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RESEARCH ARTICLE

Polyhedron Optimization for Power Allocation of Cell-Free Based IRS System

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ABSTRACT In this paper, re-configurable intelligent reflecting surfaces (IRS) based on cell-free communications to serve multi-user (MU) are considered. This is to enhance the transmission for the next generation of wireless communications. This technique has witnessed lots of interest recently due to its ability to increase diversity gain, especially in the presence of obstacles between the users and the service providers. The IRS contains low-cost and large-scale reflection elements that work passively to guide the electromagnetic waves toward the direction of interest. These re-configurable meta-surface cells have reflection coefficients that can be adjusted by changing their phase shift to enhance the desired signal of interest and apply interference mitigation. Moreover, the IRS can be exploited to improve the overall sum rate throughput and reduce outage probability. The proposed system considers a transmission between multiple base stations (BSs) that equipped with multiple antennas and several single antenna users through an IRS in the presence and absence of a traditional path between them. Optimization techniques are employed to select the optimum beamforming precoders and to control the IRS's phase shifts by steering the incident signals toward the intended users. Furthermore, an off-the-shelf power allocation optimization approach, called Polyhedron, is exploited to enhance the overall spectral efficiency (SE) and energy efficiency (EE) of the proposed system and reduce the required transmitted power. The proposed system with the suggested optimization approaches demonstrates significant improvement in the SE with a considerable reduction of the entire transmitted power by all BSs especially when increasing the number of antennas at the BSs along with using a higher number of IRS's reflected elements.

INDEX TERMS Intelligent reflecting surfaces (IRS), cell-free (CF), polyhedron optimization technique, multiple-input single-output (MISO), power allocation, optimum beamforming, multi-user communications, spectral efficiency (SE).

I. INTRODUCTION

Intelligent reflecting surfaces (IRS) have witnessed much attention recently due to the need for securing communication services for all clients in the mobile cell area [1]. For the fifth generation and beyond (B5G), the huge demand for higher quality-of-services (QoS) creates challenges for all wireless communications service providers. Moreover, to ensure user fairness, recognizable IRS can play a vital role in guiding the waves toward the direction of intended uses [2]. The IRS contains low-cost, large-scale passive metasurface reflecting elements with different reflection coefficients and phases [3]. The adjustment of these parameters in the IRS is the key to assisting the base stations (BSs) in delivering its services to all users, especially for users that have weak channel conditions due to the effect of high attenuation and obstacles [4]. Different techniques are suggested in the previous state-of-the-art, such as cooperative relays and

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small cell communications, which require continuous power supplies and complicated signal processing [5]. Furthermore, the IRS can deliver the incident wave passively in the direction of interest by controlling the IRS parameters remotely from the BS. In some scenarios, some active elements can be inserted among majorities of passive reflecting elements for processing purposes. The reflecting surfaces of the IRS reflect the incident waves toward the direction of intended users in the coverage area, in which the IRS tries to adjust the phase correctly to achieve this mission. Besides, a cell-free (CF) network is proposed to serve all users in the coverage area via all available BSs at a particular region. This technique uses the paradigm of user-centric networks to address the issues inherent in the ultra-dense networks (UDN), in which the latter networks depend on deploying small cells and activate a particular number of BSs for providing services to all users in the cell-centric wireless network. The using of UDN introduces inter-cell interference that causes a significant reduction of the upper bound capacity [6]. In this paper, we merge the cell-free network with IRS-aided wireless communication to improve the QoS and satisfy a significant reduction in the transmitted power of all BSs. In the following subsection, the most recent state-of-the-art articles in this field are reviewed.

A. LITERATURE REVIEW

Re-configurable IRS is considered in [4] for multiple-input single-output (MISO) communications system, in which the adjusting of the IRS elements' phases is achieved depending on estimating the end-to-end (E2E) channels between the multiple-input multiple-output (MIMO) base station (BS) and the single-antennas users after reflecting from the IRS. Moreover, minimum mean squared error (MMSE) channel estimation is exploited along with beamforming precoding to guide the wave to the intended direction. Wide-band cell-free network-based IRS is employed in [6] with a joint precoding framework for maximizing the whole throughput of the system. A hybrid network has been proposed in [5] and [7], in which the cooperative active relays are employed with IRS to enhance the performance of communications between a user and a BS. Moreover, the active relays have been assumed to work in full-duplex (FD) and half-duplex (HD) modes. In [8], the minimization problem for transmitting power in the downlink mode is considered with the non-orthogonal multiple access (NOMA) technique. The phase shift matrix of the IRS and the transmit beam-former are jointly optimized by using bi-quadratic non-convex and difference-of-convex programming algorithms. Applying machine learning, for the sixth generation (6G) wireless communications, is suggested in [9] for a system that exploited IRS. Moreover, machine learning for wireless communications can be considered one of the most promising and powerful computational techniques for accelerating the required signal processing, reducing latency, and enhancing the entire system's performance. The authors in [10], studied the optimum linear precoding for the MISO-IRS system that can be achieved by maximizing signal-to-interference-plus-noise ratio (SINR), in which the maximization is analyzed subject to power constraint of any phase matrix of the utilized RIS. Moreover, the ergodic spectral efficiency (ESE) is formulated for large IRS in a tight upper bound style, and the effect of the phase shift on the ESE is studied for different propagation cases in [11]. An overview of IRS technology has been introduced in [12] with the main applications, challenges, hardware architecture, and signal modeling. In this paper, the authors have investigated the design and implementation of a hybrid IRS which contains passive and active elements. In [13], IRS is used with NOMA to satisfy the best user fairness and enhance the system throughput, by maximizing the minimum decoding SINR of all users, which is equivalent to maximizing the achievable rate. This mission is achieved via applying joint optimization of the active transmitting beamforming and the IRS phase shift for the downlink phase. The latter approach has been employed in [14] but with the merging of NOMA with IRS, in which the number of users that can be served in a particular orthogonal spatial direction by using this merging is greater than those served by using spatial division multiple access (SDMA). Diagnosis of IRS failure and reflection blockage of elements is introduced in [15] for millimeter wave (mmWave) communication systems. Three scenarios are considered for full, partial, and absence availability of channel state information over this uncongested band. Maximizing the sum rate of multi-cast of multi-group massive-MIMO system aided IRS is presented in [16] by applying joint optimization of the reflection coefficients of the IRS and the precoding matrix in the BS. Multi-direction design and optimization for IRS obtained from single reflection is presented in [17]. Moreover, a practical passive beamforming design accompanied by channel estimation for IRS is introduced in [18]. IRS over the Tera-hertz band is considered in [19] to secure communication wirelessly over this uncongested and high attenuation frequency band. IRS is exploited in [20] and [21] to assist a radar system in enhancing target parameters. In [22], enhancing EE via applying an optimized scheme is considered for an IRS. Moreover, wireless power transfer for single and multiple users is introduced in [23] via designing waveform and beamforming schemes. Throughput maximization for active IRS is considered in [24] for wireless-powered communications. Optimization of IRS-aided CF networks via applying quantum computing is introduced in [25]. Simultaneous wireless information and power transfer (SWIPT) with IRS-assisted for different technologies such as internet-of-things (IoT), and energy harvesting are investigated in [26] and [27], in which beamforming optimization and discrete phase shift is considered. Active and passive beamforming are jointly optimized in [28] for aided transmission via IRS. The cooperation design of IRS with decode-and-forwards (DF) relay with beamforming is considered in [29] for wireless networks. Furthermore, an IRS can be mounted on an unmanned aerial vehicle (UAV), called UAV-IRS or Aerial IRS. This technique is exploited to improve the system performance by ensuring higher QoS with maximum security rate for users suffering low QoS due to their locations in shadow areas, i.e. these users face obstacles like tall buildings against the service providers [30], [31]. Further details about current and future trends, challenges, and research directions for the IRS-aided wireless communications are presented in [32], [33], [34], [35], [36], and [37].

B. OUR CONTRIBUTIONS

The main contributions of this paper can be listed in the following points.

- We propose an IRS-aided CF network to enhance the system's throughput along with a reduction of the required transmitted power simultaneously. The theory of CF-IRS is introduced, and the required derivation and expressions for the modeled system are presented.
- Moreover, the narrow band angle domain of the channel for the proposed system is presented by utilizing a geometric approach. This approach utilizes the angle of departure (AoD) and angle of arrival (AoA) to model the channels between all terminals of the proposed system.
- The model of the received signal at a particular user is presented and derived for the CF-IRS system. Furthermore, the signal-to-interference-plus-noise ratio (SINR) is obtained for such a system, which is consequently utilized to evaluate the entire sum rate of the system.
- Optimization techniques are employed to evaluate the optimum beamforming precoder, that is applied to maximize the sum rate subject to constraints related to the maximum available power and phase shift of the IRS.
- Besides, the polyhedron optimization technique is employed for minimizing the required transmitted power from the BSs, subject to the provision of the minimum required power for all users under the coverage area. This optimization mechanism depends on obtaining the intersection of half-spaces or hyper-planes. To the best of our knowledge, this is the first attempt at employing this optimization technique for a CF-IRS system.

It is noteworthy that the proposed system is applicable with UAV-IRS by taking into account the *xyz*-coordinate for the IRS in a suitable place area with acceptable flight altitude [30], [31].

C. PAPER ORGANIZATION AND NOTATIONS

The organization of the rest of this paper can be described as follows. In section II, the proposed CF-MISO-based IRS system is modeled, in which the download transmission and the receiving signals are defined and expressed. Moreover, a geometric approach for the modeled channel in the narrow band assumption is introduced in section III. In section IV, an optimization problem is formulated to maximize the sum rate via obtaining the optimum precoder vector for each user subject to the available power budget. Besides, the polyhedron optimization technique is employed for the proposed CF-IRS-MISO system to control the power allocation of the user in the coverage area by all BSs. The simulation results are demonstrated in section V, and the main outcomes obtained from this paper are summarized in section VI.

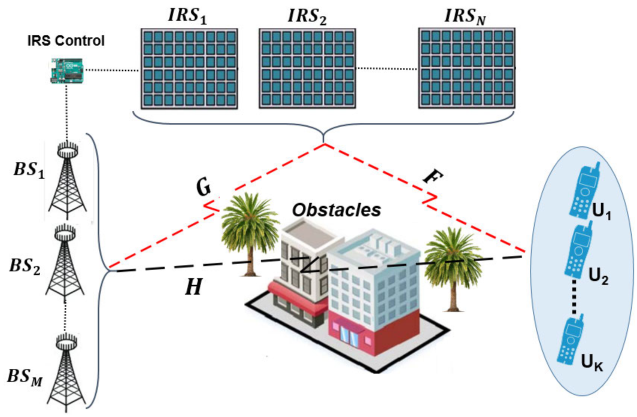

FIGURE 1. Architecture and channels modeling of CF-based IRS-aided wireless communications.

Notations: Uppercase and lowercase boldface characters are denoted for matrices and vectors, respectively. The notations A^{-1} A^T, and A^H are used to represent the inverse, transpose, and Hermitian of the matrix $\mathbf{A}$, respectively. Moreover, the expectation of the random vector $\mathbf{x}$ is denoted as $\mathbb{E}(x)$. Also, the trace process, the Euclidean and the Frobenius norms for a matrix $\mathbf{A}$ are denoted as $\mathtt{Tr}(A)$, $\|A\|$ and $\|\mathbf{A}\|_F^2$, respectively. Furthermore, the ceil, i.e. the remainder of the division process, and the floor, i.e. the quotient of the division process, are denoted using the symbols $\lceil \rceil$ and $\lfloor \rfloor$, respectively.

II. SYSTEM MODELING

In this section, re-configurable intelligent reflecting surfaces (IRS)s are considered for assisting wireless communications, in which a base station (BS) or group of BSs can serve users with weak channel circumstances. The letter case occurs due to the existence of obstacles that prevent or attenuate the incoming signals from the BS/BSs to the intended users. Each IRS consists of a uniform rectangular array (URA) of N passive elements. These elements are distributed in rows and columns with inter-space of d_{IRS}. Fig. 1 shows the architecture and channels modeling of CF-based IRS-aided wireless communications, in which M_{BS} BSs, with M URA antennas, serve K users, equipped with a single antenna, via single or multiple IRSs, R, where each IRS consists of N reflecting elements. Moreover, each BS has M antennas. Besides, we assume in this paper that each user has a single antenna. For this assumption, the end-to-end (E2E) system, from the BS to a user via the IRSs, behaves as a multiple-input single-output (MISO).

The channel between the BSs and the IRSs is denoted as $\mathbf{G} \in \mathbb{C}^{\mathcal{R}\times\mathcal{B}}$, in which $\mathcal{R} = R\times N$, while $\mathcal{B} = M_{BS}\times M$. While the channel between the IRSs and the users is denoted as $\mathbf{F} \in \mathbb{C}^{K\times\mathcal{R}}$, and the direct channel between the BS and the users, which always suffers from high attenuation due to obstacles as explained earlier, is defined as $\mathbf{H} \in \mathbb{C}^{K\times\mathcal{B}}$. The effective channel between the BSs' and the K users, $\Xi \in \mathbb{C}^{K\times M_{Bs}}$ are expressed as

$$\Xi^H = \mathbf{H}^H + \mathbf{F}^H\Psi^H\mathbf{G}, \tag{1}$$

where $\Psi \in \mathbb{C}^{\mathcal{R}\times\mathcal{R}} = [\Psi_1, \Psi_2, \ldots, \Psi_R]$ represents the overall phase response of the IRSs, with $\Psi_r \in \mathbb{C}^{N\times N} = \mathbf{diag}\left[\alpha_\mathbf{n}\exp(\mathbf{j}\theta_\mathbf{n})\right]$, for $n = 1, 2, 3, \ldots, N$, in which $\alpha_n \in (0, 1]$ and $\theta_n \in [0, 2\pi]$ are respectively the reflection coefficient and the phase shift of the n-th element in the r-th IRS. It is noteworthy that the phase shift plays a significant role in steering the incoming signal to an IRS from a BS towards a user. More specifically, the equivalent channel between the b-th BS and all users terminals, which is denoted as Ξ_b, can be expressed as

$$\Xi_b^H = \mathbf{H}_b^H + \sum_{r=1}^{R}\mathbf{F}_r^H\Psi_r^H\mathbf{G}_{r,b}, \tag{2}$$

where $\mathbf{H}_b \in \mathbb{C}^{K\times M_{BS}}$ is to represent the direct links between the b-th BS and K users, $\mathbf{G}_{r,b} \in \mathbb{C}^{R\times M_{BS}}$ is the channel from the b-th BS and the r-th IRS. Additionally, $\mathbf{F}_r \in \mathbb{C}^{K\times R}$ represents the channel between the r-th IRS and all served users.

A. DOWNLOAD TRANSMISSION

The users' signals $\mathbf{s} \in \mathbb{C}^{K\times 1} = [s_1, s_2, \ldots, s_K]$ in the download phase is created in a BS. This power normalized symbols, i.e. $\mathbb{E}\left\{\mathbf{s}\mathbf{s}^H\right\} = p_t\mathbf{I}_K$, in which p_t is the maximum allowed power by a BS. As the system under consideration serves a single antenna user by a BS with multiple antennas via an IRS with multiple reflecting elements, this system considers a scenario of multiple-input single-output (MISO). Therefore, beamforming techniques are required to be achieved at the BS. Different beamforming precoding can be employed as zero-forcing (ZF), maximum ratio transmission (MRT), maximum ratio combination (MRC), and minimum mean-squared error (MMSE). The precoding vector of the b-th BS to the k-th user, $\mathbf{w}_{b,k} \in \mathbb{C}^{M_{BS}\times 1}$, is used to generate a precoded symbol $\mathbf{x}_{b,k}$ as

$$\mathbf{x}_{b,k} = \sum_{k=1}^{K}\mathbf{w}_{b,k}s_k, \tag{3}$$

in which the precoding matrix, i.e. the transmit covariance matrix, for a particular b-th BS that serves K users is given as $\mathbf{W}_b = \left[\mathbf{w}_{b,1}, \mathbf{w}_{b,2}, \ldots, \mathbf{w}_{b,K}\right]$.

B. RECEIVING SIGNALS

At the k-th user terminal, the received signal from the b-th BS, $\mathbf{y}_{b,k}$ is obtained as

$$\begin{aligned}\mathbf{y}_{b,k} &= \sqrt{\mathcal{P}_{b,k}}\,\Xi_b^H\mathbf{x}_{b,k} + \mathbf{n}_k \\ &= \sqrt{\mathcal{P}_{b,k}}\left(\mathbf{H}_b^H + \sum_{r=1}^{R}\mathbf{F}_{k,r}^H\Psi_r^H\mathbf{G}_{r,b}\right)\sum_{k=1}^{K}\mathbf{w}_{b,k}s_k \\ &\quad + \mathbf{n}_k,\end{aligned} \tag{4}$$

where $\mathcal{P}_{b,k}$ is the transmitted power of the b-th BS to the k-th user, and $\mathbf{n}_k \in \mathbb{C}^{1\times K} \sim \mathcal{CN}\left\{0, \sigma_{n_k}^2\right\}$ is the additive white Gaussian noise (AWGN) with zero mean and a variance of $\sigma_{n_k}^2$. At the k-th user's terminal, the received signal can be extracted from (4) as

$$\begin{aligned}\mathbf{y}_{b,k} &= \sqrt{\mathcal{P}_{b,k}}\left(\mathbf{h}_{k,b}^H + \sum_{r=1}^{R}\mathbf{F}_{k,r}^H\Psi_r^H\mathbf{G}_{r,b}\right)\mathbf{w}_{b,k}s_k \\ &\quad + \sum_{\ell=1,\ell\neq k}^{K}\sqrt{\mathcal{P}_{b,\ell}}\left(\mathbf{h}_{k,b}^H + \sum_{r=1}^{R}\mathbf{F}_{k,r}^H\Psi_r^H\mathbf{G}_{r,b}\right)\mathbf{w}_{b,\ell}s_\ell \\ &\quad + \mathbf{n}_k,\end{aligned} \tag{5}$$

where the first term represents the desired signal of the k-th user, while the second term represents the interference caused by other users. It is noteworthy that the direct channel between the BSs and the users is defined as $\mathbf{H}_b = \left[\mathbf{h}_{1_b}, \mathbf{h}_{2_b}, \ldots, \mathbf{h}_{K_b}\right]$, in which $\mathbf{h}_{k_b}$ is denoted for the channel between the b-th BS and the k-th user. For more simplification, (5) can be rewritten as

$$\begin{aligned}\mathbf{y}_{b,k} &= \sqrt{\mathcal{P}_{b,k}}\,\Xi_{b,k}^H\mathbf{w}_{b,k}s_k + \sum_{\ell=1,\ell\neq k}^{K}\sqrt{\mathcal{P}_{b,\ell}}\,\Xi_{b,k}^H\mathbf{w}_{b,\ell}s_\ell \\ &\quad + \mathbf{n}_k,\end{aligned} \tag{6}$$

where $\Xi_{b,k}^H = \mathbf{h}_{k,b}^H + \sum_{r=1}^{R}\mathbf{F}_{k,r}^H\Psi_r^H\mathbf{G}_{r,b}$. The SINR can be derived from (6) for the k-th user as

$$\begin{aligned}\gamma_k =& \sqrt{\mathcal{P}_{b,k}}\mathbf{w}_{b,k}^H\Xi_{b,k} \\ &\times\left(\sum_{\ell=1,\ell\neq k}^{K}\sqrt{\mathcal{P}_{b,\ell}}\,\Xi_{b,k}^H\mathbf{w}_{b,\ell}\left(\Xi_{b,k}^H\mathbf{w}_{b,\ell}\right)^H + \sigma_{n_k}^2\right)^{-1} \\ &\times\sqrt{\mathcal{P}_{b,k}}\,\Xi_{b,k}^H\mathbf{w}_{b,k}.\end{aligned} \tag{7}$$

The achievable throughput in bits/sec per Hz (bps/Hz) for each user can be evaluated by using the SINR obtained in (7) as

$$R_k = \log_2\left(1+\gamma_k\right), \tag{8}$$

while the sum rate, which represents the entire throughput provided by the b-th BS to the K users, is given by

$$R_{sum} = \sum_{k=1}^{K}R_k = \sum_{k=1}^{K}\log_2\left(1+\gamma_k\right). \tag{9}$$

III. MODELING OF CHANNEL USING NARROW BAND GEOMETRIC APPROACH

As we employ IRS to assist wireless communications to serve users suffering from high attenuation, due to the existence of obstacles, a narrow band geometric approach is utilized for channel modeling. We consider that all transmission occurs over a narrowband system. Therefore, the channel between a BS to an IRS, $\mathbf{G}_{r,b}$, can be expressed as

$$\mathbf{G}_{r,b} = \sum_{l}^{L} \rho_{G,l}\mathbf{b}\left(\varphi_{x,G_A}(l), \varphi_{y,G_A}(l)\right) \times \mathbf{a}^T\left(\varphi_{x,G_D}(l), \varphi_{y,G_D}(l)\right), \quad (10)$$

where the coefficient of the l-th path is represented by $\rho_{G,l}$, $\mathbf{a}$ and $\mathbf{b}$ are the steering vectors to represent the array response of the BS and the IRS, respectively. Moreover, the applied difference in phases between any two adjusting BS's antennas in the x and y coordinates, which represent the l-th path's AoD, can be expressed as

$$\varphi_{x,G_D}(l) = -\frac{2\pi d_{BS}}{\lambda}\sin\left(\theta_{G_D}(l)\right),$$
$$\varphi_{y,G_D}(l) = -\frac{2\pi d_{BS}}{\lambda}\cos\left(\theta_{G_D}(l)\right)\sin\left(\phi_{G_D}(l)\right), \quad (11)$$

where the inter-space between any two adjacent BS's antennas is denoted as d_{BS}, also, $\theta_G(l)$ and $\phi_G(l)$ represent respectively, the elevation and azimuth BS's AoDs. Similarly, the IRS AoAs for the l-th path can be expressed in the same coordinates mentioned above as

$$\varphi_{x,G_A}(l) = -\frac{2\pi d_{IRS}}{\lambda}\cos\left(\theta_{G_A}(l)\right)\cos\left(\phi_{G_A}(l)\right),$$
$$\varphi_{y,G_A}(l) = -\frac{2\pi d_{IRS}}{\lambda}\cos\left(\theta_{G_A}(l)\right)\sin\left(\phi_{G_A}(l)\right), \quad (12)$$

where the inter-space between any two adjacent IRS's reflecting elements is denoted as d_{IRS}. It is noteworthy that it is assumed in this paper that $d_{BS} = d_{IRS} = \frac{\lambda}{2}$, in which λ is the wavelength of the operating frequency. Furthermore, the r-th and the s-th elements of the $\mathbf{a}\left(\varphi_x, \varphi_y\right) \in \mathbb{C}^{M\times 1}$ and $\mathbf{b}\left(\varphi_x, \varphi_y\right) \in \mathbb{C}^{N\times 1}$, respectively, are given as

$$\left[\mathbf{a}\left(\varphi_x, \varphi_y\right)\right]_r = e^{j\pi\left[(r_n-1)\varphi_x+(r_m-1)\varphi_y\right]},$$
$$\left[\mathbf{a}\left(\varphi_x, \varphi_y\right)\right]_s = e^{j\pi\left[(s_n-1)\varphi_x+(s_m-1)\varphi_y\right]}, \quad (13)$$

where r_n, r_m, s_n, and s_m in the m-th entry, for $m = 1, 2, \ldots, M$, and the n-th entry, for $n = 1, 2, \ldots, N$, can be evaluated as

$$r_n = r - \left(\left\lceil \frac{r}{\sqrt{M}} \right\rceil - 1\right)\sqrt{M},$$
$$r_m = r - \left(\left\lceil \frac{r}{\sqrt{M}} \right\rceil - 1\right),$$
$$s_n = s - \left(\left\lceil \frac{r}{\sqrt{N}} \right\rceil - 1\right)\sqrt{N},$$
$$s_m = s - \left(\left\lceil \frac{r}{\sqrt{N}} \right\rceil - 1\right). \quad (14)$$

Similarly, the multi-path reflected channel from an IRS to a user, i.e. $\mathbf{f}_{r,k} \in \mathbb{C}^{1\times N}$, can be given as

$$\mathbf{f}_{r,k}^T = \sum_{l}^{L} \rho_{f,l}\mathbf{b}^T\left(\varphi_{x,f_D}(l), \varphi_{y,f_D}(l)\right), \quad (15)$$

where the coefficient of the l-th path is denoted as $\rho_{f,l}$, also, the effective AoD in the xy coordinates from an IRS to a user are expressed as

$$\varphi_{x,f_D}(l) = -\frac{2\pi d_{IRS}}{\lambda}\sin\left(\theta_{f_D}(l)\right),$$
$$\varphi_{y,f_D}(l) = -\frac{2\pi d_{IRS}}{\lambda}\cos\left(\theta_{f_D}(l)\right)\sin\left(\phi_{f_D}(l)\right), \quad (16)$$

where $\theta_{f_D}(l)$ and $\phi_{f_D}(l)$ are the AoD in the elevation and azimuth modes, respectively, for the channel $\mathbf{f}_{r,k}$.

Moreover, the multi-path channel from a BS to a user, i.e. $\mathbf{h}_{b,k} \in \mathbb{C}^{1\times M}$, can be given as

$$\mathbf{h}_{b,k}^T = \sum_{l}^{L} \rho_{h,l}\mathbf{a}^T\left(\varphi_{x,h_D}(l), \varphi_{y,h_D}(l)\right), \quad (17)$$

where the coefficient of the l-th path is denoted as $\rho_{h,l}$, also, the effective AoD in the xy coordinates from a BS to a user are expressed as

$$\varphi_{x,h_D}(l) = -\frac{2\pi d_{BS}}{\lambda}\sin\left(\theta_{h_D}(l)\right),$$
$$\varphi_{y,h_D}(l) = -\frac{2\pi d_{BS}}{\lambda}\cos\left(\theta_{h_D}(l)\right)\sin\left(\phi_{h_D}(l)\right), \quad (18)$$

where $\theta_{h_D}(l)$ and $\phi_{h_D}(l)$ are the AoD in the elevation and azimuth modes, respectively, for the channel $\mathbf{h}_{b,k}$.

IV. PROBLEM FORMULATION AND POLYHEDRON OPTIMIZATION

In this section, we formulate an optimization problem that needs to be solved for the sake of optimizing the sum rate, R_{sum}, in (9). In other words, the conventional optimization problem tried to choose the beamforming vector along with the required phase shift applied to the IRS, which leads to maximizing the sum rate. This is done with some related constraints to avoid exceeding the maximum available power at the BS and to choose valid complex phase shifts. These details can be expressed as

$$(P_1): \max_{\mathbf{W}_b, \Psi_r} R_{sum} \quad (19a)$$
$$\text{s.t.} \quad C1: \sum_{k=1}^{K} \|\mathbf{W}_b\|^2 \leq \bar{P}_b \quad (19b)$$
$$C2: \left|exp(j\theta_{r,n})\right| \leq 1, \theta_{r,n} \in \{0, 2\pi\}, \quad (19c)$$

where $\bar{P}_b$ is the maximum available power at the b-th BS. It can be seen that the joint optimization in (P_1), for the r-th phase shift matrix of the IRS, Ψ_r, and the b-th beamforming precoder, $\mathbf{W}_b$, is non-convex and it is infeasible in this form. To solve this problem, we follow the same procedure proposed in [6], [38], [39], and [40] by using a fractional programming method and dual Lagrangian transformation to ensure a tractable solution of this joint optimization problem.

Notably, the optimization is formulated upon interference reduction caused by cells at each user's terminal. This has been achieved by obtaining the optimum beamforming precoder that satisfies the maximum signal of interest and minimum interference, which consequently leads to obtaining the optimum SINR and maximizing the overall throughput. Moreover, solving the optimization problem of the weighted precoders includes choosing the optimum phase shifts of the IRS's elements for guiding the signals toward the intended user and producing nulls for others to reduce interference.

Furthermore, an off-the-shelf optimization technique can be employed for IRS-aided CF cooperative communications. This technique depends on obtaining the intersection of half-spaces or hyper-planes. The method is utilized to control the power allocation supplied by all BSs to supply services to all users with the aid of the IRS. This optimization problem can be expressed as

$$(P_2): \sum_{b=1}^{B} \mathcal{P}_{b,k} ||\Xi_b^H||_F^2 |\mathbf{w}_{b,k}|^2 \geq \bar{P}_k, \tag{20a}$$

$$\text{s.t. } C3: \sum_{k=1}^{K} \mathcal{P}_{b,k} \leq \bar{P}_b \tag{20b}$$

where $\bar{P}_k$ represents the minimum required power for the k-th users for satisfying a particular QoS. It can be noticed that (20), in its objective function and constraint, represents a finite intersection of half-spaces, which is a convex set called Polyhedron. Besides, the total power transmitted from all BSs to serve all users can be defined as $P_T = \sum_{b=1}^{M_{BS}} \bar{P}_b$.

V. SIMULATION RESULTS

In this section, the performance of the proposed CF-aided IRS is examined and simulated. Without loss of generality, four BSs are utilized to serve two users, i.e. $M_{BS} = 4$ and $K = 2$. The four BS are positioned in the xyz-coordinates at (0,0,20), (0,400,20), (0,800,20), and (0,1200, 20). Additionally, the positions of the two single antenna users are positioned at (400,600, 1.5) and (600,600, 1.5). The system employs one IRS with N elements, which is assumed to be located at (1000,1000,10). Three scenarios for the IRS are assumed, in which a URA of $N = 16 = 4 \times 4$ elements, $N = 32 = 4 \times 8$ elements, and $N = 64 = 8 \times 8$ elements are considered. The maximum transmit power available for each BS is assumed $\bar{P}_b = 30$ dBm. Besides, the required rates for the two users are assumed $r_k = 1$bps. The latter rates can be used to evaluate the required power of each user by applying the Shannon capacity formula $\bar{P}_k = 2^{r_k} - 1$. The noise energy is expressed as $N_0 = -174$ (dBm/Hz) $+ 10\log_{10}(BW)$, where BW represents the transmission bandwidth in Hz [41]. In this paper, the operating carrier frequency and the system's bandwidth are considered 2.4 GHz and 20 MHz, respectively. Table 1 illustrates all the notation, parameters, and the considered values that are used in our simulations.

Fig. 2 shows the total spectral efficiency obtained from the proposed CF-based IRS network against the number of antennas in each BS, i.e. M, for three scenarios of IRS's reflecting elements, N, as defined earlier in this section and listed in Table 1, and over different numbers of BSs' antennas. A significant improvement of the SE can be noticed when M and N are increased.

TABLE 1. Notations and simulation parameters.

Notation	Parameter	Value
f_o	Operating frequency	2.4 GHz
B_W	System bandwidth	20 MHz
M_{BS}	Number of BSs	4
M	BS's Number of Antennas	$\{2-512\}$
R	Number of IRS	1
N	IRS's Number of Element	$\{16, 32, 64\}$
K	Number of single-antenna users	2
Modulation scheme	QPSK	$\pm\frac{1}{\sqrt{2}} \pm j\frac{1}{\sqrt{2}}$
N_0	Noise power (variance)	-100 dBm
P_b	Maximum transmit power available for each BS	30dBm
P_T	The total power transmitted from all BSs	$P_T = \sum_{b=1}^{M_{BS}} \bar{P}_b$
P_k	The required power for the k-th user	$2^{r_k} - 1$
r_k	The minimum target rate of the k-th user	1 bps/Hz
β_i	Large scale path loss for the i-th link	$d_i^{-\tau_i}$
τ_i	The path-loss exponent for the i-th link.	3.5
$\mathcal{K}_i$	The Rician factor of the i-th link.	4
Software	Matlab + CVX optimization Platform	MATLAB R2022b

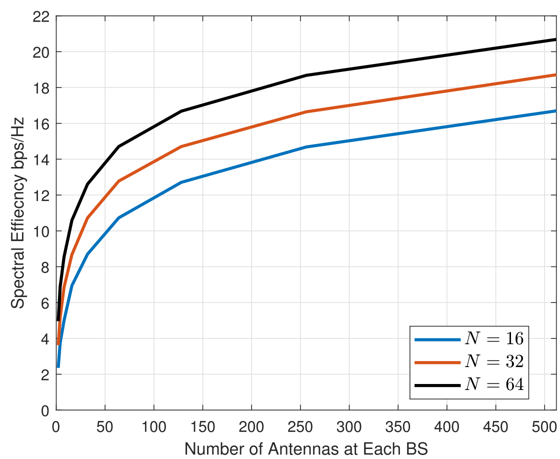

FIGURE 2. The sum of spectral efficiency for all users against the number of antennas at each BS with an IRS with a different number of elements.

Under the same configuration discussed above in this section, Fig. 3 shows the obtained reduction of the total power supplied by all BSs, i.e. P_T in dBm, against the different number of M at each BS and N of the IRS, and after applying the proposed Polyhedron optimization for power allocation. It can be seen that increasing the number of antennas at the BS, i.e. M, along with increasing the number of IRS elements, leads to a considerable reduction of the required transmitted power from all BS while maintaining the same QoS required for all users. Additionally, the obtained results are compared with the conventional equal power allocation

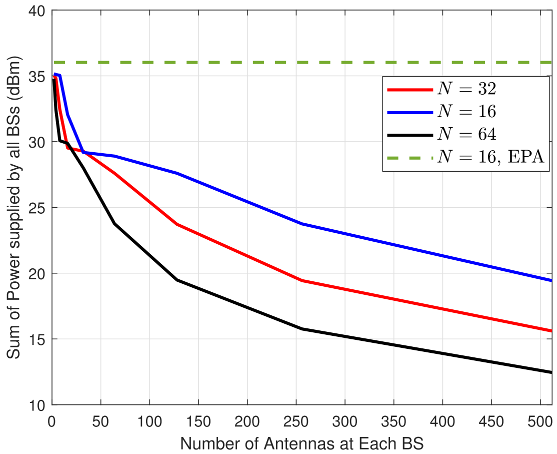

FIGURE 3. The sum of supplied power from all BSs against the number of antennas at each BS with an IRS of a different number of elements.

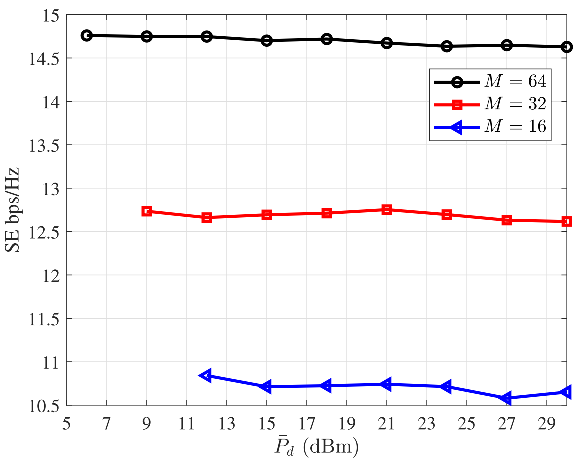

FIGURE 4. The SE in bps/Hz for $M \in \{16, 32, 64\}$, $N = 64$, $K = 2$, $M_{BS} = 4$, and after 50 iterations.

(EPA) technique with $N = 16$ and over different values of M, in which by utilizing EPA, all BSs distribute their maximum transmitted power among all users. In this figure, a significant outperforming of our proposed mechanism against the EPA approach can be noticed.

Moreover, Fig. 4 shows the SE supplied to the two users from the four BSs over different $\bar{P}_b$ from each BS. Three cases for the number of antennas at each BS are assumed, i.e. $M \in \{16, 32, 64\}$, and the number of reflecting elements is fixed at $N = 64$. Several outcomes can be obtained from this figure. It can be noticed that the SE has a direct proportion with M, and the SE is almost constant for each case of M after applying the proposed Polyhedron power allocation method, which means that the minimum required powers to ensure the target QoS for $M = \{16, 32, 64\}$ are $\bar{P}_b = \{12, 9, 6\}$ dBm, respectively. Therefore, there is no need to transmit additional power under the considered conditions after applying our technique. It is worth noting that these results are obtained after averaging 50 iterations.

Fig. 5 demonstrates the energy efficiency (EE) that can be obtained from this system over a different number of M

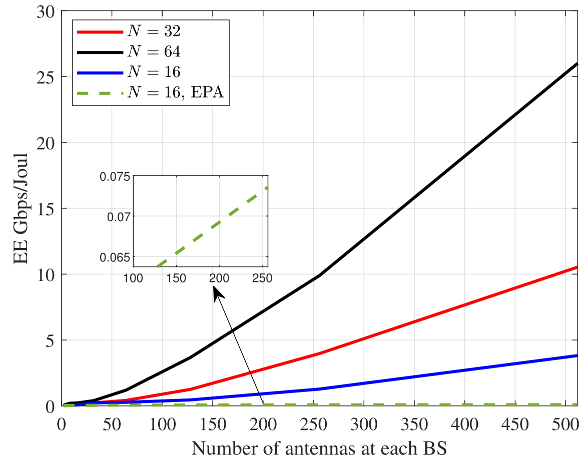

FIGURE 5. The EE of the proposed system to serve two users by four BSs, each of which is equipped with M antennas and for $N = \{16, 32, 64\}$.

at each BS and for $N = \{16, 32, 64\}$. We exploit, similar to [42] and [43], the formula $EE = BW \times R_{sum}/P_T$ (bps/Joul) to evaluate this performance metric. In this figure, it can be noticed the effect of increasing M on the EE, in which, for example, when $M = 500$, the EE reads $\{3.9, 10, 25\}$ Gbps/Joul for $N = \{16, 32, 64\}$, respectively. For comparison purposes, we employ the EPA mechanism again to share the maximum available power at each BS among all users. The EE degradation can be noticed compared to the optimization method proposed in this paper, which means the power consumed for transmission from all BSs is much greater than the users' need to achieve a particular QoS.

It is important to mention that all the results obtained for the proposed system, with the suggested polyhedron optimization approach for power allocation, can be applied to the next generation of wireless communications in the context of green communications for emitted power reduction.

VI. CONCLUSION

In this paper, an IRS-aided wireless communications system based on the cooperative CF technique has been proposed to enhance the overall SE and EE, accompanied by a significant reduction in the transmitted power from all BSs. Joint optimization methods have been exploited to design an optimum precoder to serve multiple single-antenna users by multiple antenna BSs and control the phase shifts of the IRS elements to guide the incoming signal toward the directions of interest. Furthermore, to satisfy efficient power allocation while reducing the required power transmitted by all BSs, the Polyhedron optimization technique has been applied to the proposed system with constraints related to the maximum BSs' transmitted power and the required QoS for each user. The proposed system, which utilizes the optimization technique, has significantly improved the entire SE by considerably reducing the power consumed by all BSs. Moreover, the results showed that increasing the antennas at the BSs and the IRS elements enhances the system's performance.

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