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Robust Design for Intelligent Reflecting Surface Assisted MIMO-OFDMA Terahertz IoT Networks

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Abstract—Terahertz (THz) communication has been regarded as one promising technology to enhance the transmission capacity of future internet-of-things (IoT) users due to its ultra-wide bandwidth. Nonetheless, one major obstacle that prevents the actual deployment of THz lies in its inherent huge attenuation. Intelligent reflecting surface (IRS) and multiple-input multipleoutput (MIMO) represent two effective solutions for compensating the large pathloss in THz systems. In this paper, we consider an IRS-aided multi-user THz MIMO system with orthogonal frequency division multiple access, where the sparse radio frequency chain antenna structure is adopted for reducing power consumption. The objective is to maximize the weighted sum rate via jointly optimizing the hybrid analog/digital beamforming at the base station and the reflection matrix at the IRS. Since the analog beamforming and reflection matrix need to cater all users and subcarriers, it is difficult to directly solve the formulated problem, and thus, an alternatively iterative optimization algorithm is proposed. Specifically, the analog beamforming is designed by solving a MIMO capacity maximization problem, while the digital beamforming and reflection matrix optimization are both tackled using the semidefinite relaxation technique. Considering that obtaining perfect channel state information (CSI) is a challenging task in IRS-based systems, we further explore the case with the imperfect CSI for the channels from the IRS to users. Under this setup, we propose a robust beamforming and reflection matrix design scheme for the originally formulated non-convex optimization problem. Finally, simulation results are presented to demonstrate the effectiveness of the proposed algorithms. Index Terms—Hybrid beamforming, Intelligent Reflecting Surfaces, THz, Multiple-input multiple-output.

I. Introduction

With the rapid proliferation of the internet of things (IoT) users, the future IoT networks need to support the huge transmission capacity [1], [2]. As such, the sub-6 Gigahertz (GHz) and millimeter-wave (mmWave) may not be able to support these users' communications. That being said, terahertz (THz) communication (0.1-10 THz) has been regarded as a promising technology to deal with the above problem due to its ultra-wide bandwidth [3], [4]. However, there are two major shortcomings for THz communications, namely severe signal attenuation and poor diffraction [5]. Multiple-input multiple-output (MIMO) has been recognized as an effective technique to enhance the THz signal strength owing to the high beamforming gain. Indeed, it has been shown that the signal strength grows linearly with the number of antennas at the base station (BS) [6]. Meanwhile, the small wavelength in THz makes it easy to pack more antennas together, and form a massive MIMO array. This way, the problem of severe signal antenuation of THz can be substantially relieved. Nonetheless, the property of poor diffraction still makes THz vulnerable to blocking obstacles that break the line-of-sight (LoS) links. To address this problem, intelligent reflect surface (IRS) can be deployed to create additional links [7], [8], and thus, enhance the performance of THz systems. Being equipped with a large number of reconfigurable passive elements [9]– [11], IRS can reflect the incident signals to any direction via adjusting the phase shifts. As a result, when there is no direct link between the transmitter and

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receiver, communication can still be realized via building a reflective link with the help of the IRS as shown in Fig. 1. Therefore, incorporating MIMO and IRS into the THz communication can effectively enhance the signal reception and reduce the probability of signal blockage. In this paper, we study a multi-user IRS-aided THz MIMO system, where the BS employs a sparse RF chain structure for lowering the circuit power consumption [12]. Meanwhile, considering that the wideband THz signals may suffer from frequency selective fading, orthogonal frequency division multiple (OFDM) is also adopted. Based on this system model, we design the hybrid analog/digital beamforming at the BS and the reflection matrix at the IRS for maximizing the weighted sum rate under perfect and imperfect channel state information (CSI).

A. Related Works

The MIMO THz communication has become a research hotspot in recent years. Considering the large signal attenuation, Lin et al. study the indoor short range MIMO THz communications [13], [14]. The authors propose a hybrid analog/digital beamforming to maximize the energy efficiency of the system. Busari et al. consider three hybrid beamforming array structures, namely fully-connected, sub connected and overlapped subarray [15]. Then, a single-path THz channel model is used to investigate the performance of the system under different array structures. Additionally, due to the ultra-wide bandwidth, frequency selective hybrid beamforming design in THz system is necessary. For example, Tan and Dai first analyze the array gain loss in the wideband THz system and then propose a time delay network to obtain the near-optimal array gain [16]. However, the complexity of the considered system is prohibitively high. Yuan et al. build a 3-D wideband THz channel model and propose a two-stage hybrid analog/digital beamforming for maximizing the capacity of the system [17]. After that, the imperfect CSI is also considered and a robust beamforming design scheme is developed. In parallel, IRS has attracted great attention in the past two years owing to its ability to enable cost-effective and energy-efficient communications. Wu and Zhang provide a basic IRS communication system model in [9], based upon which the joint active beamforming at the BS and passive beamforming at the IRS is designed to minimize the system power consumption. In addition, Ning et al. propose to apply THz to IRS [18], and consider the beam training and hybrid analog/digital beamforming. They propose two effective hierarchical codebooks and beamforming design schemes to obtain the near-optimal performance. To study the performance of IRS in frequency selective fading channels, Zhang et al. consider a MIMO-OFDM system [19], where only one common set of IRS reflective matrices is designed for all subcarriers. Based on this, a new alternative optimization algorithm is proposed. Yang et al. investigate the channel estimation and beamforming design problem in the IRS-based OFDM system [20], and propose a practical transmission protocol as well as channel estimation scheme. On this basis, a strategy of jointly optimizing power allocation and the reflection matrix is developed for maximizing the achievable rate. Although THz and IRS techniques have been investigated in the literature, e.g., in [9], [13]–[21], most of them do not consider the hybrid beamforming at the BS for IRS communication [9], [18]–[21]. In fact, in a THz-based IRS communication system, the BS should employ a sparse RF antenna structure for reducing the power consumption and the multiple subcarriers transmission technology for overcoming the frequency selection channel fading. As a result, how to design the hybrid analog/digital beamforming at the BS and reflection matrix at the IRS catering to all subchannels will be challenging. In addition, how to obtain the perfect CSI remains a non-trivial task for IRS-based

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reflection links. For the direct link from the BS to users, the CSI can be readily estimated by conventional channel estimation methods. For the indirect link from the BS to the IRS, the CSI is also relatively easy to obtain since the locations of IRS and BS are fixed. However, the accurate CSIs of reflection links from the IRS to users are usually difficult to obtain due to the mobility of users. Nonetheless, [9], [18]–[21] all assume perfect CSI. Although Zhou et al. investigate the robust beamforming design in an IRS system, the conventional multiple antenna structure and single-carrier scenario are considered.

B. Main Contributions

To the best of our knowledge, this is the first work to consider hybrid analog/digital beamforming in IRS-aided THz MIMOOFDMA under imperfect CSI, and the main contributions of this paper include:

• We construct an IRS-aided THz MIMO-OFDMA IoT communication system, where the BS employs sparse RF chain structure for reducing the circuit power consumption. On this basis, we investigate the joint optimization of the hybrid beamforming at the BS and reflection matrix at the IRS for maximizing the weighted sum rate under perfect CSI.

• To solve the formulated non-trivial problem, we first initialize the reflection matrix. Since all subcarriers share one analog beamforming matrix, we ignore the multi-user interference and obtain the analog beamforming by solving the corresponding MIMO capacity optimization problem. We subsequently reformulate a multi-user weighted sum rate maximization problem to optimize the digital beamforming. With the help of successive convex approximation (SCA) and semidefinite relaxation (SDR) techniques, we propose an iterative algorithm to solve the digital beamforming that mitigates the multi-user interference. Following this, we formulate the reflection matrix optimization problem under given hybrid analog/digital beamforming, and an iterative algorithm is proposed to solve it. The above procedure is repeated until convergence.

• Next, we assume that the perfect CSIs of reflection links cannot be obtained, and there exists bounded estimation error. We apply the same method to solve the analog beamforming. For the digital beamforming and reflection matrix, we develop a robust optimization scheme for the weighted sum rate optimization problem relying on the SProcedure and the convex approximation techniques. Finally, our simulation results demonstrate the effectiveness of the proposed algorithms.

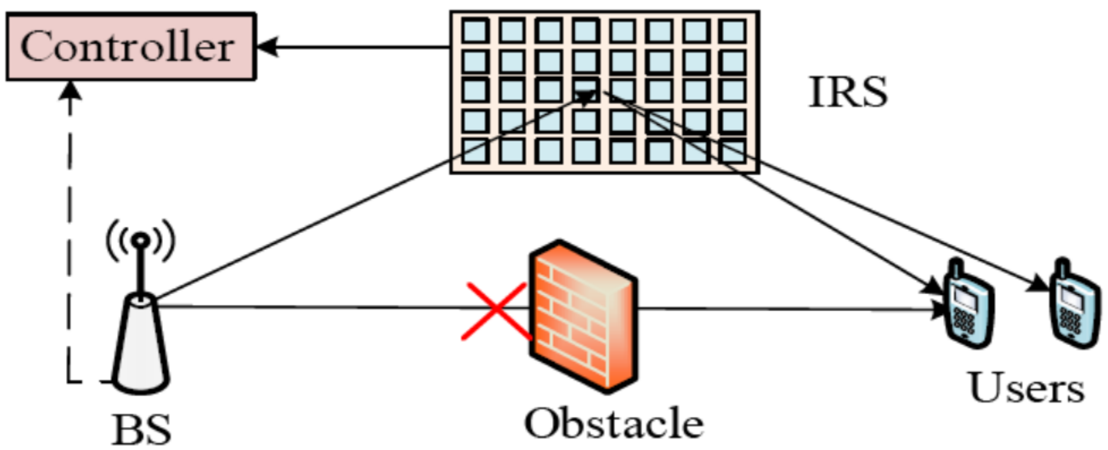

Fig. 1: The IRS system model.

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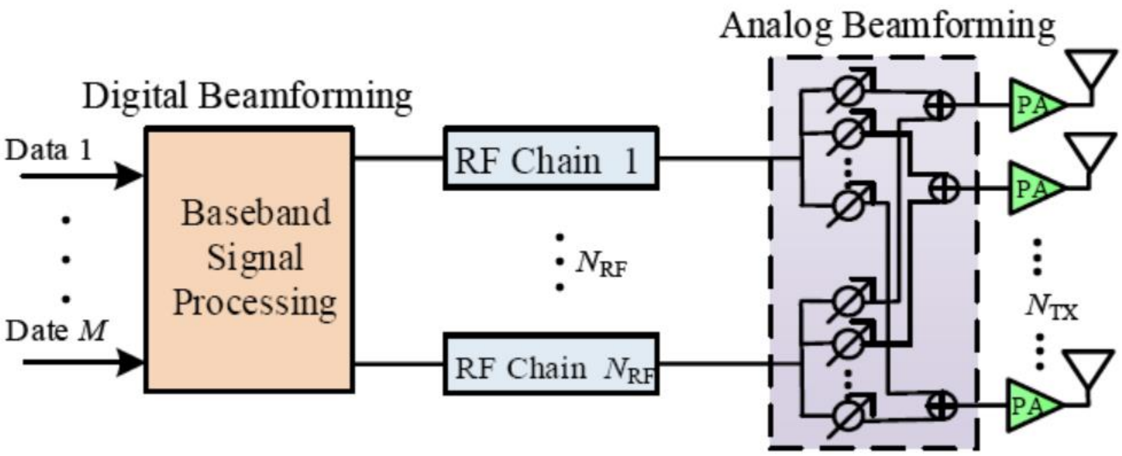

Fig. 2: The sparse RF chain structure at the BS.

II. System Model and Problem Formulation

In this section, we first describe the IRS-aided THz MIMOOFDMA system model and antenna structure. Next, we present the THz channel transmission model and corresponding parameters. Finally, we formulate the weighted sum rate maximization problem.

A. System Model

We consider an IRS-aided THz multi-user MIMO system with OFDMA as shown in Fig. 1, where the BS is equipped with NTX antennas and NRF (NRF ≤ NTX) RF chains. The diagram of the sparse RF chain at the BS is illustrated in Fig. 2. We assume that there are no direct links between BS and users due to the blockage of walls or other obstacles, and the users can only receive the reflected signals from IRS. Let NIRS, M and K denote the number of IRS elements, users and subcarriers, respectively. We assume that the CSIs of all links can be obtained using existing channel estimation schemes proposed in broadband IRS system [23]–[25]. In addition, the computation of resource allocation is executed in BS, and then the BS needs to convey the resource allocation results (refection matrix of the IRS) to IRS. As shown in Fig. 1, the IRS phased shifts are controlled by an attached controller. Therefore, the BS can transmit the reflection matrix to controller via a dedicated separate wireless control link [9]. The received signal on the kth subcarrier at the mth user can be expressed as

$$y_m[k] = \mathbf{G}_m[k]\mathbf{F}\mathbf{v}_m[k]x_m[k] + \sum_{j\neq m}^{M} \mathbf{G}_m[k]\mathbf{F}\mathbf{v}_j[k]x_j[k] + n_m[k]$$

(1)

where Gm[k] = GtGrηkbgm[k]ΦHb[k], with Gt and Gr as the transmit and receive antenna gains, respectively, and ηk as the pathloss compensation factor [18]. bgm[k] ∈ C 1×NIRS denotes the channel vector from IRS to the mth user on the kth subcarrier, Φ ∈ C NIRS×NIRS is the reflection coefficient matrix with Φ = diag{φ1, ..., φNIRS }, Hb[k] ∈ C NIRS×NTX represents the channel matrix from BS to IRS on the kth subcarrier, F ∈ C NTX×NRF is the analog beamforming matrix with F = [f1, ...,fNRF], vm[k] ∈ C NRF×1 and xm[k] denote the digital beamforming and transmit signal for the mth user on the kth subcarrier, respectively, nm[k] is the independent and identically distributed (i.i.d.) additive white Gaussian noise (AWGN) with zero-mean and variance N0. In (1), the first term is the designed signal, while the second term is the multi-user interference that must be mitigated by designing proper digital beamforming and reflection matrix. Next, we present the THz channel model. Let fc and B, respectively, represent the central frequency and bandwidth. Then, the frequency band of the kth subcarrier can be expressed as fk = fc + B K (k − 1 − K−1 2), k = 1, 2, ..., K. Although there are a few scattering components in THz communication, their power are much lower (more than 20 dB) than that of LoS component [26], and thus, we only consider the LoS component and ignore the other scattering components. Accordingly, the channel matrix Hb[k] can be expressed as

$$\widehat{\mathbf{H}}[k] = q(f_k, d)\mathbf{H}[k] \quad (2)$$

where q(fk, d) is the complex path gain satisfying

$$q(f_k, d) = \frac{c}{4\pi f d} e^{-\frac{1}{2}\tau(f_k)d} \quad (3)$$

where c stands for the speed of light, τ(fk) represents the medium absorption factor and d is the distance from the BS to IRS [27]. H[k] can be expressed as

$$\mathbf{H}[k] = \mathbf{a}_r(\theta_k)\mathbf{a}_t^H(\varphi_k) \quad (4)$$

with at(θk) and ar(ϕk), respectively, as the antenna array response vector of the transmitter and receiver, namely

$$\mathbf{a}_t(\theta_k) = \frac{1}{\sqrt{N_{\text{TX}}}} \left[1, e^{j\pi\theta_k}, e^{j2\pi\theta_k}, \cdots, e^{j(N_{\text{TX}}$$

(5)

$$\mathbf{a}_r(\varphi_k) = \frac{1}{\sqrt{N_{\text{IRS}}}} \left[1, e^{j\pi\varphi_k}, e^{j2\pi\varphi_k}, \cdots, e^{j(N_{\text{IRS}}-1)\pi\varphi_k}\right]^T$$

(6)

Here, θk = 2d0 fk sin(φt)/c and ϕk = 2d0 fk sin(φr)/c, d0 denotes the antenna distance, and φt/φr ∈ [−π/2, π/2] are, respectively, angle of departure (AoD) and angle of arrival (AoA). Similarly, gm[k] can be expressed as

$$\widehat{\mathbf{g}}_m[k] = q(f_k, d_m)\mathbf{g}_m[k]. \quad (7)$$

$$\mathbf{G}_m[k] = u_m[k]\mathbf{g}_m[k]\mathbf{\Phi}\mathbf{H}[k] \quad (8)$$

Since the rank-one constraint is non-convex, we need to drop it and formulate a SDR problem that can be solved by existing convex solvers such as the CVX toolbox. The above procedure is repeated until the results converge or the iteration number reaches its maximum value. In addition, since the SDR problem of is a convex optimization problem, the solutions are optimal for each iteration. Therefore, iteratively solving and updating variables increase or at least maintain the value of the objective function. Given the limited transmit power, the designed iterative algorithm guarantees the value of the objective function to be a monotonically non-decreasing sequence with an upper bound, and it converges to a stationary solution that is at least a local optimal. For solving (25), we remove.

Algorithm 1: The Proposed Alternative Iterative Optimization Algorithm.

Initialize the reflection matrix $\mathbf{\Phi}^{(0)}$, iteration number $r = 1$ and maximum iteration number $r_{\max}$.
repeat
    Obtain the analog beamforming $\mathbf{F}^{(r)}$ according to (19).
    Initialize variables $t_{m,k}^{(0)}$, $b_{m,k}^{(0)}$, iteration number $r' = 1$ and maximum iteration number $r'_{\max}$.
    repeat
        Obtain $t_{m,k}^{\star}$, $b_{m,k}^{\star}$ and $\mathbf{v}_m[k]^{\star}$ by solving (25).
        Update variables $t_{m,k}^{(r')} \leftarrow t_{m,k}^{\star}$, $b_{m,k}^{(r')} \leftarrow b_{m,k}^{\star}$.
        Update $r' \leftarrow r' + 1$.
    until $r' = r'_{\max}$ or Convergence;
    Initialize variables $t'^{(0)}_{m,k}$, $b'^{(0)}_{m,k}$, iteration number $r'' = 1$ and maximum iteration number $r''_{\max}$.
    repeat
        Obtain $t'^{\star}_{m,k}$, $b'^{\star}_{m,k}$ and $\mathbf{\Omega}^{\star}$ by solving (29).
        Update variables $t'^{(r'')}_{m,k} \leftarrow t'^{\star}_{m,k}$, $b'^{(r'')}_{m,k} \leftarrow b'^{\star}_{m,k}$.
        Update $r'' \leftarrow r'' + 1$.
    until $r'' = r''_{\max}$ or Convergence;
    Obtain $\mathbf{\Phi}^{\star}$ according to $\mathbf{\Omega}^{\star}$.
    Update $\mathbf{\Phi}^{(r)} \leftarrow \mathbf{\Phi}^{\star}$.
    Update $r \leftarrow r + 1$.
until $r = r_{\max}$ or Convergence;
Obtain the analog beamforming $\mathbf{\Phi}^{(r)}$, digital beamforming

Finally, we summarize the proposed alternatively iterative optimization scheme in Algorithm 1.

V. Numerical Results

In this section, simulation results are presented to evaluate the performance of the proposed shames in IRS-aided THz MIMO-OFDMA systems. Due to the severe pathloss in THz, we consider a short distance communication scenario as shown in Fig. 3, where users are located within a circle with 1:5 m radius.

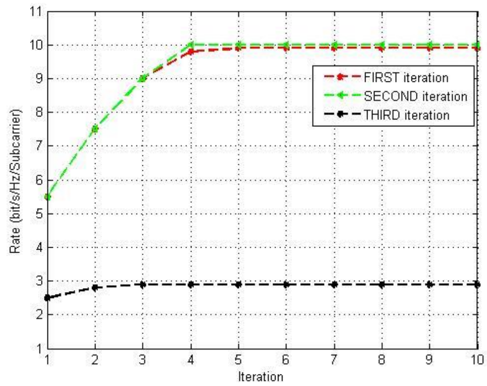

Fig. 3: The rate versus iteration for solving the digital beamforming.

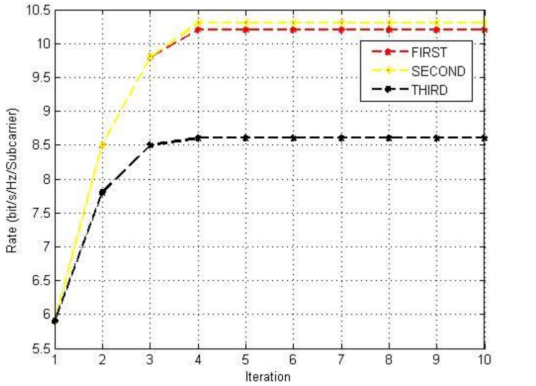

Fig. 4: The rate versus iteration for solving the reflection matrix.

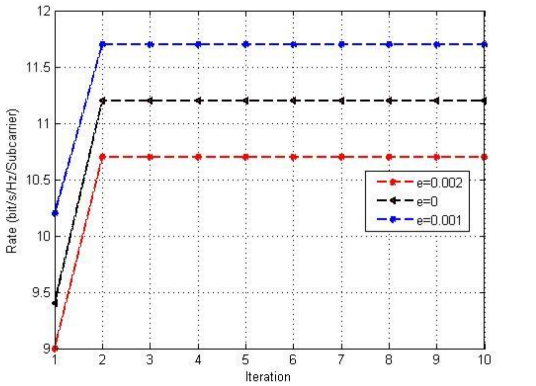

Fig. 5: The rate versus iteration for the proposed Algorithm 1.

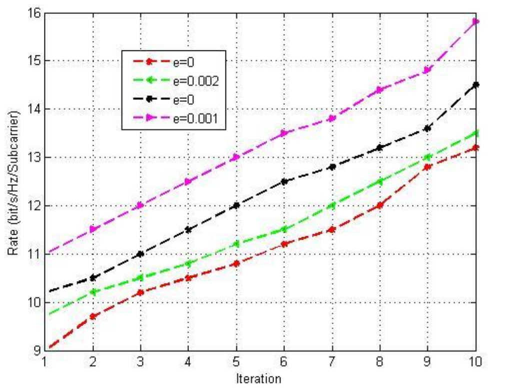

Fig. 6: The rate versus the allowable maximum transmit power.

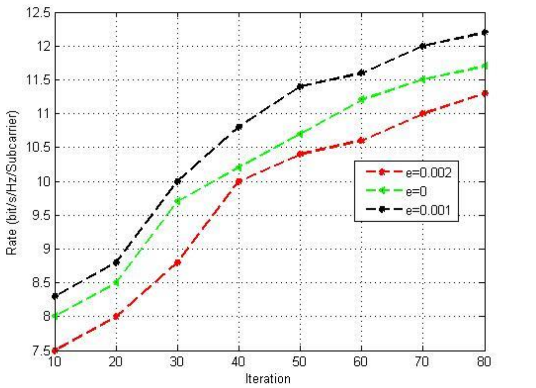

Fig. 7: The rate versus the number of antennas.

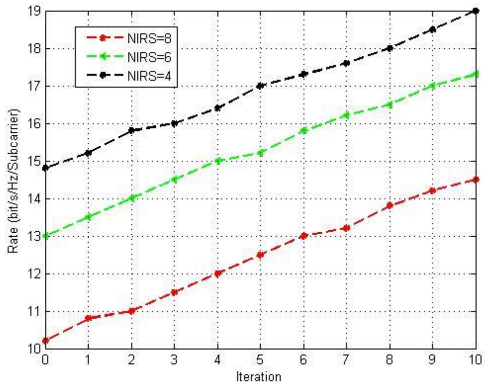

Fig. 8: The rate versus the allowable maximum transmit power under deferent numbers of IRS reflection elements.

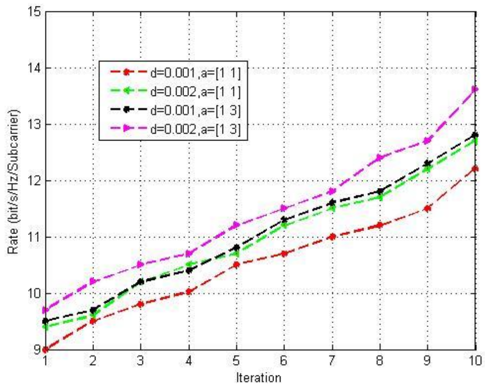

Fig. 10: The rate versus the allowable maximum transmit power with dierent weights.

VI. Conclusion

In this paper, we have considered an IRS-aided THz MIMOOFDMA system, where the BS is equipped with a sparse RF chain structure. First, we have proposed a joint hybrid analog/digital beamforming and reflection matrix design to maximize the weighted sum rate under perfect CSIs. Next, considering the imperfect CSIs from the IRS to users, we have redesigned a robust joint optimization algorithm. From simulation results, we have found that the channel estimation error has a large impact on the system sum rate. Moreover, allocating a higher weight to a particular user can improve that user's rate, but at the cost of sum rate. Consequently, channel estimation schemes and users weight selection are important criteria for the design of practical systems, and we need to adjust the weights according to different quality of service requirements of the users.

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