Resource Management for Intelligent Reflecting Surface Assisted THz-MIMO Network

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***Abstract*—As the preferred frequency band for future high frequency communication, the terahertz (THz) band has attracted wide attention. In this paper, an energy efficient resource optimization problem in THz band is studied. The massive Multiple-Input Multiple-Output (MIMO) technology and intelligent reflecting surface (IRS) are adopted to improve the capacity and energy efficiency (EE) of proposed network. An IRS assisted THz-MIMO downlink wireless network system is established. The original EE problem is decomposed into phase-shift matrix optimization and power allocation. On this basis, a distributed EE optimization algorithm is designed, which transforms the original nonlinear problem into a convex optimization problem. The simulation results reveal that the proposed distributed optimization method converges rapidly and abtains the maximum EE. This also proves that it is feasible and effective to apply both the IRS and the massive MIMO technology into THz communication network.**

I. Introduction

THz communication is a promising technology and has become a research hotspot in many countries. The THz band is located between infrared and microwave, which the frequency range is 0.1-10 THz. The future network has higher requirements for data transmission rate, and at the same time, it faces the problem of scarcity of wireless communication spectrum resources. The THz short-range wireless communication technology has attracted more and more attention. THz communication technology has great application prospect because it can provide high data rate and huge bandwidth [1]. It can solve the problem of spectrum scarcity and capacity limitation of current wireless system. Due to the high pathloss, the communication range of THz system is limited. So it is essential to combine other technologies to improve the coverage of THz network. From the point of view of low-cost and low-complexity, the massive MIMO technology can maximize the communication quality of users with relatively less investment. Using the massive MIMO technology can reduce the interference between users and improve the system communication quality in the future THz application scenario [2].

IRS is a new revolutionary technology, which can significantly improve the performance of wireless communication network. IRS can intelligently reconfigure the wireless propagation environment by integrating a great quantity of low-cost passive reflecting elements on planar surface [3][4]. IRS and its related intelligent wireless environment will become one of the development trends of network architecture in the future [5]. IRS can control the wireless environment intelligently, so that the communication channel becomes controllable. Each element of IRS can independently induce the amplitude and phase changes of the incident signal, so as to achieve fine-grained three-dimensional (3D) reflection beamforming. By adjusting the phase shift of all elements in adaptive dynamic wireless channel, IRS can also suppress the interference among multiple users [6]. A variety of scenarios using intelligent reflective surface are proposed in [7], including improving communication blind spots, enhancing physical layer security, campus edge interference suppression, large-scale device to device communication and large-scale wireless energy transmission. The IRS raises the freedom in design of communication system.

The existing work has made a lot of contributions from the direction of hardware and algorithm, which proves that the IRS can improve the performance and effectiveness of the system. In the researches of IRS assisted MIMO system [8], IRS assisted Orthogonal Frequency Division Multiplexing (OFDM) system [9] and IRS assisted Non-Orthogonal Multiple Access (NOMA) system [10], this technology has greatly improved the system performance. At present, the terahertz communication network assisted by IRS has become the most potential research hotspot. However, with the increasing density of access network, the problem of energy consumption has become increasingly serious. On this basis, it is feasible and meaningful to explore the resource optimization problem of IRS assisted wireless network.

In this paper, an IRS assisted communication network in the THz band is established. In order to ensure the capacity and EE of THz communication network, the massive MIMO technology is adopted. A hybrid precoding partially connected architecture is adopted. The phase-shift matrix optimization of IRS is considered. On the basis of the above, the research on resource allocation is carried out. Considering the constraints of THz-MIMO communication network, a distributed power allocation algorithm is proposed to deal with the EE optimization problem of the system. The nonlinear problem in the original problem is transformed into a convex optimization problem to maximize EE. The simulation results verify the effectiveness of the proposed algorithm.

II. System Model and Problem Formulation

A. System Model

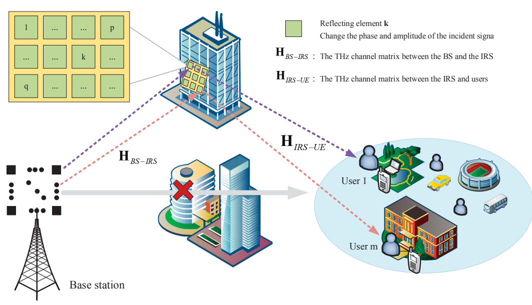

Fig. 1. The IRS assisted THz-MIMO downlink wireless network.

In Fig. 1, an IRS assisted THz-MIMO downlink wireless network is presented, including a base station (BS) with N_t antennas, an IRS with K reflecting elements and single antenna user m, where $m \in \{1, 2, \cdots, M\}$. When the direct link between BS and user is blocked, the signal transmission cannot be completed. In this case, an IRS is deployed to bypass obstacles and realize signal reflection, so as to a virtual line-of-sight (LoS) link is created between BS and user. The received signal of user m can be given by

$$\mathbf{y}_m = \mathbf{h}_{r,m} \mathbf{\Phi} \mathbf{H}_{BS-IRS} \mathbf{F}_{RF} \mathbf{F}_{BB} \mathbf{s} + \upsilon_m, \tag{1}$$

where $\mathbf{h}_{r,m} \in \mathbb{C}^{K \times 1}$ is the channel vector between the IRS and user m. Denote by $\mathbf{H}_{IRS-UE} = [\mathbf{h}_{r,1}, \mathbf{h}_{r,2}, \cdots, \mathbf{h}_{r,M}] \in \mathbb{C}^{M \times K}$ the THz channel matrix between the IRS and users. And $\mathbf{\Phi} = \text{diag}\left[e^{j\varphi_1}, e^{j\varphi_2}, \cdots, e^{j\varphi_K}\right] \in \mathbb{C}^{K \times K}$ is the phase-shift matrix, where $\varphi_k \in [0, 2\pi]$ reprents the phase-shift of element k; $\mathbf{H}_{BS-IRS} = [\mathbf{h}_{t,1}, \mathbf{h}_{t,2}, \cdots, \mathbf{h}_{t,K}] \in \mathbb{C}^{K \times N_t}$ is the THz channel matrix between the BS and IRS. This paper adopts hybrid precoding scheme based on partially connected architecture. $\mathbf{F}_{RF} \in \mathbb{C}^{N_t \times N_{RF}}$ and $\mathbf{F}_{RF} \in \mathbb{C}^{N_{RF} \times M}$ are analog precoding matrix and digital precoding matrix, respectively. υ_m is the additive white Gaussian noise (AWGN) vector with zero mean and varianc σ^2.

B. THz Indoor Communication Channel Model

In the system model established in this paper, there are two THz channel matrices $\mathbf{H}_{BS-IRS}$ and $\mathbf{H}_{IRS-UE}$. Taking $\mathbf{H}_{BS-IRS}$ as an example, the THz channel matrix between the BS and IRS is modeled as

$$\mathbf{H}_{BS-IRS} = \sqrt{\frac{N_t N_r}{\mathcal{L}(f, d)}} \sum_{l=1}^{L_n} \alpha_l \mathbf{a}_r(\theta_{r,l}, \phi_{r,l}) \mathbf{a}_t(\theta_{t,l}, \phi_{t,l})^H \tag{2}$$

where N_t is the number of of transmitting antennas, and N_r is the number of receiving antennas; $\mathcal{L}(f, d)$ stands the pathloss by THz frequency f and distance d between BS and IRS; α_l is the fading coefficient of the lth path.

The distinctest difference between THz band and other transmission channels lies in the characteristics of pathloss and channel noise. The path loss in THz band includes two parts: spreading loss and molecular absorption loss. When the path gain is calculated in THz band, the spreading loss L_{spread} and molecular absorption loss L_{abs} need to be paid special attention. Among them, the spreading loss L_{spread} refers to the energy loss caused by electromagnetic wave propagation in medium, which is related to signal frequency and transmission distance. The molecular absorption loss L_{abs} is caused by the energy loss of polar molecules, which is related to the concentration and species of molecules in the path. The the pathloss $\mathcal{L}(f, d)$ can be given by

$$\begin{aligned} \mathcal{L}(f, d) &= L_{spread}(f, d) \times L_{abs}(f, d) \\ &= \left(\tfrac{c}{4\pi f d}\right)^2 \times e^{-k_{abs}(f) d}, \end{aligned} \tag{3}$$

or

$$\mathcal{L}(f, d) = 20\log_{10}\left(\frac{4\pi f d}{c}\right) + 10 k_{abs}(f) d \log_{10} e, \tag{4}$$

where c is the speed of light, $k_{abs}(f)$ is the absorption coefficient of frequency-dependent medium.

Because the IRS is a plane, the antenna steering vector should be calculated according to the uniform planar array (UPA), not the uniform linear array (ULA). For the UPA antenna array with P rows and Q columns, the antenna steering vector is given by (5), where θ is the azimuth angle and ϕ is the elevation angle of the receiver, respectively; λ is the communication wavelength, d_r is the interval between the antennas, which the interval is equal to half-wavelength $d_r = \frac{1}{2}\lambda$ by default.

In this paper, the antenna response arrays of BS and IRS are set as UPA. On this basis, the channel modeling of $\mathbf{H}_{BS-IRS}$ is completed. $\mathbf{H}_{BS-IRS}$ can also be modeled as the above channel model.

C. Problem Formulation

In view of the established system model, an resource allocation problem is proposed by optimizing the reflection phase-shift matrix, power management subproblems for EE maximization. The achievable rate of user m can be written as

$$c_m = \frac{W}{M} \log_2(1 + \gamma_m), \tag{6}$$

$$\mathbf{a}_r\left(\theta_{r,l},\phi_{r,l}\right)=\frac{1}{\sqrt{PQ}}\left[1,\cdots,e^{j\frac{2\pi}{\lambda}d_r\left(p\sin\theta\sin\phi+q\cos\phi\right)},\cdots,e^{j\frac{2\pi}{\lambda}d_r\left(\left(\sqrt{Q}-1\right)\sin\theta\sin\phi+\left(\sqrt{P}-1\right)\cos\phi\right)}\right]^T, \tag{5}$$

where W is the THz bandwidth employed; γ_m is the signal-to-interference-plus-noise ratio (SINR) of user m can be written as

$$\gamma_m=\frac{p_m\left\|h_{r,m}\mathbf{\Phi}\mathbf{H}_{BS-IRS}\mathbf{F}_{RF}\mathbf{F}_{BB}\right\|^2}{\sum\limits_{j=1,j\neq m}^{M}p_j\left\|h_{r,j}\mathbf{\Phi}\mathbf{H}_{BS-IRS}\mathbf{F}_{RF}\mathbf{F}_{BB}\right\|^2+\sigma^2}, \tag{7}$$

where $\mathbf{F}_{RF}$ and $\mathbf{F}_{BB}$ can be given by the low complexity zero-forcing (ZF) precoding algorithm.

The EE of system is defined as the specific value of total system capacity to total power consumption, which can be given by

$$\mathbb{E}\left(\mathbf{\Phi},\mathbf{P}\right)=\frac{R\left(\mathbf{\Phi},\mathbf{P}\right)}{U\left(\mathbf{P}\right)}, \tag{8}$$

where $U\left(\mathbf{P}\right)$ is the total power consumption and given as

$$U\left(\mathbf{P}\right)=\mathrm{P}_c+\sum_{m}^{M}p_m, \tag{9}$$

where P_c is the circuit power consumption of BS in system.In addition, the sum-rate $R\left(\mathbf{\Phi},\mathbf{P}\right)$ is given by

$$R\left(\mathbf{\Phi},\mathbf{P}\right)=\sum_{m}^{\mathrm{M}}c_m=\sum_{m}^{\mathrm{M}}\frac{W}{M}\log_2\left(1+\gamma_m\right). \tag{10}$$

Based on the established network model, an IRS assisted THz-MIMO network utility function is defined, including phase-shift matrix optimization and power allocation. Based on these work above, modeling the problem as follows

$$\max_{(\mathbf{\Phi},\mathbf{P})}\mathbb{E}\left(\mathbf{\Phi},\mathbf{P}\right) \tag{11}$$

$$\begin{aligned} s.t.\quad & C1:\left\|\mathbf{F}_{RF}\mathbf{F}_{BB}\right\|^2\leq 1\\ & C2:\sum_{m}^{M}p_m\leq P_{\max},\forall m\in M\\ & C3:p_m\geq 0,\forall m\in M\\ & C4:\sum_{m}^{\mathrm{M}}c_m\geq R_t,,\forall m\in M\\ & C5:\sum_{j=1,j\neq m}^{M}p_j\left\|h_{r,j}\mathbf{\Phi}\mathbf{H}_{BS-IRS}\mathbf{F}_{RF}\mathbf{F}_{BB}\right\|^2\leq I \end{aligned} \tag{12}$$

where $C1$ is the normalization limitation of precoding vectors, $C2$ is the limit that the sum-power cannot exceed the maximum transmit power, $C4$ denotes the QoS constraints of users, $C5$ cross-layer interference constraints.

III. Phase-Shift Matrix Optimization and Power Allocation

This section mainly introduces the distributed algorithm of EE optimization, which is divided into two parts phase-shift matrix optimization and power allocation. Based on phase shift matrix optimization, the alternating direction method of multipliers (ADMM) algorithm is adopted for power allocation.

A. Phase-shift Matrix Optimization

As mentioned above, all elements of the IRS can adjust the amplitude and phase of the input signal. In practice, the phase or amplitude of the IRS is adjustable discrete values with finite precision. Mathematically, the reflected signal of IRS is obtained by multiplying the corresponding incident signal with the complex reflection coefficient $\kappa e^{j\varphi}$. To maximize the received power of the user, all elements are set their reflection amplitude κ as the maximum value 1 in this paper. First, we design a matrix $\mathbf{\Gamma}=\left[0,\frac{2\pi}{2^\delta},\ldots,\frac{2\pi}{2^\delta}\left(2^\delta-1\right)\right]$, where δ is the bit-quantization number. The design algorithm obtains the phase shift matrix from this matrix to maximize the transmission sum-rate. A dual-layer iterative algorithm is set: the outer layer randomly selects $\varphi_{i+1},\varphi_{i+2},\ldots,\varphi_K$ from the matrix $\mathbf{\Gamma}$; the inner layer is used to traverse the matrix to find φ_i that can maximize the sum-rate. When the loop is finished, the phase-shift matrix is obtained to complete the subsequent power allocation.

B. Power Allocation

After the phase-shift matrix optimization, the power allocation in EE optimization problem is further considered. Given the phase-shift matrix, the power allocation subproblem can be given by

$$\begin{aligned}&\max\mathbb{E}\left(\mathbf{P}\right)\\&s.t.C2,C3,C4,C5.\end{aligned} \tag{13}$$

The EE optimization problem is non-convex, and the objective function is a nonlinear fraction. To solve these problems, the formula needs to be changed. In order to decrease the computational complexity, the fraction is converted to the subtraction. After phase-shift matrix optimization, only the power allocation optimization problem is considered. An auxiliary variable ξ^* is derived and given by

$$\xi^*=\frac{R\left(\mathbf{P}^*\right)}{U\left(\mathbf{P}^*\right)}, \tag{14}$$

Algorithm 1 Distributed Energy Efficient Phase-Shift Matrix Optimization and Power Allocation

Initialize The THz channel matrix $\mathbf{H}_{BS-IRS}$ and $\mathbf{H}_{IRS-UE}$, bit-quantization number δ,auxiliary variable $\xi^* = 0$, the power is allocated equally
Step one: Phase-Shift Matrix Optimization
Set $\boldsymbol{\Gamma} = \left[0, \frac{2\pi}{2^\delta}, \cdots, \frac{2\pi}{2^\delta}\left(2^\delta - 1\right)\right]$
for $i = 1 : K$ **do**
    Randomly generate $\varphi_{i+1}, \varphi_{i+2}, \cdots, \varphi_K$ from $\boldsymbol{\Gamma}$
    for $j = 1 : 2^\delta$ **do**
        $\varphi_i = \boldsymbol{\Gamma}(j)$
        Construct $\boldsymbol{\Phi}^{\#} = \operatorname{diag}\left[e^{j\varphi_1}, e^{j\varphi_2}, \cdots, e^{j\varphi_K}\right]$
        Calculate the sum rate $R^{\#}$
    end for
    Select the maximal sum-rate R_{max} from all $R^{\#}$
    $\varphi_i = \boldsymbol{\Gamma}(max)$
end for
Get the final $\boldsymbol{\Phi} = \operatorname{diag}\left[e^{j\varphi_1}, e^{j\varphi_2}, \cdots, e^{j\varphi_K}\right]$
Step two: Power Allocation
for $p = 1 : max\_Iter$ **do**
    Set $t = 1$
    repeat
        Calculate and update $\mathbf{X}^{\mathrm{t+1}}$ according to (19)
        Calculate and update $\mathbf{Z}^{\mathrm{t+1}}$ according to (19)
        Calculate and update $\mu^{\mathrm{t+1}}$ according to (19)
    until converge
    calculate $\xi^* = EE$ according to (11)
end for

where $R\left(\mathbf{P}^*\right) - \xi^* U\left(\mathbf{P}^*\right) = 0$. Optimization problems can be redefined as

$$\begin{array}{l} \max R\left(\mathbf{P}\right) - \xi^* U\left(\mathbf{P}\right) \\ s.t. C2, C3, C4, C5. \end{array} \tag{15}$$

Then, the ADMM algorithm is used to deal with the optimal power allocation problem. Introducing auxiliary variables two auxiliary variables $\mathbf{X}$ and $\mathbf{Z}$. $\mathbf{X}$ denotes the power allocation matrix of users and $\mathbf{Z}$ is a global auxiliary vector. Then, the indicator function is given by

$$\mathrm{g}\left(\mathbf{Z}\right) = \left\{ \begin{array}{l} 0, \mathbf{Z} \in \Lambda \\ +\infty, otherwise \end{array} \right. \tag{16}$$

where Λ is defined as the set of variable vectors of $C4$. On this basis, the power optimization problem is changed to

$$\begin{array}{c} \min\limits_X \left\{ \xi^* \left(\mathrm{P}_c + \sum\limits_m^M p_m \right) - \sum\limits_m^{\mathrm{M}} \frac{W}{M} \log_2\left(1 + \gamma_m\right) + \mathrm{g}\left(\mathbf{Z}\right) \right\} \\ s.t. \mathbf{X} - \mathbf{Z} = 0 \end{array} \tag{17}$$

The augmented Lagrangian L_ρ is given as follows

$$\begin{array}{c} L_\rho = \xi^* \left(\mathrm{P}_c + \sum\limits_m^M p_m \right) - \sum\limits_m^{\mathrm{M}} \frac{W}{M} \log_2\left(1 + \gamma_m\right) \\ + \mathrm{g}\left(\mathbf{Z}\right) + \mu^T \left(\mathbf{X} - \mathbf{Z}\right) + \frac{\rho}{2} \left\| \mathbf{X} - \mathbf{Z} \right\|_2^2 \end{array} \tag{18}$$

where μ is the vector of dual variable, $\rho > 0$. To deal with the power allocation problem, the iteration steps are as follows

$$\begin{array}{l} X^{t+1} = \arg\min_X L_\rho\left(X, Z^t, \mu^t\right) \\ Z^{t+1} = \arg\min_Z \left[\left(\mu^t\right)^T \left(X^{t+1} - Z\right) + \frac{\rho}{2} \left\| X^{t+1} - Z \right\|^2 \right] \\ \mu^{t+1} = \mu^t + \rho\left(X^{t+1} - Z^{t+1}\right) \end{array} \tag{19}$$

where t is the iteration index. Based on the above analysis, the distributed phase-shift matrix optimization and power allocation is given in detail in Algorithm 1.

IV. Simulation Results

The simulation results show the performance of the proposed algorithm in this section. In phase shift matrix optimization, the influence of bit quantization number on sum-rate of system is verified. The effectiveness and convergence of the proposed EE optimization algorithm are also verified, and the influence of the number of IRS elements on the system EE in THz-MIMO network is analyzed.

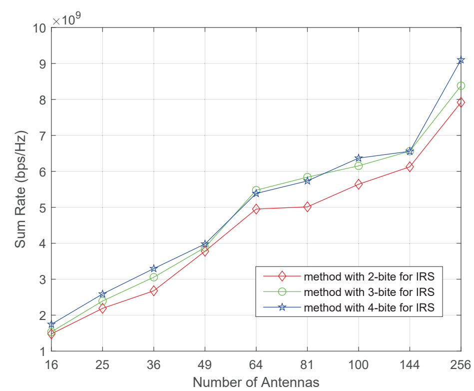

Fig. 2. The sum rate varies with the number of antennas under different bit quantization numbers.

Fig. 2 shows the sum-rate varies with the number of antennas under different bit quantization numbers, where

$$X^{t+1} = \arg\min_X \left[\xi^* \left(P_c + \sum_m^M p_m \right) - \sum_m^M \frac{W}{M} \log_2\left(1 + \gamma_m\right) + \left(\mu^t\right)^T \left(X - Z^t\right) + \frac{\rho}{2} \left\| X - Z^t \right\|^2 \right] \tag{20}$$

the number of users M is 4, the number of IRS' elements K is 64, power average distribution. Three different bit-quantization numbers are set in Fig. 2, which $\delta = 2$, $\delta = 3$ and $\delta = 4$. As can be seen from Fig. 2, the IRS with high bit-quantization number can achieve high sum-rate than low bit-quantization number in THz-MIMO system. Meanwhile, the simulation results also show that with the increasing antenna quantity, the system sum-rate is also improving. The effectiveness of massive MIMO technology is verified.

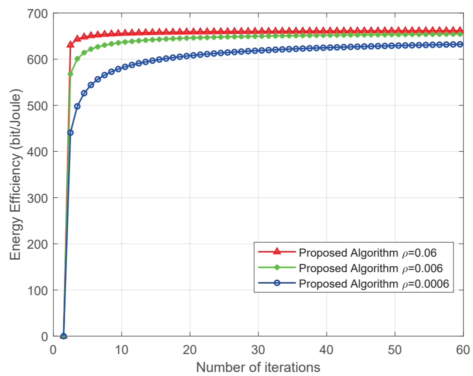

Fig. 3. Convergence of the total EE with different ρ.

Fig. 3 shows the EE comparison against different ρ implemented by proposed algorithm for power allocation. As shown in the Fig. 3, the beginning of the algorithm iteration, the EE curve rises rapidly with the number of iterations until the performance of the algorithm begins to converge. The simulation structure shows that the larger the ρ, the faster the convergence of the algorithm, the fewer iterations. This verifies the effect of ρ on the convergence of the proposed algorithm. At the same time, the change of EE proves that the proposed algorithm shows good convergence.

V. Conclusions

In this paper, an IRS assisted THz-MIMO wireless communication system is established. In this paper, the massive MIMO technology and IRS are used to increase the capacity and EE of proposed communication network. The original problem is decomposed into phase-shift matrix optimization and power allocation. On this basis, a distributed EE optimization algorithm is designed, which transforms the original nonlinear problem into a convex optimization problem, and achieves the maximum EE with stable convergence. It is feasible and effective to apply both the IRS and the massive MIMO technology into THz communication network.

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