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Research on IRS-assisted NOMA energy efficiency transmission scheme

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Abstract: The combination of intelligent reflect surface (IRS) and non-orthogonal multiple access (NOMA) is an effective solution to improve communication coverage and energy efficiency. Energy efficiency (EE) is an important performance index of communication system. In this paper, the IRS-assisted NOMA downlink multi-cluster system is taken as the research object. Under the requirement of user quality of services (QoS), the energy efficiency of the system is maximized by alternately optimizing the power allocation of the base station and the phase shift of the IRS passive components. However, the non-convexity of the optimization problem and the coupling of the optimization variables make the optimization problem difficult to solve. Therefore, a new alternating optimization scheme is proposed in this paper. The problem is divided into two sub-problems, which are solved by first-order Taylor expansion method, successive convex approximation method and semi-definite relaxation method respectively. The simulation results show that the IRS-NOMA transmission scheme proposed in this paper has better performance than other transmission schemes of RIS-NOMA system.

Keywords: Intelligent reflect surface; Non-orthogonal multiple access; Energy efficiency; Power allocation; Phase shift optimization.

1. Introduction

Intelligent reflect surface (IRS) is considered to be a revolutionary technology beyond the fifth-generation wireless network. Compared with traditional wireless relay technology, IRS only reflects signals and operates in full-duplex mode with low energy consumption. By adjusting the phase of the low-cost passive reflection element integrated on the IRS, the propagation path of the reflected signal can be modified cooperatively to improve the communication coverage, throughput and energy efficiency. Specifically, the IRS is a met surface integrated with a large number of reflective elements, and the cost is low. It can be quickly deployed on the surface of buildings or indoor walls, making it a great application scenario in future wireless communications.

Non-orthogonal multiple access (NOMA) is considered to be the key technology of B5G due to its high spectral efficiency and high energy efficiency. Due to the respective advantages of IRS and NOMA, IRS and NOMA are naturally compatible [6-7]. This paper mainly studies the IRS-assisted NOMA downlink multi-cluster system. Different from the sum rate maximization [8-9] and the transmission power minimization, our goal is to maximize energy efficiency in the downlink IRS-NOMA network.

Different from the design strategy of the traditional NOMA system, in the IRS-NOMA system, the transmitter and phase shift need to be jointly optimized, so the design is more difficult. Reference studied the low-power transmission problem of IRS-NOMA system. By establishing the relationship between the user 's transmission power and the IRS phase shift, the original joint optimization problem is transformed into a pure phase shift optimization problem. In, the semidefinite relaxation (SDR) and difference-of-convex (DC) methods are used to optimize the transmission beamforming of BS and the passive beamforming of IRS to reduce the total transmission power of the system. In Reference, researchers proposed a sub-optimal algorithm combining block coordinate descent (BCD) and SDR to jointly optimize the power allocation of BS and the phase shift of IRS, so as to maximize the minimum signal-to-interference-plus-noise-ratio (SINR) of the decoding signal at the user side. At present, most of the research on IRS-NOMA systems focuses on the total system power consumption or system rate, while considering the influence of both, the research on maximizing the data transmission rate per unit energy consumption is still relatively rare. The increasing communication throughput causes huge energy consumption. The future communication system will develop towards green communication, and it is urgent to design a higher EE transmission scheme.

This paper studies the EE optimization problem of IRS-NOMA system. Firstly, for the IRS assisted NOMA downlink multi-cluster system transmission model, the minimum communication rate requirement of each cluster user and the maximum transmission power constraint of BS are considered, and the EE maximization problem of each cluster based on the model is established. Secondly, in order to solve the non-convex optimization problem of the coupling of the optimization variables, the original problem is decomposed into two sub-problems: BS power allocation and IRS phase shift optimization. The alternating optimization algorithm is used to solve the problem, and the first-order Taylor expansion method, successive convex approximation method and semi-definite relaxation method are used to solve the problem until the convergence condition is triggered. Finally, the simulation results show that the IRS-NOMA transmission scheme proposed in this paper can obtain higher EE performance than other schemes of IRS-NOMA system and IRS-OMA scheme.

2. System Model

The research scenario is that the IRS-assisted NOMA

downlink system includes two types of users, namely central users and cell edge users. They are also served by the base station, and the central user is much closer to the base station and the IRS and the channel between the base station and the center user are modeled with Rice fading channels as follows:

$$\mathbf{f}=\sqrt{\frac{\kappa}{1+\kappa}}\mathbf{f}^{LoS}+\sqrt{\frac{1}{1+\kappa}}\mathbf{f}^{nLoS} \tag{1}$$

Where κ is the Rice factor, $\mathbf{f}^{LoS}$ is the line-of-sight component, and $\mathbf{f}^{nLoS}$ is the non-line-of-sight component following the Rayleigh distribution.

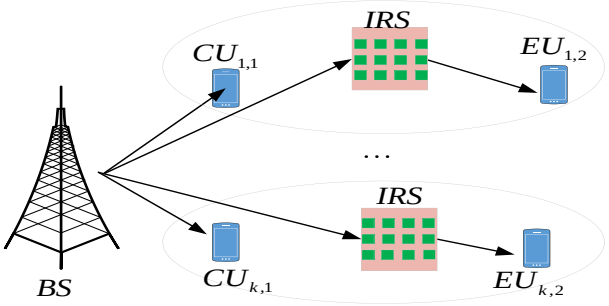


Fig.1 System model

The superimposed signal of the base station is:

$$\sum_{i=1}^{K}\left(\sqrt{p_{i,c}}x_{i,c}+\sqrt{p_{i,e}}x_{i,e}\right) \tag{2}$$

Where $x_{i,c}$ and $x_{i,e}$ represent the signals that the base station sends to the central user and the edge user of cluster i, respectively. $p_{i,c}$ and $p_{i,e}$ are their power allocation factors, respectively. The superimposed signal of the central user is:

$$y_{k,c}=h_{k,c}^{H}\sqrt{p_{k,c}}x_{k,c}+h_{k,c}^{H}\sqrt{p_{k,e}}x_{k,e}+h_{k,c}^{H}\sum_{\substack{i=1\\ i\neq k}}^{K}\left(\sqrt{p_{i,c}}x_{i,c}+\sqrt{p_{i,e}}x_{i,e}\right)+n_{k,c} \tag{3}$$

Where $h_{k,c}\in\mathbb{C}^{M\times 1}$ represents the channel vector of the base station and the central user, and $n_{k,c}$ is the received Gaussian white noise. The received signal of the edge user is:

$$y_{k,e}=\left(h_{k,e}^{H}\Theta_k G_k\right)\sqrt{p_{k,e}}x_{k,c}+\left(h_{k,e}^{H}\Theta_k G_k\right)\sqrt{p_{k,c}}x_{k,c}+\left(h_{k,e}^{H}\Theta_k G_k\right)\sum_{\substack{i=1\\ i\neq k}}^{K}\left(\sqrt{p_{i,c}}x_{i,c}+\sqrt{p_{i,e}}x_{i,e}\right)+n_{k,e} \tag{4}$$

where $G_k\in\mathbb{C}^{N\times M}$ represents the channel matrix of the base station and the IRS, $h_{k,e}\in\mathbb{C}^{N\times 1}$ represents the channel vector of the IRS and the edge user, $n_{k,e}$ is the received Gaussian white noise, $\Theta_k=diag\left(\beta e^{j\theta_1^k},\cdots,\beta e^{j\theta_n^k}\right)$ represents the IRS phase shift matrix, and $\theta_n^k\in(0,2\pi],n\in\{1,\cdots N\},\beta\in[0,1]$ is the phase shift and amplitude coefficient of each reflection element n on the signal. Considering that the passive reflection element can only change the phase of the reflected signal, but can't change the amplitude to take $\beta=1$. Due to the path loss, this paper argues that the signal can only be effectively reflected by the IRS once. In addition, the position separation ensures that the IRS between clusters does not interfere with each other. Since the cell-edge users are far away from the base station, the signal will suffer serious large-scale path loss. Therefore, the strategy of performing SIC only at the central user to eliminate the interference of the edge users in the cluster, and the cell-edge users directly decode their data is adopted.

Therefore, the edge user 's $SINR_{k,e}$ is:

$$SINR_{k,e}=\frac{\left|h_{k,e}^{H}\Theta_k G_k\right|^2 p_{i,e}}{\left|h_{k,e}^{H}\Theta_k G_k\right|^2 p_{i,c}+\sum_{\substack{i=1\\ i\neq k}}^{K}\left|h_{k,e}^{H}\Theta_k G_k\right|^2+\sigma^2} \tag{5}$$

For the central user, the SIC decoding signal $x_{k,e}$ needs to be applied first. Therefore, the $x_{k,e}$ of the observed signal $SINR_{k,c\to e}$ can be expressed as:

$$SINR_{k,c\to e}=\frac{\left|h_{k,c}^{H}\right|^2 p_{k,e}}{\left|h_{k,c}^{H}\right|^2 p_{k,c}+\sum_{\substack{i=1\\ i\neq k}}^{K}\left|h_{k,c}^{H}\right|^2+\sigma^2} \tag{6}$$

The $SINR_{k,c}$ of the central user decoding its own signal is:

$$SINR_{k,c}=\frac{\left|h_{k,c}^{H}\right|^2 p_{k,c}}{\sum_{\substack{i=1\\ i\neq k}}^{K}\left|h_{k,c}^{H}\right|^2+\sigma^2} \tag{7}$$

The rates of central users and edge users are:

$$R_{k,c}=B\,log\left(1+SINR_{k,c}\right) \tag{8}$$

$$R_{k,e}=B\,log\left(1+SINR_{k,e}\right) \tag{9}$$

For a multi-cluster downlink NOMA system with two users in each cluster, the energy efficiency is expressed as:

$$e=\frac{\sum_{k=1}^{K}R_k(p_k)}{\sum_{k=1}^{K}p_k} \tag{10}$$

Where $R_k\left(p_k\right)$ is the maximum sum rate of two users in the K-th cluster when the power of the K-th cluster is p_k:

$$R_k(p_k)=B\,log\left(1+SINR_{k,c}\right)+B\,log\left(1+SINR_{k,e}\right) \tag{11}$$

3. Problem description

In this section, this paper proposes to maximize the system EE, and the joint optimization problem of BS power allocation and IRS phase shift is modeled as:

$$\begin{aligned}
&P(1)\max_{p_{k,\Theta}}\frac{\sum_{i=k}^{K}R_k\left(p_k\right)}{\xi\sum_{i=k}^{K}p_k+p_c}\\
&s.tC1:\sum_{k=1}^{K}p_k\le P_{\max}\\
&C2:R_{k,c}\ge R_{k,c}^{\min},\forall k\\
&C3:\log\left(1+\min\left(SINR_{k,e},SINR_{k,c\to e}\right)\right)\ge R_{k,e}^{\min},\forall k\\
&C4:0\le\theta_{k,n}\le 2\pi,\forall k,n\\
&C5:\left|\Theta_{k,n,n}\right|\le 1,\forall k,n
\end{aligned} \tag{12}$$

Where ξ is the power transmission efficiency, p_c is the circuit power consumption, C1 represents the power of the base station as $P_{\max}$, C2 and C3 to ensure the QoS of each cluster of users, C4 defines the phase shift range of the reflection element, and C5 ensures that the IRS is a passive component.

4. Alternating optimization solution method

In this paper, an alternating optimization method is proposed to solve the problem. The optimization problem P (1) is decomposed into two sub-problems. Firstly, the phase shift of the IRS is fixed, and the power distribution coefficient

is optimized. Then, the phase shift of the IRS is optimized according to the coefficient. The two are continuously iterated. When the difference between the objective function values of the two iterations is less than 10^4, or the total number of iterations reaches the maximum value, the iteration is terminated, and the optimal power distribution coefficient and IRS phase shift can be obtained. In the alternating optimization process, the order of the user 's equivalent channel gain needs to remain unchanged.

4.1. Optimal Power Allocation

For a given phase shift matrix Θ, the channel gain $h_{k,e}^H \Theta_k G_k$ is fixed. Therefore, the power optimization problem can be expressed as:

$$P(2) \max_{p_k} \frac{\sum_{i=k}^{K} R_k(p_k)}{\xi \sum_{i=k}^{K} p_k + p_c} \quad s.t \quad C1, C2, C3 \tag{13}$$

Since the objective function is complex and non-convex, and the constraints C2 and C3 are not convex sets, the optimization is still difficult to solve. Therefore, the objective function, constraints C3 and C4 will be transformed to obtain an approximate problem which is easy to solve.

First, the constraint C2 is changed:

$$\frac{p_{k,c}\left|h_{k,c}^H\right|^2}{\sum_{\substack{i=1 \\ i\neq k}}^{K}\left|h_{k,c}^H\right|^2 + \sigma_k^2} \geq 2^{R_{\min}} - 1 \tag{14}$$

$$p_{k,c}\left|h_{k,c}^H\right|^2 \geq \left(2^{R_{\min}} - 1\right)\left(\left|\sum_{\substack{i=1 \\ i\neq k}}^{K}\left|h_{k,c}^H\right|\right|^2 + \sigma_k^2\right) \tag{15}$$

The constraint C3 needs to be transformed into a convex form. The constraint can be rewritten as:

$$\frac{\left|e_k^H D_{k,e} G_k\right|^2 p_{k,e}}{\left|e_k^H D_{k,e} G_k\right|^2 p_{k,c} + \sum_{\substack{i=1 \\ i\neq k}}^{K}\left|e_k^H D_{k,e} G_k\right|^2 + \sigma^2} \geq r_{k,e} \tag{16}$$

Where $r_{k,e} = 2^{R_{k,e}} - 1$, e_k is a vector of $N \times 1$ containing all diagonal elements of Θ_k^H, $D_{k,e}$ is a diagonal matrix, and the diagonal elements come from $h_{k,e}^H$. At the same time, the first-order Taylor approximation in SCA is used to solve the problem of (17).

$$\left|e_k^H D_{k,e} G_k\right|^2 \left(1 + r_{k,e}\right) p_{k,c} \leq \left|\left|e_k^H D_{k,e} G_k\right|^2\right| - \sum_{\substack{i=1 \\ i\neq k}}^{K}\left|e_k^H D_{k,e} G_k\right|^2 r_{k,e} - \sigma^2 r_{k,e} \tag{17}$$

Since BS is fully aware of CSI, the channel $e_k^H D_{k,e} G_k$ is fixed with a given phase shift matrix. To simplify the representation, let $z_{k,e}^H = e_k^H D_{k,e} G_k$, re-represent (17) as follows:

$$p_{k,c}\left|z_{k,e}^H\right|^2 \leq \frac{\left|z_{k,e}^H\right|^2}{1 + r_{k,e}} - \left(\sum_{\substack{i\neq 1 \\ i=k}}^{K}\left|z_{k,e}^H\right|^2 + \sigma^2\right)\frac{r_{k,e}}{1 + r_{k,e}} \tag{18}$$

Let $Z_{k,e} = z_{k,e} z_{k,e}^H$ be a positive semidefinite matrix of rank 1. Equation (18) is rewritten as:

$$\begin{aligned} & p_{k,c} Tr\left(Z_{k,e}\right) \leq \frac{Tr\left(Z_{k,e}\right)}{1 + r_{k,e}} - \left(\sum_{\substack{i=1 \\ i\neq k}}^{K} Tr\left(Z_{k,e}\right) + \sigma^2\right)\frac{r_{k,e}}{1 + r_{k,e}} \\ & Z_{k,e} \succeq 0 \\ & Rank\left(Z_{k,e}\right) = 1 \end{aligned} \tag{19}$$

At this time, the optimization problem P (2) is transformed into P (3).

$$P(3) \max_{p_k} \frac{\sum_{i=k}^{K} R_k(p_k)}{\xi \sum_{i=k}^{K} p_k + p_c} \quad s.t \quad C1, (15), (19) \tag{20}$$

At this time, the problem P (3) is asked by its SDR, and the constraint of rank 1 is relaxed, and the optimal solution can be obtained by using CVX software package. Since the rank one constraint is removed, the optimal solution of P (3) may not be the optimal solution of P (2). Therefore, Gaussian randomization will be applied to achieve the suboptimal solution of P (2).

4.2. Phase Shift Optimization

After obtaining the optimal solution p_k through power allocation optimization, the power allocated to the user is fixed and the IRS phase shift matrix is optimized. At this time, the optimization problem P (3) is transformed into P (4).

$$\begin{aligned} & P(4) \textbf{find} \quad \Theta \\ & s.t \quad C6: \log_2\left(1 + SINR_{k,e}\right) \geq R_{k,e} \quad , \forall k \\ & \quad C7: 0 \leq \theta_{k,n} \leq 2\pi \quad , \forall k, n \\ & \quad C8: \left|\Theta_{k,n,n}\right| = 1, \quad \forall k, n \end{aligned} \tag{21}$$

It is obvious that the constraint C6 is nonconvex, and we change it.

$$\left|h_{k,e}^H \Gamma_{p_i} e_k\right|^2 \left(1 + r_{k,e}\right) p_{k,c} \leq \left|\left|h_{k,e}^H \Gamma_{p_i} e_k\right|^2\right| - \sum_{\substack{i=1 \\ i\neq k}}^{K}\left|h_{k,e}^H \Gamma_{p_i} e_k\right|^2 r_{k,e} - \sigma^2 r_{k,e} \tag{22}$$

where Γ_{p_i} is a diagonal matrix whose main diagonal elements come from G_k, and e_k is a phase shift vector? Let $R_{k,e}^i = r_{k,e}^i r_{k,e}^{iH}$ and $V_i = e_i e_i^H$ change linearly to obtain:

$$\begin{aligned} & Tr\left(R_{k,e}^k V_k\right)\left(1 + r_{k,e}\right) p_{k,c} \leq Tr\left(R_{k,e}^k V_k\right) - \sum_{\substack{i=1 \\ i\neq k}}^{K} Tr\left(R_{k,e}^i V_i\right) - \sigma^2 r_{k,e} \\ & V_k \succeq 0 \\ & Rank\left(V_k\right) = 1 \end{aligned} \tag{23}$$

Therefore, the optimization problem becomes P (4) into P (5).

P (5) is a SDR problem, which can be effectively solved by CVX. Since the rank one constraint is removed, the optimal

solution of P (5) may not be the optimal solution of

$$\begin{aligned} & P(5)\ \textbf{find} \quad V_k \\ & s.t \quad (24), \quad \forall_k \\ & C4 \quad V_k \succ 0 \quad \forall_k \\ & C5 \quad V_{k,n,n} = 1 \forall_{k,n} \end{aligned} \tag{24}$$

P (4). Therefore, Gaussian randomization will be applied to achieve the suboptimal solution of P (5).

The alternating algorithm proposed in this paper is summarized in algorithm 1. For a given phase shift matrix Θ, the power allocation vector p_k can be obtained by solving the optimization problem P (3), and then fixed p_k to optimize the IRS phase by solving the problem P (5). The optimized Θ will affect the previously obtained power allocation vector p_k, which in turn affects the design of the phase shift vector Θ. Therefore, the power allocation and IRS phase shift of BS are alternately optimized to gradually approximate the optimal solution of the optimization problem. In each iteration, the objective function value of the original optimization problem will not be reduced, and the convergence of the algorithm can be guaranteed according to the monotonically bounded convergence principle.

Table 1. Alternating optimization algorithm

step 1 Initialize the phase shift angle matrix Θ, set the number of iterations $t=0$, energy efficiency $EE^{(t)}$;
step 2. According to the given Θ, the power allocation vector p_k is updated by solving the problem P (3).
step 3. According to the given p_k, Θ is updated by solving the problem P (5) ;
step 4. Let $t=t+1$;
step 5. By p_k and Θ, calculate $EE^{(t)}$;
step 6. Until $EE^{(t)} - EE^{(t-1)} < \varepsilon$;
step 7. End and output the result

5. Simulation analysis

In this section, we give the simulation results to show the proposed transmission scheme. Assuming that BS is located at (− 3,0,0) of the three-dimensional plane, four clusters of eight users are randomly distributed in a circle with a radius of four centers (− 3,10). The other parameters are set as follows: noise power of $\sigma^2 = 144dBm$, The Rylance factor is 4, precision $\varepsilon = 10^{-4}$.

Figure 2 shows the change of EE performance relative to the number of IRS reflection units. The maximum transmission power $P_{\max} = 15dbm$ of BS and the minimum communication SINR of each user are set as $r_k^{\min} = 5dB$.From Figure 2, it can be seen that the EE value increases with the increase of the number of reflection elements of IRS, which is because more reflection units can generate stronger channel gain, thereby improving the system sum rate. The proposed IRS-NOMA transmission scheme is superior to other reference schemes. Compared with the non-IRS-assisted NOMA and IRS-assisted OMA schemes, the transmission scheme proposed in this paper can achieve better EE performance, which shows the importance of deploying IRS in the communication system and optimizing the phase shift of IRS. The EE performance gap between IRS-NONA and IRS-OMA schemes is because NOMA has higher spectral efficiency than OMA.

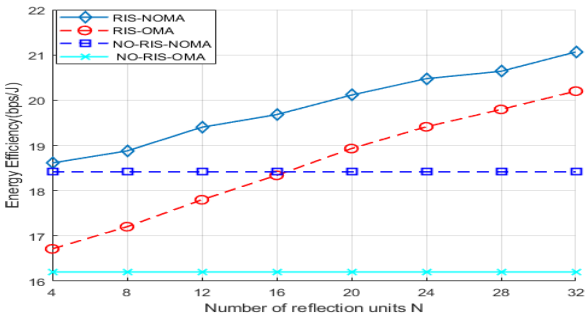


Fig.2 Relationship between energy efficiency and reflection unit

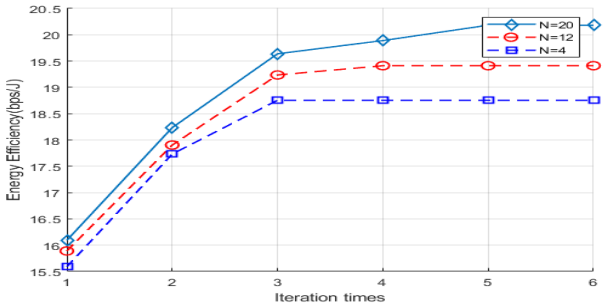


Fig.3 Comparison of convergence diagrams of different IRS unit numbers.

Figure 3 shows the relationship between the sum rate of the system and the number of iterations in the case of the number of IRS reflection units $N = 4,12,20$. As the number of iterations increases, the system sum rate increases and eventually converges. It can be seen from the figure that the algorithm converges to a unique value after the fifth iteration, which proves that the algorithm used in this paper has good convergence. At the same time, the relationship between the system and the rate increases with the increase of the number of IRS reflection units is revealed.

6. Conclusion

This paper studies the EE maximization problem of the downlink of the IRS-assisted NOMA system, taking into account the minimum communication rate requirements of each user and the maximum transmission power limit of the BS. Due to the coupling of variables, it is difficult to directly solve the EE maximization problem. In this paper, the non-convex optimization problem is solved by alternately designing the power allocation of BS and the phase shift of IRS. The simulation results show that the IRS-NOMA transmission method designed in this paper can significantly improve the EE performance of the system compared with the existing benchmark schemes.

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