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# Achievable Rate Maximization for Aerial Intelligent Reflecting Surface-aided Cell-free Massive MIMO System

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***Abstract*—An intelligent reflecting surface (IRS) has significant advantages in enhancing network coverage, spectrum efficiency, energy efficiency, and deployment costs. IRSs are envisioned to be a key technology in sixth-generation (6G) communication systems. Consisting of a new multiple-input-multiple-output (MIMO) network architecture, cell-free massive MIMO is capable of providing users with high quality-of-service (QoS) and is consequently expected to be the core architecture of the next generation communication system. This paper first considers an aerial intelligent reflecting surface (AIRS)-aided cell-free downlink system, where multiple access points (APs) equipped with single or multiple antennas serve a smaller number of users by using an AIRS to assist communication. Both the APs and the AIRS are controlled by a central processing unit (CPU). The goal of this paper is to maximize the achievable user transmission rate. We use an iterative optimization strategy to jointly design the power allocation at each AP, the phase shift matrix of the AIRS, and the beamforming vector at each AP to obtain the optimal solution. The simulation results show that we can obtain a good achievable rate performance using the proposed optimization strategy.**

***Index Terms*—Intelligent reflecting surface (IRS), aerial intelligent reflecting surface (AIRS), cell-free massive multiple-input-multiple-output (MIMO), joint optimization.**

## I. Introduction

An intelligent reflecting surface (IRS), which is also called a software-controlled metasurface [1], is a revolutionary new technology. Using an IRS, we can achieve intelligent and reconfigurable wireless transmission based on the environment. In contrast to the traditional parabolic antenna, an IRS is a planar structure usually composed of a large number of subwavelength, passive, low-cost reflection elements. Each element can independently change the phase and amplitude of the incident signal [2]. The phase shift values of the elements determine the direction of the reflected signal; thus, we can change the direction of the reflected beam to a desired direction by designing the phase shift for all the IRS elements [3]–[6]. When a direct path between the base station (BS) and the user is blocked, the transmission power must be increased to improve the user's quality of service (QoS). However, if we deploy an IRS at a location suitable for beamforming the signal from the base station to the user, we can provide better QoS for the user without increasing the transmitting power at the BS.

It is worth noting that although an IRS looks similar to a traditional relay, there are obvious differences. First, relay operations such as decoding and forwarding (DF) and amplifying and forwarding (AF) need to demodulate the received signals before forwarding them; consequently, the relays must possess signal processing capabilities. In contrast, an IRS usually does not possess signal processing capability; instead, it simply reflects signals passively. Therefore, there is no need to equip the IRS with any transmission radio frequency (RF) chain [7]. Second, compared with traditional relays, the IRS energy consumption is low and no additional thermal noise is introduced during the reflection. IRS deployment costs are also low: they can even be deployed on urban building walls. Third, in previous studies, most transmission designs have concentrated on the receiver or transmitter and considered the wireless channels as random and uncontrollable. We can only passively adapt to a wireless channel by optimizing the two ends of the transceiver. However, an IRS can change the phase shift of each element to achieve control of a wireless channel, enabling intelligent and controllable wireless transmission, which greatly improves system performance. Based on the above advantages, IRSs have attracted increasing attention and have broad application prospects.

The academic community has already performed considerable research on IRSs. In [8], the authors studied an IRS-aided single-input-single-output (SISO) wireless communication system and compared its performance with that of a DF relay. The results showed that an IRS can achieve better performance. The authors of [9] studied an IRS-aided multiple-input-single-output (MISO) system in which an IRS was deployed to assist the communication between a multiple-antenna BS and several single-antenna users. The capacity of an IRS auxiliary multiple-input-multiple-output (MIMO) system was analyzed in [10], The authors proposed an alternative strategy to jointly optimize phase shift coefficients of the IRS and the transmission covariance matrix to enhance system capacity. Recently, a new airspace IRS (AIRS) structure was proposed in [11]. Compared with a traditional ground IRS, an AIRS can be deployed on some lift off platforms such as unmanned aerial vehicles (UAV). An AIRS can provide more Los paths. In addition, airs can move to achieve the dynamic adjustment of reflected signal, while the position of IRS is usually fixed.

A new form of network MIMO was proposed in [12], where many APs serve several users over the coverage area. All the access points (AP) are controlled by a central processing unit (CPU). This is called a cell-free massive MIMO system. Compared with the traditional cellular network, a cell-free massive MIMO system overcomes the limitation of inter cell interference in traditional cellular mobile network. Multiple APS serve a small number of users in the coverage area under the control of central processing unit (CPU), and realize the coherent transmission centered on users [13].

In fact, the combination of AIRS and the cell-free massive MIMO is very suitable.Firstly, in terms of control mode, both of them can be connected to a CPU through a return link, and the CPU achieves resource allocation and optimal configuration of AIRS parameters; Secondly, configuring AIRS in cell-free massive MIMO system can improve the coverage of the system to achieve ultra-dense networking; Thirdly, cell-free massive MIMO system can allocate resources in real time according to user's needs. Deploying AIRS can adjust user's requirement in communication in real time. This fits "user-centered" characteristics very well. In a cell-free massive MIMO system, we can obtain the user's actual location information, channel state information (CSI) by channel estimation, we call them "fingerprint information". Using the fingerprint information, the CPU knows which regions have poor communication quality and deploy an AIRS to enhance the communication quality within the region.

The existing research on IRSs has focused primarily on performance analysis and system design of IRS-assisted single-cell communication systems. In contrast, almost no research exists on IRS-assisted cell-free systems. These two technologies are very compatible. First, both an IRS and the APs in a cell-free massive MIMO system can be controlled by a CPU to achieve intelligent and reconfigurable communication. Second, an IRS is useful for solving the problem of area coverage and interference for a cell-free system. Moreover, by using the IRS to assist in communication, we need to deploy only a small number of antennas at the AP to obtain a good performance gain due to the large number of elements in the IRS. Inspired by the above reasons, this paper considers a new scenario in which multiple APs serve users through one AIRS in a cell-free system. The transmission power of all the APs is limited to $P$. The goal of this paper is to maximize the achievable user transmission rate by designing the power allocation vector of each AP, the beamforming vectors at each AP, and the phase shift matrix at the AIRS.

The remainder of this paper is organized as follows: In Section II, we will study the system model and the channel model of an AIRS-aided cell-free massive MIMO system. Then, we describe the problem to be solved in this paper. In Section III, we propose an optimization strategy to jointly design the power allocation at each AP, the phase shift matrix of the AIRS, and the beamforming vector at each AP to maximizing the achievable rate of the user. In Section IV, we simulate an actual scene to test the performance of the algorithm. Finally, Section V summarizes this paper.

The notations used in this paper are listed below. We use $j=\sqrt{-1}$ to express an imaginary unit. For readability, we use bold capital letters to denote matrices. A vector is denoted by an italic and bold lowercase letter. Here, we denote the space of $M \times N$ as a complex-valued matrix by $\mathbb{C}^{M\times N}$. For a vector $\boldsymbol{g}$, we use $\|\boldsymbol{g}\|$ to denote the $\ell_1-$ norm and use $\|\boldsymbol{g}\|_2$ to denote the $\ell_2-$ norm. Additionally, we use $\arg(\boldsymbol{g})$ to denote a vector, each element of which is a phase of the corresponding element in $\boldsymbol{g}$. We use diag($\boldsymbol{g}$) to denote a diagonal matrix, where each diagonal element is the corresponding element in $\boldsymbol{x}$. For a matrix $\mathbf{F}$, $\mathbf{F}^{\mathrm{T}}$ and $\mathbf{F}^{\mathrm{H}}$ denote its transpose and conjugate transpose, respectively. For a plural $C$, we use $|\mathrm{C}|$ to express the modulus of $C$, and we use $\arg(C)$ to denote the phase of $C$.

## II. System Model and Problem Formulation

### A. System model of AIRS-aided cell-free massive MIMO system

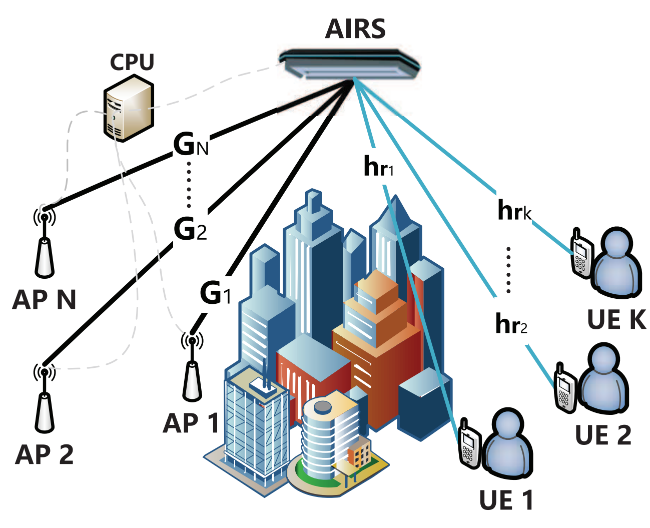


Fig. 1. AIRS-aided cell-free massive MIMO system

As shown from Fig. 1,

we consider a cell-free downlink system, where multiple $N$APs and an AIRS are controlled by a CPU to provide services for $K$ single-antenna users. The reason for using an

AIRS instead of an IRS is that the location of an IRS is usually fixed, but an AIRS can be moved. In a cell-free massive MIMO system, we can change the location of the AIRS in real time to meet the users' service needs. The AIRS is deployed on an unmanned aerial vehicle (UAV). Direct paths between each AP and user are blocked by tall buildings, so we can assume that they do not exist. Each AP is equipped with *M* antennas. To facilitate the analysis, we assume that one user exists in the system who is served by *N* APs simultaneously. A study involving multiuser scenarios will be deferred to future work. Suppose the total transmit power of *N* APs is limited to $\sum_{n=1}^{N} P_n \leq P$. Then, the signals received by the user can be expressed as follows:

$$y = (\boldsymbol{h}_\mathbf{r}\boldsymbol{\Theta}\mathbf{G}_1\boldsymbol{w}_1 + \mathbf{h}_\mathbf{r}\boldsymbol{\Theta}\mathbf{G}_2\boldsymbol{w}_2 + \ldots + \boldsymbol{h}_\mathbf{r}\boldsymbol{\Theta}\mathbf{G}_N\boldsymbol{w}_N)\mathrm{x} + \xi, \quad (1)$$

where $\boldsymbol{h}_\mathbf{r} \in \mathbb{C}^{1\times R}$ represents the channel from the IRS to the user; $\mathbf{G}_n \in \mathbb{C}^{R\times M}$ represents the channel of the *n*-th AP to the AIRS; $\boldsymbol{\Theta} \in \mathbb{C}^{R\times R}$ denotes the phase shift matrix at the AIRS; and $\boldsymbol{\Theta} = \mathrm{diag}(\eta_1 e^{j\theta_1}, \eta_2 e^{j\theta_2}, \ldots, \eta_R e^{j\theta_R})$, where $\eta_r \in [0,1], \theta_r \in [0,2\pi)$ represent the phase shift value and reflection coefficient of the *r*-th element at the AIRS, respectively. To maximize the IRS reflection performance, we usually set all the amplitude reflection coefficients to 1, that is, $\eta_r = 1, r = 1,2,\ldots,R$. $\boldsymbol{w}_n$ denotes the beamforming vector at the *n*-th AP, and $\|\boldsymbol{w}_n\|^2 \leq s_n P, n = 1,2,\ldots,N$, $s_n$ represents the power distribution coefficient of the *n*-th AP. We use $\boldsymbol{s}$ to denote the power allocation vector, and $\boldsymbol{s} = (s_1, s_2, \ldots, s_n)$, $n = 1,\ldots,N$. $\xi \sim \mathcal{CN}(0,\sigma^2)$ is additive white Gaussian noise (AWGN). We assume that the CPU can obtain all the channel state information (CSI).

### B. Channel model

We assume that all the APs and the AIRS are in the form of a uniform linear array (ULA). The AIRS consists of *R* subwavelength elements, and each AP consists of *M* subwavelength elements. Thus, the channel $\mathbf{G}_n$ can be expressed as follows:

$$\mathbf{G}_n = \sqrt{\beta_n}\left(\sqrt{\frac{\varepsilon}{\varepsilon+1}}\boldsymbol{a}_\mathbf{r}(\phi_{r_n})\boldsymbol{a}_\mathbf{t}^H(\phi_{t_n}) + \sqrt{\frac{1}{\varepsilon+1}}\widetilde{\mathbf{G}}_\mathbf{n}\right), \quad (2)$$

where $\beta$ is a distance-dependent path loss that can be modeled as $\beta_n = \beta_0\left(\frac{d_n}{d_0}\right)^{-\kappa}$, and $\kappa$ is the path loss exponent. $\beta_0$ represents the path loss at the reference distance $d_0$; here, we set $d_0 = 1m$. $\boldsymbol{a}_t(\phi_{t_n})$ and $\boldsymbol{a}_r(\phi_{r_n})$ denote the array response of the *n*-th AP and AIRS, respectively. $\phi_{r_n}$ is the angle of arrival (AOA) of the signals from the *n*-th AP to the AIRS, and $\phi_{t_n}$ is the angle of departure (AOD) of the signals from the *n*-th AP to the AIRS. $\varepsilon$ is the Rician K-factor. $\widetilde{\mathbf{G}}_\mathbf{n}$ denotes the non-line-of-sight (NLoS) part of the channel $\mathbf{G}_n$, and each element of $\widetilde{\mathbf{G}}_\mathbf{n}$ can be chosen from $\mathcal{CN}(0,1)$. The array response can be expressed as follows:

$$\boldsymbol{a}_\mathbf{r}(\phi) = \left[1, e^{-j\pi\sin(\phi)}, e^{-j\pi 2\sin(\phi)}, \ldots, e^{-j\pi(R-1)\sin(\phi)}\right]^T, \quad (3)$$

$$\boldsymbol{a}_\mathbf{t}(\theta) = \left[1, e^{-j\pi\sin(\theta)}, e^{-j\pi 2\sin(\theta)}, \ldots, e^{-j\pi(M-1)\sin(\theta)}\right]^T. \quad (4)$$

The channel $\boldsymbol{h}_\mathbf{r}$ can be expressed similarly:

$$\boldsymbol{h}_\mathbf{r} = \sqrt{\beta_{h_r}}\left(\sqrt{\frac{\varepsilon}{\varepsilon+1}}\boldsymbol{a}_\mathbf{t}^H(\varphi_t) + \sqrt{\frac{1}{\varepsilon+1}}\widetilde{\boldsymbol{h}_r}\right). \quad (5)$$

### C. Problem formulation

Suppose that *N* APs exist, all of which simultaneously serve a single user and that the total transmit power of all the APs is limited to *P*. Our goal is to maximize the achievable user rate by jointly designing the power allocation vector $\boldsymbol{s} = (s_1, s_2, \ldots, s_N)$, the beamforming vectors $\boldsymbol{w}_n$ at each AP, and the phase shift matrix $\boldsymbol{\Theta}$ at the AIRS. The signal-to-noise ratio (SNR) at the user can be expressed as follows:

$$\gamma = \frac{\left|\sum_{n=1}^{N}\boldsymbol{h}_\mathbf{r}\boldsymbol{\Theta}\mathbf{G}_n\boldsymbol{w}_n\right|^2}{\sigma^2}. \quad (6)$$

The achievable user rate can be expressed as

$$R_u = \log_2\left(1 + \frac{\left|\sum_{n=1}^{N}\boldsymbol{h}_\mathbf{r}\boldsymbol{\Theta}\mathbf{G}_n\mathbf{w}_n\right|^2}{\sigma^2}\right). \quad (7)$$

Thus, the problem can be formulated as follows:

$$\begin{aligned} \mathrm{P1}: \max_{\boldsymbol{s},\boldsymbol{w}_n,\boldsymbol{\Theta}} \ & \log_2\left(1 + \frac{\left|\sum_{n=1}^{N}\boldsymbol{h}_\mathbf{r}\boldsymbol{\Theta}\mathbf{G}_n\boldsymbol{w}_n\right|^2}{\sigma^2}\right) \\ s.t. \ & \sum_{n=1}^{N} s_n = 1 \\ & \|\boldsymbol{w}_n\|^2 \leq s_n P, \ n = 1,2,\ldots,N \\ & \theta_r \in [0,2\pi), \ r = 1,...,R \end{aligned}. \quad (8)$$

## III. Optimization Strategy

The problem in (P1) is difficult to solve because it is nonconvex, and each variable is coupled. In this section, we use an iterative optimization strategy to solve (P1). First, we assume that all the APs are equipped with just one antenna. Then, the problem in (P1) can be simplified to

$$\begin{aligned} & \mathrm{P2}: \\ & \max_{\boldsymbol{s},\boldsymbol{\Theta}} \ \log_2\left(1 + P\frac{\left|\sum_{n=1}^{N}\boldsymbol{h}_r\boldsymbol{\Theta}\mathbf{G}_n\sqrt{s_n}\right|^2}{\sigma^2}\right) \\ & \quad s.t. \ \sum_{n=1}^{N} s_n = 1 \\ & \qquad \theta_r \in [0,2\pi), r = 1,...,R \end{aligned} \quad (9)$$

Note that the equivalent joint channel $\mathbf{G} = \sum_{n=1}^{N}\mathbf{G}_n\sqrt{\boldsymbol{s}_n}$ is determined when the power allocation vector $\boldsymbol{s}$ is determined; then, the problem can be rewritten as follows:

$$\begin{aligned} & \mathrm{P3}: \\ & \max_{\boldsymbol{\Theta}} \ \log_2\left(1 + P\frac{|\boldsymbol{h}_\mathbf{r}\boldsymbol{\Theta}\mathbf{G}|}{\sigma^2}\right) \\ & s.t. \ \theta_r \in [0,2\pi), r = 1,...,R; \end{aligned} \quad (10)$$

Then, (P3) becomes the phase shift design problem in a general IRS-aided system. To maximize the user rate, the phase shift $\theta_r$ should be designed so that the signals are coherently superimposed at the user. Therefore, the optimal phase shift parameters are:

$$\theta_r{}^* = \Omega - \arg([\boldsymbol{h}_{\mathbf{r}}]_r [\mathbf{G}]_r), r = 1, ..., R; \tag{11}$$

$\Omega$ is a coherent angle, here we set $\Omega = \pi$.

After $\boldsymbol{\Theta}$ has been found by (11), the subchannel between the $n$-th AP and the user $\mathbf{H}_n$=$\boldsymbol{h}_{\mathbf{r}}\boldsymbol{\Theta}\mathbf{G}_n$ can be determined. Intuitively, in this case, $\mathbf{H}_n$ contains only one plural element. Thus, we can reallocate the power according to the current gain of each subchannel $|\mathbf{H}_n|^2, n = 1, ..., N$. The power allocation criterion is

$$s_n{}^* = \frac{|\mathbf{H}_n|^2}{\sum\limits_{m=1}^{N} |\mathbf{H}_m|^2}, n = 1, ..., N \tag{12}$$

To obtain an optimal solution, the above steps should be iterated until the achievable rate reaches convergence.

Now, we consider the case of multi-antenna APs. In this case, the problem focuses on (P1). The optimal beamforming vector of each AP reaches maximum ratio transmission (MRT) after $\boldsymbol{s}$ and $\boldsymbol{\Theta}$ have been determined. The optimized $\boldsymbol{w}_n$ can be expressed as follows:

$$\boldsymbol{w}_n{}^* = \sqrt{s_n P} \frac{(\boldsymbol{h}_{\mathbf{r}}\boldsymbol{\Theta}\mathbf{G}_n)^{\mathrm{H}}}{\|\boldsymbol{h}_{\mathbf{r}}\boldsymbol{\Theta}\mathbf{G}_n\|_2}, n = 1, ..., N \tag{13}$$

Then, we can use the optimized $\boldsymbol{w}_n{}^*$ to obtain the channel $\mathbf{G} = \sum\limits_{n=1}^{N} \mathbf{G}_n \boldsymbol{w}_n$, and we can use (11) to optimize the phase shift matrix $\boldsymbol{\Theta}$. According to the optimized $\boldsymbol{\Theta}$, we can reallocate the power according to the current gain of each subchannel using (12), where

$$s_n{}^* = \frac{\|\mathbf{H}_n\|^2}{\sum\limits_{m=1}^{N} \|\mathbf{H}_m\|^2}, n = 1, ..., N \tag{14}$$

After iterative optimization, the achievable rate converges to an optimal value. The specific algorithmic implementation is as follows:

**Algorithm 1** Proposed Algorithm for Problem (P1)

**1.** Initialize $\boldsymbol{s}$ and $\boldsymbol{\Theta}$ randomly. Obtain the initial $\boldsymbol{w}_n, n = 1, ..., N$ by (13).
**2.** Obtain $\mathbf{G}$, $\mathbf{G} = \sum\limits_{n=1}^{N} \mathbf{G}_n \boldsymbol{w}_n$.
**3.** **for** $r = 1 \rightarrow R$ **do**
**4.** Optimize $\boldsymbol{\Theta}$ by (11).
**end**
**5.** Obtain $\mathbf{H}_n, n = 1, ..., N$, $\mathbf{H}_n$=$\boldsymbol{h}_{\mathbf{r}}\boldsymbol{\Theta}\mathbf{G}_n$. Reallocate the power according to (14) get a new $\boldsymbol{s}$. Obtain the optimized $\boldsymbol{w}_n, n = 1, ..., N$ by (13).
**6.** Calculate the achievable rate $R_u$ by (7). Check convergence, if yes, stop; if not, go to Step **2**.

## IV. Simulation Results

In this section, we conduct a simulation of a real scenario to verify the performance of the optimization algorithm proposed in Section 3. As shown in Fig. 2, we assume that three APs serve a user through an AIRS placed on a drone. All the APs and the AIRS are controlled by a CPU. Each AP is equipped with four antennas, and the AIRS has $R = 100$ elements. All of the APs and the AIRS are in the form of a half-wavelength-spaced ULA. The path loss exponent is set to $\alpha = 2.2$. The bandwidth is 1 MHz, and the power spectral density of the noise is -170 dBm/Hz. The Rician K-factor is set to $\varepsilon = 10$, and we set $\beta_0 = -30$ dB. The parameter settings are summarized in detail in Table I.

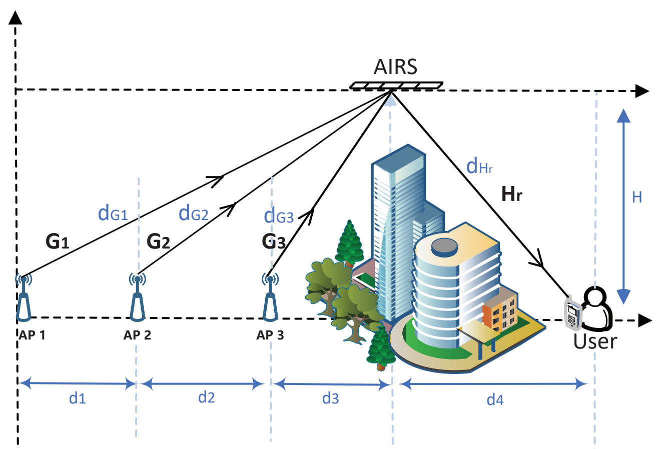


Fig. 2. Simulation scene

TABLE I
THE PARAMETER SETTINGS

| Parameters | Value |
|---|---|
| Number of APs $N$ | 3 |
| Number of antennas at each AP $M$ | 4 |
| Number of elements at AIRS $R$ | 100 |
| Bandwidth $B$ | 1 MHz |
| power spectral density of the noise | $-170$ dBm/Hz |
| Path loss exponent $\alpha$ | 2.2 |
| Reference distance $\beta_0$ | $-30$ dB |
| The Rician factor $\varepsilon$ | 10 |
| Distance $d_1$ | 100 m |
| Distance $d_2$ | 100 m |
| Distance $d_3$ | 100 m |
| Distance $d_4$ | 150 m |
| Hight of the AIRS H | 200 m |
| Distance $d_{G1}$ | $\sqrt{\mathrm{H}^2 + (d_1 + d_2 + d_3)^2}$ |
| Distance $d_{G2}$ | $\sqrt{\mathrm{H}^2 + (d_2 + d_3)^2}$ |
| Distance $d_{G3}$ | $\sqrt{\mathrm{H}^2 + (d_3)^2}$ |
| Distance $d_{Gh}$ | $\sqrt{\mathrm{H}^2 + (d_4)^2}$ |

First, we analyzed the performance of the proposed iterative strategy. We compared three different settings:

1) **No optimization**: In this case, we neither optimize the phase shift matrix $\boldsymbol{\Theta}$ of the AIRS nor the power allocation vector $\boldsymbol{s}$ of the APs. All the APs are allocated equal power, and each AP performs MRT.

2) **Random phase shift with power allocation**: In this case, we optimize only the power allocation vector $\boldsymbol{s}$. The phase shift matrix $\boldsymbol{\Theta}$ of the AIRS is randomly set, and each AP performs MRT.

3) **Simple power allocation**: In this case, we allocate equal power for each AP and optimize the phase shift matrix $\boldsymbol{\Theta}$ of the AIRS. Each AP conducts MRT.

4) **Proposed algorithm**: In this case, we optimize both the power allocation vector $\boldsymbol{s}$ and the phase shift matrix $\boldsymbol{\Theta}$ of the AIRS using the proposed method in section III.

As shown in Fig. 3, compared with no optimization, we can obtain a better performance by optimizing the power allocation vector $\boldsymbol{s}$. After the power allocation is optimized, we can achieve a higher rate by optimizing the phase shift matrix $\boldsymbol{\Theta}$. Furthermore, we can gain an excellent performance improvement by using the proposed algorithm to optimize both the power allocation vector $\boldsymbol{s}$ and the phase shift matrix $\boldsymbol{\Theta}$.

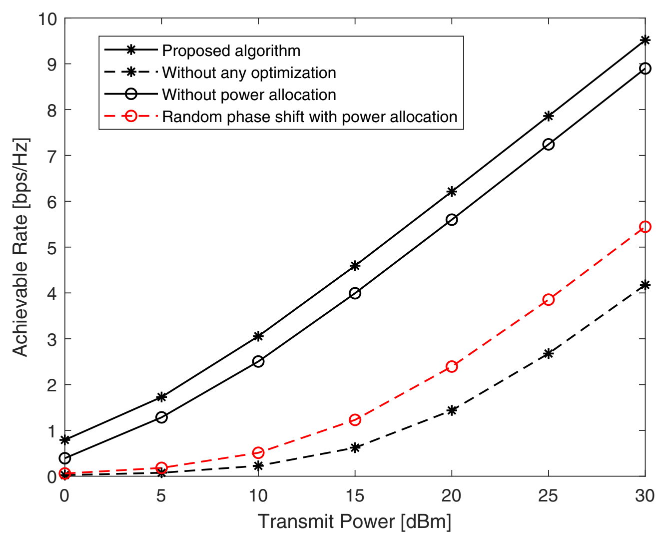


Fig. 3. Performance comparison

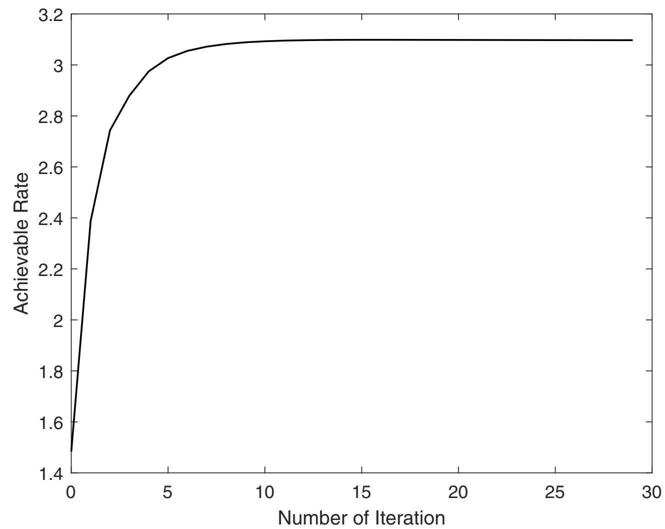


Fig. 4. Convergence of proposed algorithm

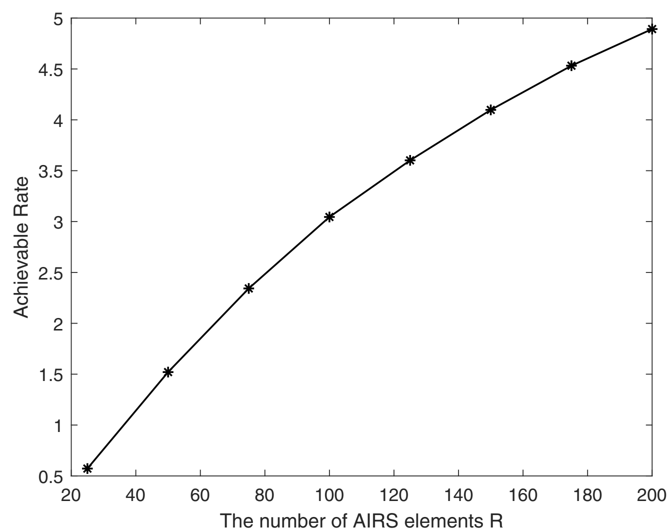


Fig. 5. The effect of elements at the AIRS

As shown in Fig. 4, we set the transmit power to $P = 10$ dBm to verify the convergence of the proposed algorithm in section III. As Fig. 4 shows, the proposed algorithm converges quickly. In practice, we need only a handful of iterations to obtain good performance. We can improve the achievable rate performance through iterative optimization.

As shown in Fig. 5, we set the transmit power to $P = 10$ dBm to study the impact of the number of AIRS elements on system performance. Intuitively under the same transmit power, increasing the number of IRS elements improves the system's achievable rate performance. This result means that under the same rate requirement, we can save transmit power by increasing the number of AIRS elements.

## V. Conclusion

In this paper, we study a new AIRS application scenario, where the AIRS is deployed in a cell-free massive MIMO system to assist the communication. We use a joint iterative optimization strategy to maximize the achievable user rate. The simulation results show that we can substantially improve the achievable rate performance using the joint optimization algorithm proposed in this paper. To the best of our knowledge, this study is the first to combine emerging AIRS technology with a cell-free system. In this paper, we studied only the rate optimization problem of an AIRS-assisted cell-free system. Further research on an AIRS-assisted cell-free massive MIMO system will be performed in future work.

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