulation and Analysis

4.1 Parameters Setup

In this section, we consider a 200-meter square area with an 8-antenna BS in the center and one user randomly distributed in the area, as shown in **Fig. 2**. The performance of the proposed algorithm will be analyzed and compared with the following two algorithms: a centralized regular RIS (CRIS) scheme of RIS: the joint optimization of phase and power with one centralized regular RIS located at a distance of d_0 meters from the user; Distributed regular RIS scheme (DRIS) scheme: the joint optimization of AP selection, phase and power with L regular RISs evenly distributed d_0 meters away from the user. The proposed algorithm: the joint optimization proposed in Section 3 with L irregular distributed RISs deployed in the system.

The channel gain is determined by both large-scale fading and small-scale fading [19]. The Rayleigh fading channel model is used to account for the small-scale fading, i.e. $h_l, h_d, G_l \sim CN(0,1)$. The large-scale fading model is based on the distance between the transmitter and the receiver which is calculated by $\beta = \frac{\gamma_0}{d^a}$, where γ_0 is the reference pathloss at one-meter distance. a is the path loss exponent. We set $\beta = \frac{10^{-3.53}}{d^{3.76}}$ for the following simulations.

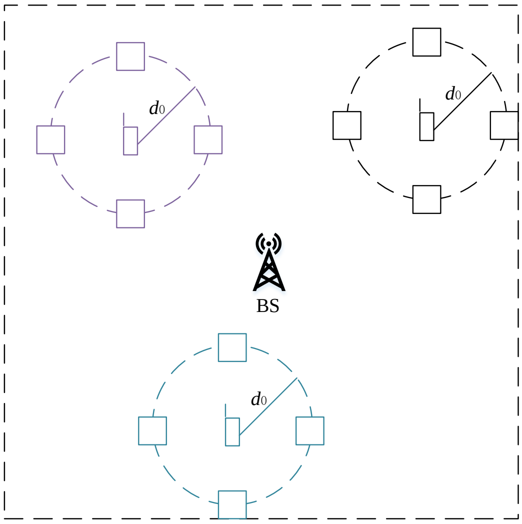


Fig. 2. Simulation scenario with one user randomly distributed in the 200-meter square area

In our simulation, the irregular RIS has $N_S = 20$ points over its surface and N elements. In the distributed RIS case, each regular RIS has N elements, and in the centralized RIS case, each regular RIS has LN elements. Transmit power amplifier efficiency $\tau^{-1} = 1/8$, Bandwidth B=1MHz. $P_R = 10dBm$, $P_K = 10dBm$. The maximum transmit power of the BS is $P_{max} = 50dBm$.

4.2 Performance Analysis

Fig. 3 describes the relationship between the average EE and the maximum transmission power. It shows that the EE of the proposed algorithm is superior to other algorithms. Compared with centralized RIS schemes, the proposed algorithm and distributed algorithm with RIS selection improve the energy efficiency by about 9.2% and 4.7% respectively when $P_{max} = 30dBm$. Furthermore, as observed, the EE of the system increases first and then becomes stable with the increase of transmission power. This is because the data rate cannot keep up with the transmission power growth rate.

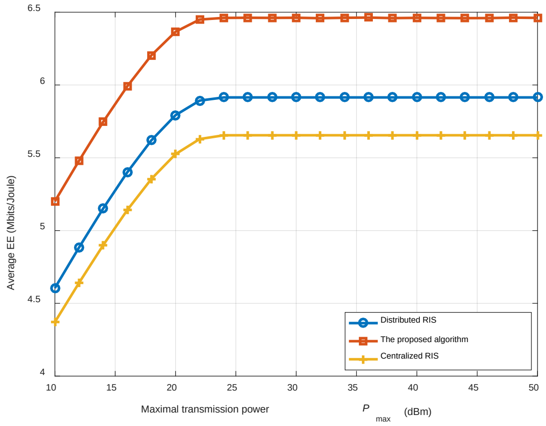


Fig. 3. EE v.s. the maximal transmission power ($d_0 = 20m, N = 4, L = 8$)

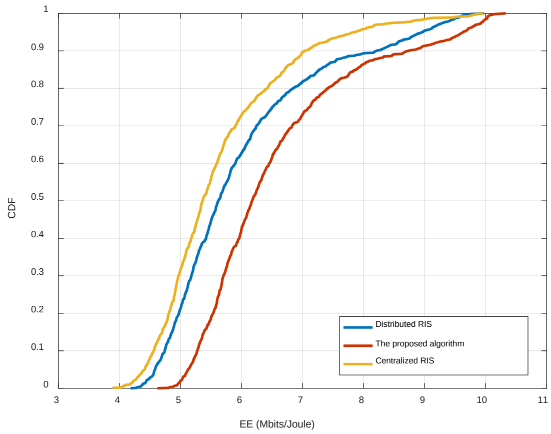


Fig. 4. the CDF of EE $(d_0 = 20m, N = 4, L = 8,\ Pmax = 30)$

Fig. 4 describes the CDF of EE with different schemes. As observed, the probability that the user is in low energy efficiency is much less than the other two cases.

Fig. 5 shows the relationship between the sum-rate versus the maximum BS transmission power. It can be seen that as the maximum transmit power increases, the sum-rate increases. Compared with the CRIS scheme, DRIS improves sum-rate effectively. This is due to the advantages of distributed deployment. Deploying multiple RIS in a DRIS network increases the received signal path for both user-RIS links and RIS-BS links, which provides greater diversity gain and thus increases data rate. However, in the case of CRIS, there is only one RIS, which results in a single path direction for user-RIS and RIS-BS, providing a less effective path diversity. **Fig. 5** also shows that the sum-rate of the algorithm combined with irregular RIS is better than the case with regular RIS.

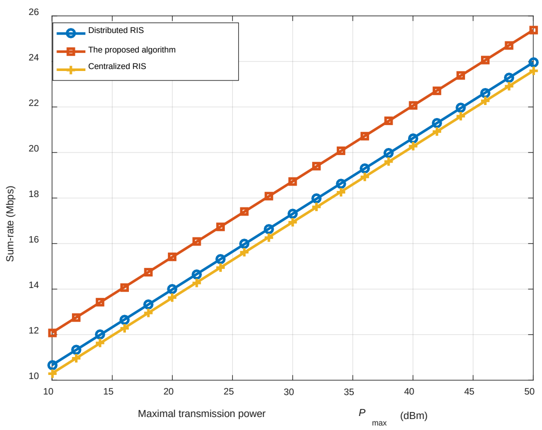


Fig. 5. Sum-rate v.s. the maximal transmission power $(d_0 = 20m, N = 4, L = 8)$

Fig. 6 gives the relationship between the user's minimum rate requirement and the EE. As observed, with the increase of the minimum rate requirements, the EE first stabilizes and then decreases. This is because, when the minimum rate threshold is relatively small, the system can easily achieve the rate requirement without additional increase in transmit power. However, when the threshold is large, the transmitted power needs to be increased to meet the minimum rate requirement, and the contribution brought by the rate increase is not enough to offset the increase in power consumption, so the energy efficiency is reduced. In addition, and the proposed algorithm is significantly better than other algorithms. This comes from the fact that the power consumption of the two distributed RIS is much lower than the transmission power of the centralized RIS, and the achievable rate is also lower than that of the centralized RIS. Therefore, the EE of the two distributed RIS is obviously better than that of the centralized RIS. Meanwhile, the proposed algorithm optimizes RIS topology structure and effectively improves EE.

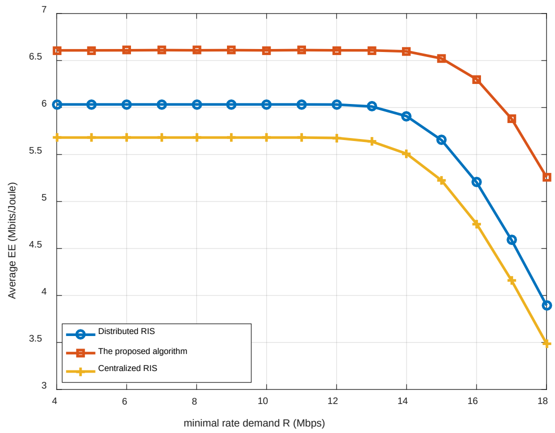


Fig. 6. the EE v.s. the minimal demand of date-rate ($d_0 = 20m, N = 4, L = 8$)

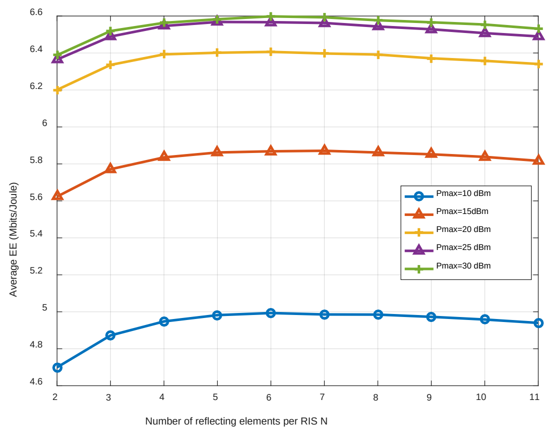


Fig. 7. the number of reflecting elements of RIS v.s. EE ($d_0 = 20m$)

Fig. 7 provides the relationship between the EE and the number of reflecting elements of RIS (N) in the 8-RIS scenario. It shows that as N increases, the EE of the proposed algorithm first increases and then decreases. This is because when N is relatively small, the contribution from the rapid growth of the system rate compensates for the increase in power consumption as N increases, which leads to the increase in EE. However, when N is relatively large, the increase in the system rate cannot catch up with the increase in power consumption, which leads to a decrease in EE. Meanwhile, the system complexity and deployment cost are also increasing with the increase of N. Therefore, the number of RIS elements should not be blindly increased in practice. Note that N here represents the number of active RIS elements, not the number of optional RIS primitives. Otherwise, EE will increase first and then becomes stable.

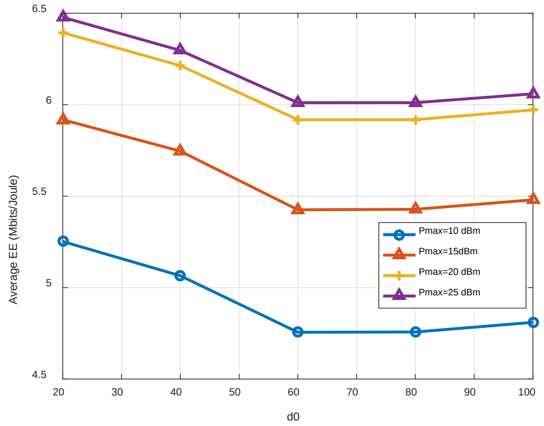


Fig. 8. EE v.s. the user-RIS distance d_0

Fig. 8 gives the relationship between EE and the user-RIS distance with different maximal power. It shows that energy efficiency decreases first and then increases as distance d_0 increases. This is because the greater the user-RIS distance, the lower the data rate. Later, as the distance further increases, the RIS-BS link enhancement compensates for the loss of EE, so the EE increases.

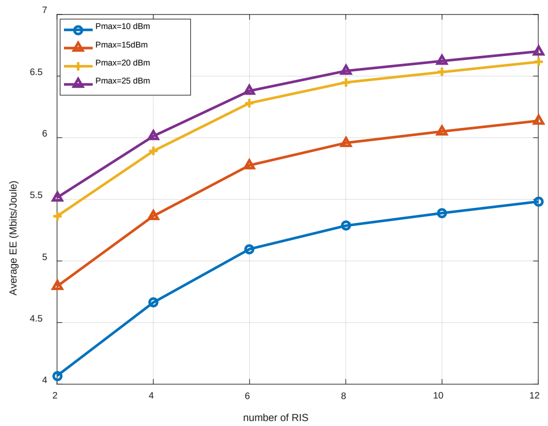
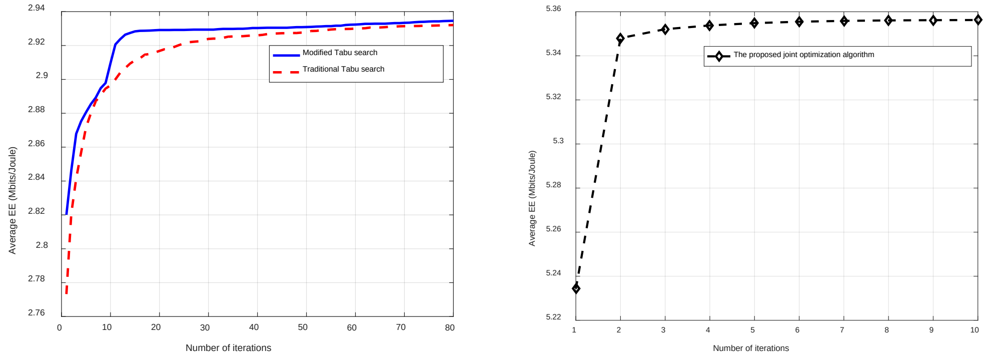


Fig. 9. EE v.s. the number of RISs L

Fig. 9 depicts the effect of the number of RISs (L) on EE. As observed, EE increases with the increase of L. This is because more RISs provide more freedom of selection. Furthermore, when L continues to increase, Algorithm 2 will help select an appropriate number of RISs from L RISs to provide service for the user. Therefore, EE finally tends to be flat here. Compared with **Fig. 7** and **Fig. 9**, EE shows different trends. This is because the N in **Fig. 7** represents the number of RISs reflection elements participating in the service, and the higher the N, the higher the power consumption, which leads to the decrease of EE. However, L in **Fig. 9** represents the number of the optional RISs. RIS will not be selected if there are already enough activated RISs, so EE will not decrease after reaching the maximum value.



(a) The topology optimization algorithm (b) The proposed joint optimization algorithm
(b)

Fig. 10. EE v.s. the number of iterations ($N_S = 12, N = 4$)

Fig. 10 (a) compares the convergence performance of topology designs of different algorithms. It shows that the modified Tabu search has a larger initial value. This is because, we initialize to avoid starting from the possible case of low diversity gain. As observed, the modified Tabu search based topology design has better convergence than the traditional Tabu search. It can be seen that after a certain number of iterations, the modified algorithm changes the step size to accelerate the convergence. **Fig. 10 (b)** gives the convergence performance of the alternate iteration in Algorithm 3. It shows that the proposed algorithm converges after about 4 iterations.

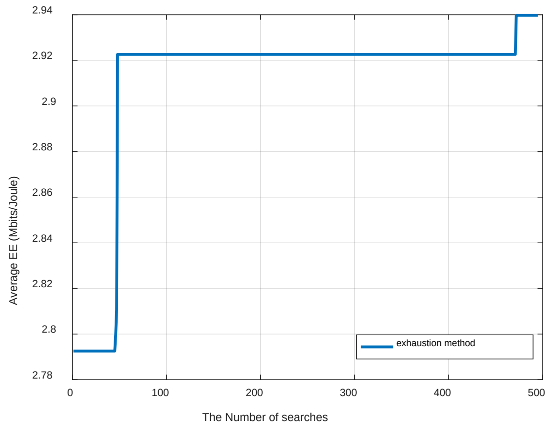


Fig. 11. the maximum value of exhaustive search ($N_S = 12, N = 4$)

In **Fig. 11**, we activate 4 of the 12 RISs elements by exhaustive search, with a total of 495 possibilities, of which the maximum is 2.94 Mbits/Joule. By comparing **Fig. 10 (a)**, it can be concluded that the algorithm proposed in this paper achieves near-optimal performance with low complexity.

5. Conclusion

In this paper, for multiple irregular RIS-assisted communication systems, we investigate the joint optimization problem with the goal of maximizing energy efficiency under the minimum user data-rate constraint. However, the joint optimization problem in terms of 4-

dimensional variables considering RIS topology structure, RIS switch, phase shift and power control is a nonlinear non-convex optimization problem and is very hard to be solved. To this end, we first decompose the hybrid optimization problem into four sub-problems. Then, the four sub-problems are iteratively optimized until convergence. The simulation results show that the proposed irregular RIS assisted communication system improves the system energy efficiency and sum-rate effectively.

6. Future research

In the communication scenario where multiple RISs are deployed around the user and RIS elements are irregularly distributed, this paper establishes the system model and proposes the optimization framework of energy efficiency, which is beneficial for the application of RIS in the sixth generation (6G). However, there are still some shortcomings in the paper, which can be further studied from the following aspects:

1) The research in this paper is based on the assumption of perfect CSI, but in the practical communication systems, there are always errors in channel estimation. Therefore, the optimization of imperfect CSI will be a part of our work in the future.
2) In this paper, we focus on the optimization for the single cell scenario, where the interference between the cells is ignored. Optimization research in multi-cell scenario will also be the focus of future research.
3) Recently, with the development of metasurfaces, the concept of simultaneous transmit and reflect RIS (STAR-RIS) has been proposed which has ability of providing full-space coverage in wireless environments. In our future work, EE optimization for irregular STAR-RIS will also be considered.

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