

# Reconfigurable Intelligent Surface Assisted Wireless Network Rate Optimization Design

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**Abstract.** To enhance the communication rate, we deploy one active reconfigurable intelligent surface (RIS) and one passive RIS to cooperatively assist the downlink communication, while meeting the constraints of base station transmission power, total Active RIS power, and RIS unit modulus constraint. Due to the nonlinear coupling of multiple variables in the objective function, non-convexity is caused. Therefore, an alternating optimization algorithm (AO) is proposed, which uses semi-definite programming (SDP) based algorithm to optimize the transmit beamforming vector, ARIS reflection matrix, and PRIS diagonal phase shift matrix. The simulation results have verified the effectiveness of the proposed algorithm, which indicates that optimizing the coefficients can significantly improve the spectrum efficiency of wireless networks.

**Keywords:** Reconfigurable Intelligent Surface; Convex Optimization

## 1. Introduction

With the development of 6G communication technology, a new era of wireless communication has been ushered in by us. However, in urban areas, signal propagation is severely disrupted due to the obstruction of high-rise buildings and various obstacles. The introduction of Reconfigurable Intelligent Surface (RIS) [1] technology has become an important solution to solve this problem. This technology is widely recognized as a key technology[2] for future communication systems. Its main function is to dynamically adjust the amplitude and phase of electromagnetic units through software programming based on communication link information, and control the propagation direction and intensity of electromagnetic waves[3], Thereby enhancing the expected signal power at the receiving end and improving communication quality.

At present, there have been many research works on RIS. Literature [4] studied the joint optimization of the precoding matrix of the base station and the reflection matrix of the RIS under the condition of a single reconfigurable surface, in order to minimize the transmission power of the transmitter. In order to reduce the complexity of the algorithm, an alternating optimization algorithm was proposed, and semi definite relaxation technique was used to obtain more efficient suboptimal solutions. Literature [5] studied a RIS assisted unmanned aerial vehicle (UAV) communication system, which jointly optimized the UAV trajectory, RIS phase shift to minimize transmission error rate, and proposed a penalty algorithm to obtain suboptimal solutions. Literature [6] studied the deployment of RIS at the edge of multiple cells to achieve downlink MIMO transmission to edge users in the community, the block coordinate descent algorithm is used to optimize the beamforming and RIS phase shift of BS transmission, thereby maximizing the weighted sum rate of users. Literature [7] studied the problem of limiting maximum information leakage, implementing, and maximizing rate performance in RIS assisted multi user multi input single output systems, and proposed a penalty algorithm to solve this problem. Literature [8] studied the joint design of active and passive beamforming for RIS assisted millimeter wave systems, and studied two scenarios of multiple RIS and single RIS, demonstrating that RIS can help improve the robustness of millimeter wave systems to prevent blockages.

However, most RIS devices are passive RIS. Passive RIS consists of a series of low-cost and low-power reflection units, each of which can independently control the phase of the incident signal, thereby changing the propagation path of the signal. In the past few years, significant progress has

been made in research on passive RIS. However, passive RIS has limitations, namely the Multipath Loss Effect, which limits their performance in practical applications. In order to overcome the limitation of passive RIS, researchers have proposed the Active RIS [9] method. Unlike passive RIS, active RIS integrates amplifiers or other active components in its structure to enhance the strength of reflected signals. This design significantly reduces the impact of multipath loss and improves signal quality. Given the advantages and limitations of active and passive RIS, in this paper, we propose a novel wireless communication system for collaborative design of active RIS and passive RIS. The system aims to balance performance and energy consumption, while fully utilizing the advantages of both types of RIS.

## 2. System models and optimization problems

### 2.1 System models

#### 2.1.1 Channel model

We consider the Rician channel model for the channels from base stations to RIS1, RIS1 to RIS2, and RIS2 to users. The channel includes both Line of Sight (LOS) and Non-Line of Sight (NLOS) components. The channel from the base station to RIS1,  $\mathbf{H}_1 = \sqrt{\frac{k}{1+k}}\mathbf{H}_{1,LoS} + \sqrt{\frac{1}{1+k}}\mathbf{H}_{1,NLoS}$ ; The channel from RIS1 to RIS2,  $\mathbf{S} = \sqrt{\frac{k}{1+k}}\mathbf{S}_{LoS} + \sqrt{\frac{1}{1+k}}\mathbf{S}_{NLoS}$ ; The channel from RIS2 to the user,  $\mathbf{g} = \sqrt{\frac{k}{1+k}}\mathbf{g}_{LoS} + \sqrt{\frac{1}{1+k}}\mathbf{g}_{NLoS}$ ; Where  $k$  is the Rician factor.

#### 2.1.2 System model

The system is composed of a base station (BS), two reconfigurable intelligent surfaces (active RIS and passive RIS), and a user (U). The base station is equipped with  $N_t$  transmitting antennas, while active RIS and passive RIS are equipped with  $N_1$  and  $N_2$  reflector units, respectively. The user is equipped with a single receiving antenna. The signal received by the user can be represented as:

$$y = \mathbf{g}^H \mathbf{\Theta}_2 \mathbf{S} \mathbf{\Lambda}_1 \mathbf{H}_1 \mathbf{w} x + \mathbf{g}^H \mathbf{\Theta}_2 \mathbf{S} \mathbf{\Lambda}_1 \mathbf{n}_1 + n.$$

where  $\mathbf{g}$  is the channel from passive RIS to the user.  $\mathbf{\Theta}_2$  is the reflection coefficient matrix of the passive RIS,  $\mathbf{S}$  is the channel from the active RIS to the passive RIS, and  $\mathbf{\Lambda}_1$  is the gain matrix of the active RIS.  $\mathbf{H}_1$  is the channel from the base station to the active RIS, and  $\mathbf{w}$  is the transmit beamforming vector of the base station.  $x$  is the signal sent from the base station,  $\mathbf{n}_1$  is the thermal noise of active RIS,  $n$  is the additive noise at the receiving end, assumed to be Gaussian white noise.

### 2.2 Problem Formulation

The goal of this article is to optimize the beamforming  $\mathbf{w}$  of the base station and the amplification coefficient  $\mathbf{\Lambda}_1$  of ARIS and reflection coefficient of PRIS  $\mathbf{\Theta}_2$ . Maximizing the signal-to-noise ratio (SINR) to maximize the system's capacity, the problem can be expressed as:

$$P1: \max_{\mathbf{\Theta}_2, \mathbf{\Lambda}_1, \mathbf{w}} \frac{|\mathbf{g}^H \mathbf{\Theta}_2 \mathbf{S} \mathbf{\Lambda}_1 \mathbf{H}_1 \mathbf{w}|^2}{(\sigma^2 + |\mathbf{g}^H \mathbf{\Theta}_2 \mathbf{S} \mathbf{\Lambda}_1|^2 \sigma^2)}, \quad (1)$$

$$s. t. \quad \|\mathbf{w}\|^2 \leq P_B, \quad (2)$$

$$\|\mathbf{\Lambda}_1 \mathbf{H}_1 \mathbf{w}\|^2 + \|\mathbf{\Lambda}_1\|^2 \sigma \leq P_A, \quad (3)$$

$$|\mathbf{\Theta}_i|_{n_i} = 1, i = 1, 2, n_i = 1, \dots, N_i. \quad (4)$$

The first constraint ensures that the total transmission power of the base station does not exceed the predetermined maximum value ( $P_B$ ). The second constraint considers the maximum power limit that ARIS can withstand when reflecting signals. The third constraint considers that PRIS can only change the phase of the reflected signal without enhancing its amplitude, and the amplitude of the reflection coefficient for each unit is limited to 1.

### 3. Optimization algorithm

#### 3.1 Dinkelbach method

The objective function in maximizing SNR is in fractional form, so the dinkelbach fractional programming algorithm is adopted, introducing auxiliary variable  $t$  to optimize  $t = \frac{|g^H \Theta_2 S \Lambda_1 H_1 w|^2}{\sigma^2 + |g^H \Theta_2 S \Lambda_1|^2 \sigma^2}$ .

Translate problem P1 into the following parameter subtraction form P2:

$$P2: \max_{\Theta_2, \Lambda_1, w} |g^H \Theta_2 S \Lambda_1 H_1 w|^2 - t(\sigma^2 + |g^H \Theta_2 S \Lambda_1|^2 \sigma^2), \quad (5)$$

The constraints remain as shown in (2), (3), and (4).

#### 3.2 Alternating optimization algorithm

Although problem P2 has simplified the fractional form, due to variables  $w$ ,  $\Lambda_1$ ,  $\Theta_2$  highly coupled, therefore alternating optimization algorithms are adopted.

##### 3.2.1 Optimizing the beamforming of base stations $w$

Given the RIS amplification coefficient  $\Lambda_1$  and reflection coefficient  $\Theta_2$ . The optimization problem of optimizing the beamforming  $w$  of the base station is shown in P2-1:

$$P2 - 1: \max_w |a_1^H w|^2, \quad (6)$$

$$s. t. ||w||^2 \leq P_B, \quad (7)$$

$$||a_2 w||^2 \leq c_1. \quad (8)$$

In the formula,  $a_1 = g^H \Theta_2 S \Lambda_1 H_1$ ,  $a_2 = \Lambda_1 H_1$ ,  $c_1 = P_A - ||\Lambda_1||^2 \sigma$ .

Due to the non convexity of formula P2-1 with respect to  $w$ , the semi definite programming SDR algorithm is adopted, introducing auxiliary variables  $W = ww^H$ ,  $A_1 = a_1 a_1^H$ ,  $A_2 = a_2 a_2^H$ . The problem is transformed into P2-1-1:

$$P2 - 1 - 1: \max_W \text{trace}(A_1 W), \quad (9)$$

$$s. t. \text{trace}(W) \leq P_B, \quad (10)$$

$$\text{trace}(A_2 W) \leq c_1, \quad (11)$$

Then, the problem is solved using CVX in MATLAB, and multiple samples are generated using Gaussian randomization to obtain an optimal solution from the optimized solution.

##### 3.2.2 Optimizing amplification factor $\Lambda_1$

Given optimized base station beamforming  $w$  and  $\Theta_2$ . The optimization problem for the amplification factor  $\Lambda_1$  is shown in P2-2:

$$P2 - 2: \max_v |v^H A_3|^2 - t(||v^H B||^2 \sigma^2 + \sigma^2), \quad (12)$$

$$s. t. ||C v^H||^2 + ||v^H||^2 \sigma \leq P_A, \quad (13)$$

In the formula,  $v$  is the vectorized  $\Lambda_1$ ,  $A_3 = \text{diag}(g^H \Theta_2 S) H_1 w$ ,  $B = \text{diag}(g^H \Theta_2 S)$ ,  $C = \text{diag}(H_1 w)^H$ .

Due to the non convexity of formula P2-2 with respect to  $v$ , the semi definite programming SDR algorithm is adopted, and the auxiliary variable  $V = vv^H$  is introduced,  $A_4 = A_3 A_3^H$ ,  $B_1 = B B^H$ ,  $C_2 = C C^H$ . The problem is transformed into P2-2-1:

$$P2 - 2 - 1: \max_V \text{trace}(A_4 V) - t \cdot (\text{trace}(B_1 V) \sigma^2 + \sigma^2), \quad (14)$$

$$s. t. \text{trace}(C_2 V) + \text{trace}(V) \cdot \sigma \leq P_A, \quad (15)$$

$$V \geq 0. \quad (16)$$

After solving this problem using CVX in MATLAB, multiple samples are generated using Gaussian randomization method to obtain an optimal solution from the optimized solution.

##### 3.2.3 Optimize reflection coefficient $\Theta_2$

Given the beamforming  $w$  and RIS amplification coefficient  $\Lambda_1$  of the base station, optimize the reflection coefficient  $\Theta_2$ . The optimization problem of 2 is shown in P2-3:

$$P2 - 3: \max_z |z^H A_5|^2 - t(||z^H B_2||^2 \sigma^2 + \sigma^2), \quad (17)$$

In the formula,  $z$  is vectorized  $\Theta_2$ ,  $A_5 = \text{diag}(g^H) S \Lambda_1 H_1 w$ ,  $B_2 = \text{diag}(g^H) S \Lambda_1$ .

Due to the non convexity of formula P2-3 with respect to  $\mathbf{z}$ , the semi definite programming SDR algorithm is adopted, and the auxiliary variable  $\mathbf{Z} = \mathbf{z}\mathbf{z}^H$  is introduced,  $\mathbf{A}_6 = \mathbf{A}_5\mathbf{A}_5^H$ ,  $\mathbf{B}_3 = \mathbf{B}_2\mathbf{B}_2^H$ . The problem is transformed into P2-3-1:

$$P2-3-1: \max_{\mathbf{Z}} \text{trace}(\mathbf{A}_6\mathbf{Z}) - t(\text{trace}(\mathbf{B}_3\mathbf{Z})\sigma^2 + \sigma^2), \quad (18)$$

$$\text{s.t. } \mathbf{Z} \geq 0. \quad (19)$$

After solving this problem using CVX in MATLAB, multiple samples are generated using Gaussian randomization method to obtain an optimal solution from the optimized solution.

#### 4. Simulation analysis

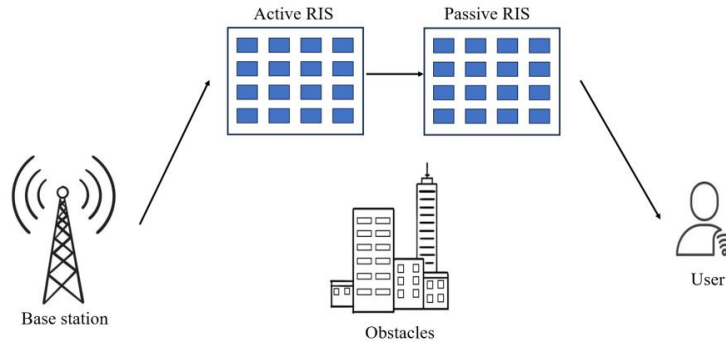
Table 1 shows some basic parameters in the simulation. For comparison, a double passive RIS system is chosen as the baseline.

Table 1 Simulation Parameter Settings

Parameter	Parameter Settings
Base Station Power $P_B$	40
ARIS Unit Number $N_1$	64
PRIS Unit Number $N_2$	64
Base Station Transmission Antenna $N_t$	10
Simulation Times RAN	5
Rayleigh Factor rician	10
RIS Power PRIS	0.01

The algorithm performance is simulated and verified here. The simulation scenario is shown in Fig. 1, which includes one base station, one ARIS, one PRIS, and one user. Their respective position coordinates are [0 0 5], [10 10 10], [10 40 10], and [0 50 2].

Fig. 1 Communication scenario



The main simulation parameters include the number of RIS units ( $N_1$ ,  $N_2$ ), base station power (PB), and reflection coefficient (PRIS).

Fig. 2 shows the performance of the system capacity (Cbps/Hz) in two different configurations when changing  $N_1$  (ranging from 16 to 64). From the graph, it can be seen that as the number of RIS1 units increases, the system capacity using ARIS-PRIS configuration significantly increases and remains higher than the system capacity using only PRIS-PRIS configuration. The use of ARIS can significantly improve system performance. The impact of the number of units on system capacity gradually converges, usually due to several reasons: power allocation and beamforming strategies may encounter performance bottlenecks when approaching the optimal solution, resulting in a decrease in capacity gain.

Fig. 2 Comparison between system capacity and the number of RIS1

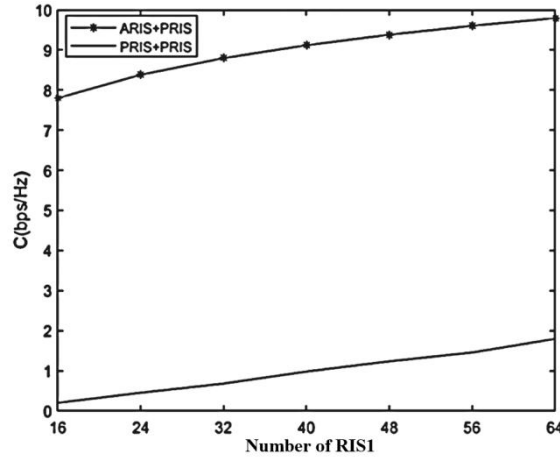


Fig. 3 shows the performance of the system capacity (Cbps/Hz) in two different configurations when changing  $N_2$  (ranging from 16 to 64). Similar to Figure 2.

Fig. 3 Comparison between system capacity and the number of RIS2

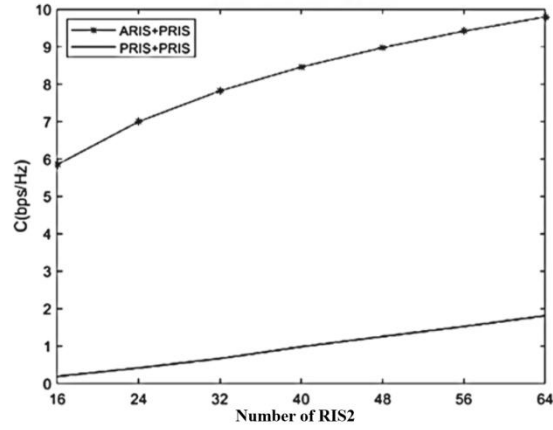


Fig. 4 shows the performance of the system capacity (Cbps/Hz) under two different configurations when changing the base station power. With the increase of base station power, ARIS-PRIS configuration shows a significant increase in capacity, especially in high-power areas. When the transmission power is low, the performance of the system is limited by noise. In PRIS-PRIS configuration, system capacity growth slows down at high power.

Fig. 4 Comparison of System Capacity and Base Station Power

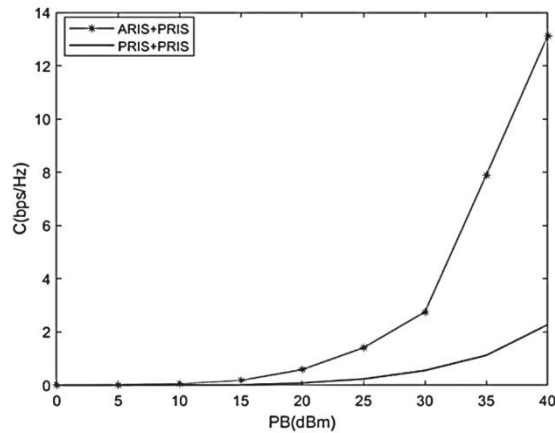
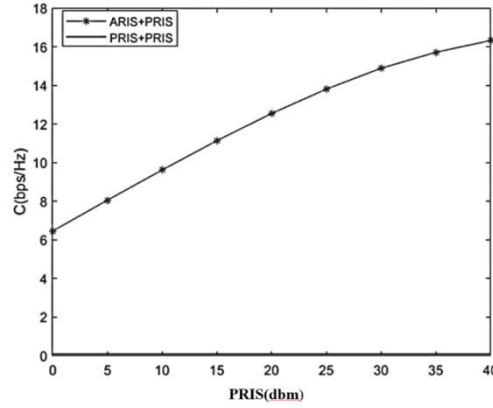


Fig. 5 shows the variation of network capacity with RIS power for two different system configurations. ARIS can better control the phase and amplitude of reflected signals, thereby improving the signal-to-interference plus noise ratio (SINR) and enhancing system capacity. The capacity of PRIS-PRIS configuration will not significantly increase with the increase of RIS power,

because passive RIS does not amplify the signal, but only changes the phase of the signal, which limits its performance improvement in high-power areas.

Fig. 5 Comparison of System Capacity and RIS Power



## 5. Conclusion

This article investigated the communication system of Active RIS-Passive RIS for wireless networks assisted by Reconfigurable Intelligent Surface (RIS), which maximized user rate while meeting the constraints of base station transmission power, total Active RIS power, and RIS unit modulus. To solve non-convex objective functions, an AO method was proposed, which used semi-definite programming (SDP) and randomization to optimize the transmitter weight vector, ARIS diagonal matrix, and PRIS diagonal adjustment matrix. The simulation results verified the effectiveness of the ARIS-PRIS communication system. And it indicated that by optimizing the coefficients, the system capacity of wireless networks could be significantly improved.

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