On Energy Efficiency of Wideband RIS-Aided Cell-Free Network

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ABSTRACT Cell-free (CF) network is a favorable technique against inter-cell interferences to improve the network capacity. However, to further improve the network capacity, a large number of base stations (BSs) are required to be deployed with high cost and power consumption. To tackle this problem, an energy-efficient technique called reconfigurable intelligent surface (RIS)-aided CF network has been recently proposed. By replacing some of the required power-hungry BSs with low-power RISs, the energy efficiency of CF network can be enhanced with guaranteed performance. To achieve this goal, in this paper, we first formulate a joint active and passive beamforming problem to maximize the energy efficiency of RIS-aided CF networks. Then, we propose an alternate optimization algorithm to solve this problem. Specifically, we decompose the original energy efficiency maximization problem into multiple subproblems and solve them alternatively. Particularly, we adopt the zero-forcing (ZF) beamforming scheme to optimize the active beamforming at BSs, while the sequential programming (SP) method is adopted to realize the passive beamforming at RISs. Moreover, a realistic energy-consumption model for wideband RIS-aided CF networks is provided, and the effectiveness of the proposed scheme is evaluated by simulations. Finally, simulation results verify that, the proposed scheme is able to achieve a higher energy efficiency than the existing benchmark solution.

INDEX TERMS Cell-free network, reconfigurable intelligent surface (RIS), beamforming, wideband, energy efficiency.

I. INTRODUCTION

Wireless communication systems are expected to support high data rate applications, such as augmented reality and virtual reality [1]. To achieve this goal, various promising techniques such as massive multiple-input and multiple-output (MIMO) [2], millimeter-wave (mmWave) communication [3], and ultra-dense network (UDN) [4], [5] have been proposed.

In UDN, multiple base stations (BSs) are deployed in small cells [6] using cell-centric approach. However, the densification of BSs will result in the severe inter-cell interferences, which fundamentally limit the network capacity [7]. To cope with this problem, the concept of cell-free (CF) network has recently been proposed in [8]. In CF networks, the BSs cooperatively serve all users without cell boundaries. Consequently, the inter-cell interferences can be mitigated via the cooperations among BSs [9]. In this way, the throughput of CF networks can be improved. Up to now, CF network has gained enormous attentions in academia and industry with the focus on power allocation [10], beamforming [11], channel estimation [12], and so on. Nevertheless, a large-scale deployment of BSs results in the high cost and power consumption. In the practical systems, the power budget is limited, and we cannot exceed that power limit to realize high network capacity. As a consequence, energy consumption has become a challenging problem in future wireless networks to ensure green and sustainable wireless communications.

On the other hand, reconfigurable intelligent surface (RIS) has recently emerged as a low-cost and energy-efficient solution to boost the energy efficiency for wireless networks [13]–[18]. Specifically, an RIS is a reflective array composed of a large number of low-cost and energy-efficient passive reflecting elements, and these elements are able to realize passive beamforming with reconfigurable parameters. After receiving the incident signals from BSs, the embedded
passive elements adjust their phase shifts and redirect the signals towards the users with high beamforming gains. Note that, as a reflector, RIS does not perform any complex signal processing operations and does not amplify the signals while reflecting the incident signals [19]–[21]. Benefiting from this working mechanism, by replacing some of the power-hungry BSs with RISs, the energy efficiency of the CF network can be improved with guaranteed performance.

A. PRIOR WORKS

In recent years, most existing works have utilized RIS as a reflector to maximize the spectral efficiency of wireless networks [22]–[25]. For instance, [22] considered the spectral efficiency maximization problem for the RIS-aided communications. An asymptotic analysis for the uplink transmission rate in an RIS-based wireless system was discussed in [23]. Moreover, [24] presented a two time-scale transmission protocol to enhance the network capacity of RIS-aided multi-user systems, while [25] considered an iterative near-optimal low-complexity solution to maximize the spectral efficiency of RIS-aided system. To realize the cooperative gain, multi-BS and multi-RIS scenarios were investigated in [26] and [27], respectively. In addition, [28] considered an OFDM-based scenario to realize the benefits of wideband systems.

Except for the conventional performance indicator of spectral efficiency, another important widely considered performance indicator for wireless communications is energy efficiency. To boost energy efficiency, beamforming design is a well-known solution. However, only a few works have reported related researches the maximization of energy efficiency in RIS-aided communication systems [29]–[32]. For example, the researchers in [29] considered a RIS-aided MISO system to maximize the energy efficiency of wireless systems. Furthermore, the energy efficiency maximization problem for cooperative MIMO was discussed in [30], while the same problem for the RIS-aided CF network with limited backhaul was investigated in [31]. To maintain fairness among users, [32] proposed algorithm to enhance the energy efficiency of the worst user in the CF network. However, all of the above-mentioned papers have not discussed the power consumption analysis to gain a deep insight into cooperative RIS-aided communications. Thus, we still lack in exploring the answer of the question that how much energy-efficient a system will be by incorporating multiple RISs into wideband cooperative MIMO systems? Recently, the authors in [33] considered the RIS-aided CF network for the wideband scenario. However, they only considered the network capacity, while the energy efficiency was ignored in [33].

B. CONTRIBUTIONS

Motivated by the above discussions, in this paper we study the energy efficiency of wideband RIS-aided CF network. Specifically, by replacing some of the required power-hungry BSs with low-power RISs, the energy efficiency of the CF network can be enhanced with guaranteed performance. The main contributions of this paper can be summarized as follows.

- By taking the power consumption at the BSs, RISs, and backhaul into account, we develop a power consumption model of the considered wideband RIS-aided CF network. The embedded phase-resolution of each reflecting element is involved to establish the power consumption model of RIS-aided CF networks. This model allows us to formulate the energy efficiency maximization problem, where the reflecting elements at RISs and the transmit power at BSs can be jointly optimized under the constraints of RIS element modulus and per subcarrier power constraints.

- To solve the energy efficiency maximization problem, we jointly exploit Dinkelbach’s method with the sequential programming (SP) method to alternatively optimize the active beamforming at BSs and passive beamforming at RISs. Specifically, we optimize the active beamforming at BSs by exploiting the zero-forcing method, while the passive beamforming at RISs is optimized via the SP method. To this end, the original energy efficiency maximization problem is decomposed into multiple subproblems at first. Then, Dinkelbach’s and SP methods are exploited alternatively to obtain a locally optimal solution.

- Finally, the proposed scheme is evaluated by extensive numerical simulations. It is shown that compared with the existing benchmark schemes, our proposed beamforming algorithms can achieve much higher energy efficiency.

C. ORGANIZATION AND NOTATION

Organization: The rest of this paper is organized as follows. The system model of RIS-aided CF network and the corresponding energy efficiency maximization problem are discussed in Section II. To solve energy efficiency problem, the proposed joint beamforming solution is presented in Section III. Subsequently, simulation results are provided in Section IV to evaluate the performance of the proposed scheme. Finally, conclusions are drawn in Section V.

Notations: The scalar, vector, and matrix are presented by $x$, $x$, and $X$ respectively. $X^T$, $X^H$, $X^{-1}$, $X^\dagger$, and $\|X\|_F$ stands for transpose, conjugate transpose, inverse, pseudo inverse, and Frobenius norm of a matrix $X$, respectively. The real part of the argument is denoted by $\Re\{\cdot\}$, and the modulus part is represented by $|\cdot|$. $E\{\cdot\}$ denotes the expected operator; $\text{Tr}\ (\cdot)$ is the trace function of a matrix; $\text{diag}\ (\cdot)$ denotes the diagonal operator; Kronecker product is represented by $\otimes$; vec($X$) is a vectorized form of a matrix $X$. Finally, the notations $\angle (\cdot)$ and $\mathbf{I}_N$ represent the angle of the argument, and identity matrix of dimension $N \times N$.

II. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we firstly introduce the system model and the power consumption model of the wideband RIS-aided CF network model of RIS-aided CF network and the corresponding energy efficiency maximization problem are discussed in Section II. To solve energy efficiency problem, the proposed joint beamforming solution is presented in Section III. Subsequently, simulation results are provided in Section IV to evaluate the performance of the proposed scheme. Finally, conclusions are drawn in Section V.
Thus, the signal $s_k$ BSs transmit the same symbols for the efficient RISs are coordinated to support users. In a CF network, the available BSs and low-cost energy-work contains RISs are directly connected to a central processing unit (CPU) we install the RISs to reconstruct the extra link between the buildings. The obstruction caused by any of these obstacles or both thwarts to establish a quality link between the BSs and users due to large-scale fading. Thus, to mitigate this effect, we install the RISs to reconstruct the extra link between the BSs and users to maintain the communication. The BSs and RISs are directly connected to a central processing unit (CPU) through wireless backhauls. Our studied wideband CF network contains $B$ BSs, $R$ RISs, and $L$ subcarriers. Moreover, the $b$-th BS is equipped with $M_b$ antennas, while the $r$-th RIS is furnished with $N_r$ passive elements. For convenience, we use the notations $M$ and $N$ for $M_b$ and $N_r$. Let us denote the sets of BS elements, RIS phase shifters, BSs, RISs, and subcarriers as $M = \{1, 2, \ldots, M\}, N = \{1, 2, \ldots, N\}, B = \{1, 2, \ldots, B\}, R = \{1, 2, \ldots, R\},$ and $L = \{1, 2, \ldots, L\}$, respectively.

### A. TRANSMITTER

In a CF network, the available BSs and low-cost-energy-efficient RISs are coordinated to support $K$ users by coherent transmission [10]. In the coherent downlink transmission, all BSs transmit the same symbols for the $k$-th user. Suppose $s_l = [s_{l,1}, s_{l,2}, \ldots, s_{l,K}] \in \mathbb{C}^K$ denote the symbols on the $l$-th subcarrier, and $s_{l,k}$ is the symbol intended for the $k$-th user. Thus, the signal $x_{b,l} \in \mathbb{C}^M$ transmitted from the $b$-th BS on the $l$-th subcarrier can be represented by

$$x_{b,l} = \sum_{k=1}^{K} \sqrt{p_{b,l,k}} v_{b,l,k} s_{l,k},$$

where $p_{b,l,k}$ and $v_{b,l,k} \in \mathbb{C}^M$ represent the transmit power and the beamforming vector from the $b$-th BS on the $l$-th subcarrier intended for the $k$-th user, respectively. Subsequently, frequency-domain signal $x_{b,l}$ is transformed into time-domain signal by applying inverse discrete Fourier transform (IDFT) at the $b$-th BS. After inserting the guard interval, the signal is re-scaled to the analog domain and transmitted through $M$ RF chains of the $b$-th BS. In practical system, the power of the transmitted signal at the $b$-th BS is constrained by the following expression

$$\mathbb{E}(\|x_{b,l}\|^2) = \text{Tr}(P_{b,l} V_{b,l}^H V_{b,l}) \leq \rho_{b,l},$$

where $V_{b,l} \triangleq [v_{b,l,1}, v_{b,l,2}, \ldots, v_{b,l,K}] \in \mathbb{C}^{M \times K}$ is the active precoding matrix at the $b$-th BS. $P_{b,l} \triangleq \text{diag}(p_{b,l,1}, p_{b,l,2}, \ldots, p_{b,l,K}) \in \mathbb{R}^{K \times K}$ denotes the power allocation, where $\rho_{b,l}$ is the maximum allowable transmitted power per subcarrier for the $b$-th BS.

### B. RECEIVER

At first, the received time-domain signal is converted to the baseband signal, and the original signal is recovered after removing the guard interval and applying Discrete Fourier Transform (DFT) on the baseband signal. The received signal $y_{b,l,k}$ at the $k$-th user from the $b$-th BS on the $l$-th subcarrier is expressed as

$$y_{b,l,k} = \sqrt{\beta_k} \sum_{r=1}^{R} g_{r,l,k} \Psi_{r} H_{b,r,l} x_{b,l} + n_k,$$

where $g_{r,l,k} \in \mathbb{C}$ is the channel attenuation coefficient represented by $\beta_k$, and the channel from the $r$-th RIS to the $k$-th user on the $l$-th subcarrier is $g_{r,l,k} \in \mathbb{C}^{1 \times N}$. The channel from the $b$-th BS to the $r$-th RIS is designated as $H_{b,r,l} \in \mathbb{C}^{N \times M}$. Furthermore, $\Psi_{r} \in \mathbb{C}^{N \times N}$ is the passive beamforming matrix for the $r$-th RIS:

$$\Psi_{r} = \text{diag}(\psi_{r,1}, \psi_{r,2}, \ldots, \psi_{r,N}), \quad \forall r \in \mathcal{R},$$

where the $n$-th reflecting element of the $r$-th RIS $\psi_{r,n}$ satisfies the element modulus constraint, $\forall n \in \{1, 2, \ldots, N\}$. Finally, $n_k \sim \mathcal{CN}(0, \sigma^2)$ denotes the additive white Gaussian noise (AWGN) at user $k$.

According to (3), the downlink SINR for the $k$-th user on the $l$-th subcarrier can be derived as

$$\text{SINR}_{l,k} = \frac{\sum_{b=1}^{B} \sqrt{p_{b,l,k}} \left| \sqrt{\beta_k} \sum_{r=1}^{R} g_{r,l,k} \Psi_{r} H_{b,r,l} v_{b,l,k} \right|^2}{\sum_{b=1}^{B} \sum_{j=1, j \neq k}^{K} p_{b,l,j} \left| \sqrt{\beta_k} \sum_{r=1}^{R} g_{r,l,j} \Psi_{r} H_{b,r,l} v_{b,l,j} \right|^2 + \sigma^2}.$$
Then, for all $K$ users, the overall sum-rate $SR$ can be expressed as
\[
SR = \sum_{l=1}^{L} \sum_{k=1}^{K} \log_2 \left(1 + \text{SINR}_{l,k}\right).
\] (6)

**C. Power Consumption Analysis**

Since the considered wideband RIS-aided CF network is composed of $R$ RISs, $B$ BSs, $K$ users, and a CPU, the entire power dissipation of the wideband CF network is given by
\[
\mathcal{P}_{\text{sum}} = \zeta \sum_{b=1}^{B} \sum_{l=1}^{L} \sum_{k=1}^{K} \left( p_{b,l,k} + B P_{\text{BS}} + R P_{\text{RIS}} + K P_{\text{ME}} + P_{\text{bh}} \right),
\]

where $\zeta \equiv \varphi^{-1}$ with $\varphi$ being the efficiency of the transmit power amplifier. $P_{\text{BS}}$ and $P_{\text{RIS}}$ are the total hardware static power consumption at BS and RIS respectively and $P_{\text{ME}}$ stands for the power dissipated by the $k$-th mobile equipment.

In addition, the power consumed by the backhaul link for each RIS and BS is represented by $P_{\text{bh}}$. In our work, we assume that (i) the amplifier operates in its linear region; (ii) backhaul consumed a fixed power which is independent to the traffic load. These assumptions are common in wireless networks to guarantee that the amplifier could perform well in its operation and the power consumed by the hardware of the wireless system can be maintained to a fixed value [29].

Note that, the power consumed by an RIS typically depends on the resolution of its phase shifting elements. These elements reflect the incident signals to the desired direction through reflective beamforming. Usually, an RIS phase shifter consumes less power in its operation. For instance, RIS elements with 5-bit and 6-bit phase resolution only consume 6.0 mW, and 7.8 mW, respectively [29], [31]. Hence, we can express the power consumed by the $r$-th RIS with $N$ passive reflecting elements in terms of bit resolution as
\[
P_{\text{RIS}} = N P_n(b),
\] (8)

where $P_n(b)$ is the power consumed by the $n$-th reflecting element with $b$-bit resolution i.e. $1 \leq b \leq \infty$. By substituting (8) into (7), the total power required by the wideband RIS-aided CF network is given by
\[
\mathcal{P}_{\text{sum}} = \zeta \sum_{b=1}^{B} \sum_{l=1}^{L} \sum_{k=1}^{K} \left( p_{b,l,k} + B P_{\text{BS}} + R N P_n(b) + K P_{\text{ME}} + P_{\text{bh}} \right).
\] (9)

**D. Problem Formulation**

Our goal is to enhance the energy efficiency of wideband RIS-aided CF network under the per subcarrier constraint at the BS and the unit modulus constraint at the RIS. To this end, we jointly design the active beamforming with power allocation for all $K$ users at the $b$-th BS, and the passive beamforming at the $r$-th RIS. Thus, the energy efficiency ($\eta_{\text{EE}}$) of the considered wideband RIS-aided CF network could be defined as the ratio of total sum-rate to total power consumption, i.e.,
\[
\eta_{\text{EE}} = \frac{R_{\text{sum}}}{\mathcal{P}_{\text{sum}}}. \tag{10}
\]

Let $P_c = B P_{\text{BS}} + K P_{\text{ME}} + R N P_n(b)$, and then $\eta_{\text{EE}}$ can be rewritten as
\[
\eta_{\text{EE}} = \frac{R_{\text{sum}}}{\xi \sum_{b=1}^{B} \sum_{l=1}^{L} \sum_{k=1}^{K} \left( p_{b,l,k} + P_c + P_{\text{bh}} \right)} \tag{11}
\]

Moreover, in practical system, the available transmit power is limited. To this end, energy efficiency can be enhanced by imposing per subcarrier power constraint along with the individual quality-of-service (QoS) requirement for all $K$ users. In our problem, we have assumed that each reflecting element induces a phase shift over the impinging signal. In addition, we have also assumed that the channel state information (CSI) is perfectly known at the $b$-th BS, and the CSI can be determined by the methods discussed in [34], [35]. We will consider Imperfect CSI [36] in our future works. With the known CSI, the $b$-th BS employs the classical zero-forcing (ZF) beamforming, which eliminates the interference among the users, for the signal transmission. However, it is worth mentioning here that the number of BSs elements $M$ is not large enough to suppress the interference among the users. However, thanks to the large number of reflecting elements $N$ at the RISs that help us in completely eliminate the interference among the users.

Let us define, $\Psi = \text{diag}(\Psi_1, \Psi_2, \ldots, \Psi_{R_s})$, $G_l = \left[ \sqrt{\beta_l} g_{l,1,1}^{(1)}, \sqrt{\beta_l} g_{l,2,1}^{(1)}, \ldots, \sqrt{\beta_l} g_{l,K,K}^{(1)} \right]$, and $H_{b,l} = \left[ H_{b,1,1}^{(l)}, H_{b,2,1}^{(l)}, \ldots, H_{b,K,K}^{(l)} \right]$. Then the equivalent channel matrix $H_{b,l}$ is given by $H_{b,l} = G_l \Psi H_{b,l}$. Subsequently, the pseudo inverse of the equivalent channel $H_{b,l}$ gives the ZF beamforming matrix, i.e. $V_{b,l} = H_{b,l}^H$. By substituting $V_{b,l}$ into (5), the energy efficiency maximization problem can be formulated as
\[
\begin{align}
\max_{p_{b,l}, \Psi} \sum_{b=1}^{B} \sum_{l=1}^{L} \sum_{k=1}^{K} \log_2 \left( 1 + \text{SINR}_{b,l,k} \right) + \sum_{b=1}^{B} \sum_{k=1}^{K} \left( \xi p_{b,l,k} \right)^2 \\
\text{s.t.} \; C_1 : \log_2 \left( 1 + \sum_{b=1}^{B} \sum_{k=1}^{K} p_{b,l,k} \right) \geq R_{\text{min}}, \\
C_2 : \text{Tr}(V_{b,l} P_{b,l} V_{b,l}) \leq \rho_{b,l}, \\
C_3 : |\Psi| = 1, \quad \forall n = 1, 2, \ldots, R_N, \tag{12}
\end{align}
\]

where constraint (12b) ensures that each user must satisfy the same QoS at each subcarrier for the $b$-th BS. Therefore, we have dropped the $l$-th subcarrier subscript at $R_{\text{min}}$. The constraint (12c) indicates that the $b$-th BS transmit power should be lower than the maximum power threshold at the $l$-th subcarrier. Furthermore, (12d) ensures that each reflecting element of RIS satisfies unit modulus constraint.

Our original problem (12a) is a non-convex problem, and it’s hard to solve it. Thus, in the subsequent section, we propose an efficient alternating optimization solution to solve the formulated problem.
III. ENERGY EFFICIENCY MAXIMIZATION

The formulated energy efficiency maximization problem (12) is hard to solve due to the presence of constraints (12c) and (12d). To convert the original problem into a more tractable form, we decompose the original optimization problem into multiple subproblems, and then solve these subproblems alternatively. Based on this approach, we fix one variable and solve subproblem for the other, and vice versa. The process continues until the final solution is obtained.

A. OPTIMIZATION OF $\Psi$

For all $K$ users, while the power allocation matrix $P_{b,l}$ for the $b$-th BS on the $l$-th subcarrier is given, the original problem (12) is decomposed to the following subproblem:

$$\max \ C_{\text{const}}$$

subject to $C_2 : \text{Tr}(V_{b,l} P_{b,l} V_{b,l}^H) \leq \rho_{b,l},$

$$C_3 : |\Psi_n| = 1,$$

where $C_{\text{const}}$ is a constant number. Specifically, we have assumed that the power allocation matrix $P_{b,l}$ is given, and this reduces the original objective function (OF) (12a) to a constant-value OF under the constraints of $C_2$ and $C_3$. However, solving such a problem is still a tedious task, because the OF is not differentiable and $C_3$ is non-convex. Fortunately, we can observe that (13a) could be feasible if we make the constraint as an OF such that the trace of the function could be maintained lower than the per subcarrier constraint $\rho_{b,l}$. Hence, we can rewrite the OF as

$$\min_{\Psi} \text{Tr}(V_{b,l} P_{b,l} V_{b,l}^H)$$

subject to $C_3 : |\Psi_n| = 1.$

Then, we substitute the expression of $V_{b,l}$ into the above subproblem, which can be rewritten as

$$\min_{\Psi} \text{Tr}(G_{l} \Psi H_{b,l})^H P_{b,l} (G_{l} \Psi H_{b,l})^H$$

subject to $C_3 : |\Psi_n| = 1.$

We can apply the Cholesky decomposition method to the power allocation matrix $P_{b,l}$ for the $b$-th BS at $l$-th subcarrier to convert it into the factorization form, i.e., $P_{b,l} = \mathcal{Q}_{b,l} \mathcal{Q}_{b,l}^H$. Then the OF (15a) can be rewritten as

$$\text{Tr}(G_{l} \Psi H_{b,l})^H P_{b,l} (G_{l} \Psi H_{b,l})^H$$

$$= \text{Tr}(Q_{b,l} G_{l} \Psi H_{b,l})^H (Q_{b,l}^{-1} G_{l} \Psi H_{b,l})^H$$

$$= \mathcal{H}_{b,l} \Psi^H \mathbf{1}$$

$$= \text{vec} (\mathcal{H}_{b,l} \Psi^H G_{l}^H)$$

$$= \text{vec} (\mathcal{H}_{b,l} \Psi^H G_{l}^H)$$

$$= |\Psi_n| = 1,$$

where step (16b) and (16d) are obtained by using the Frobenius matrix norm as well as the connection between the vectorization operator and the Kronecker product, respectively. The final expression (16e) enables us to cope with the non-convex constraint (15b) by exploiting an efficient sequential programming (SP) method, also known as majorization-minimization method [37]–[39]. By substituting (16e) into (15a), we obtain the following minimization problem at a given $P_{b,l}$:

$$\min_{\Psi} f(\Psi) \triangleq \text{vec}(\Psi^{-1})^H \Upsilon_{b,l} \text{vec}(\Psi^{-1})$$

subject to $C_3 : |\Psi_n| = 1,$ $\forall n = 1, 2, \cdots, RN,$

where $\Upsilon_{b,l} \triangleq \left( G_{l}^H \mathcal{H}_{b,l} \right)^H \left( G_{l}^H \mathcal{H}_{b,l} \right) \in \mathcal{C}^{RN^2 \times RN^2}.$

B. SEQUENTIAL PROGRAMMING (SP) METHOD

To solve subproblem (17), we exploit an iterative SP solution. The SP method can be used to tackle a tedious problem by creating a sequence of tractable subproblems. Inspired by this method, we at first obtain the solution for $\Psi^i$ at the $i$-th iteration. Then, we compute OF value $f(\Psi^i)$ from subproblem (17). In the $(i+1)$-th iteration, we need to determine an upper bound for the OF from the prior solution, which is denoted by $g(\Psi^i | \Psi^{i-1})$. At this $(i+1)$-th iteration, the approximate subproblem can be solved with the assistance of the new function $g(\Psi^i | \Psi^{i-1})$. If for each $\Psi^i$, the new OF $g(\Psi^i | \Psi^{i-1})$ fulfills the following conditions:

1) $g(\Psi^i | \Psi^{i-1}) = f(\Psi^i),$

2) $\nabla g(\Psi^i | \Psi^{i-1})_{\Psi = \Psi^{i-1}} = \nabla f(\Psi^i)_{\Psi = \Psi^{i-1}},$

3) $g(\Psi^i | \Psi^{i-1}) \geq f(\Psi^i),$

then the series of the optimal solutions of $f(\Psi^i), i = 1, 2, \cdots$ will decrease monotonically and converges at the end of the iterations. When the solution converges, it satisfies the Karush-Kuhn-Tucker (KKT) optimality conditions of problem (17) [26]. Moreover, the first two conditions show that the new function $g(\Psi^i | \Psi^{i-1})$ and its gradient should be the same as the primal OF $f(\Psi^i)$ and its gradient at a specific point $\Psi^i$. The third condition represents that the new OF $g(\Psi^i | \Psi^{i-1})$ would be an upper bound of the primal OF $f(\Psi^i)$.

To realize this algorithm practically, we need to find the upper bound function $g(\Psi^i | \Psi^{i-1})$ that satisfies the above mentioned three conditions.

To find an upper bound for the OF $f(\Psi)$ of problem (17), we exploit the following lemma. By defining $x = \text{vec}(\Psi^{-1})$ the OF in (17) can be written as $x^H \Upsilon_{b,l} x$.

**Lemma 1:** For any given feasible point $x^i$ at the $i$-th iteration and for any feasible $x$, a suitable upper bound to exploit SP method is:

$$x^H \Upsilon_{b,l} x \leq x^H Z_{b,l} x - 2 \text{Re}(x^H (Z_{b,l} - \Upsilon_{b,l}) x^i)$$

$$+ (x^i)^H (Z_{b,l} - \Upsilon_{b,l}) (x^i) \triangleq y(x|x^i)$$

where $Z_{b,l} = \lambda_{\text{max}} \mathcal{I}_{RN^2}$, and $\lambda_{\text{max}}$ denotes the maximum eigen-value of $\Upsilon_{b,l}$.

**Proof:** Detailed constructive proof of **Lemma 1** is given in [38], [39].
The Lemma 1 gives a suitable surrogate function with respect to x, which can be exploited in SP method. Next, we need to apply the unit modulus constraint to the obtained variable x, which is a vectorized form of Ψ. However, the constraint (18) requires that the diagonal elements of Ψ must satisfy a unit modulus. This implies that, the elements with the indices (n − 1)NR + n, where n = 1, 2, · · · , RN, must have unit modulus, and all other entries must be zero. To this end we have,

\[
x_n = \begin{cases} 
\frac{1}{(n-1)} e^{\text{j}c_n}, & \text{if } (n-1)NR + n, \ n = 1, 2, \cdots, \ RN, \\
0, & \text{otherwise}, 
\end{cases}
\]

(20)

where c_n is the n-th element of C = (Z_{b,l} − Υ_{b,l})x'.

C. OPTIMIZATION OF P

After obtaining Ψ from SP-method, we fix Ψ and solve the problem (12) for P_{b,l}. The problem (12) can be decomposed into the following optimization problem

\[
P_{b,l}^{\text{opt}} = \arg \max_{P_{b,l}} \sum_{l=1}^{L} \sum_{k=1}^{K} \log_2(1 + \sum_{b=1}^{B} P_{b,l,k} \sigma^{-2}) - \sum_{b=1}^{B} \sum_{l=1}^{L} \sum_{k=1}^{K} (\xi_{b,l,k}) + P_c + P_{th} \\
\text{s.t. } C_1 : \log_2(1 + \sum_{b=1}^{B} P_{b,l,k} \sigma^{-2}) \geq R_{\text{min}}, \\
C_2 : \text{Tr}(V_{b,l}P_{b,l}V_{b,l}^H) \leq P_{b,l}.
\]

(21)

We can observe that, for a fixed Ψ, the subproblem (21) is a fractional programming problem where the denominator is convex and the numerator is concave, which can easily be handled by Dinkelbach’s algorithm. By applying Dinkelbach’s algorithm to the subproblem with respect to P_{b,l}, the problem becomes convex and can easily be solved using CVX tool. The pseudocode of the Dinkelbach’s algorithm is summarized in Algorithm 2. In Dinkelbach’s algorithm, firstly an initialization process is performed. Subsequently, in each iteration, we optimize the power allocation matrix P_{b,l} for each subcarrier l of b-th BS over the updating variable Ψ. The optimal result of P_{b,l} can be obtained, when a tolerance condition for the Ψ is satisfied. After obtaining the solutions to Ψ, discussed in Algorithm 1, and P_{b,l} from Algorithm 2, we can find the best pair of Ψ^{\text{opt}} and P_{b,l}^{\text{opt}} that maximizes the J_{\text{IEEE}}(Ψ^{\text{opt}}, P_{b,l}^{\text{opt}}) at all L for the b-th BS. The obtained solutions to Ψ^{\text{opt}} and P_{b,l}^{\text{opt}} are iteratively and alternatively updated until the final solution is obtained over the feasible set of (12). The same procedure is performed for all BSs.

D. COMPUTATIONAL COMPLEXITY

The complexity of the proposed algorithm mainly involves in computing the RIS phase shifters. At first, the complexity lies in computing the largest eigenvalue λ_{max}, the complexity involved in this step is (N^3). The other major contribution in computing the y_l in step 6 of SP algorithm. The associated complexity is given by (N^2). Thus, the total complexity of the algorithm is (N^3 + N^2) for the r-th RIS.

Remarks: In comparison to the existing research works, in this work, we have considered B BSs with M antennas, Algorithm 1 Sequential Programming Method

Input: Channel matrices G_l, H_{b,l}; Number of users K; Number of basestations B; Number of subcarriers L; Number of RISs R; Tolerance \( \epsilon > 0 \);

Output: \( \Psi \)

Stage 1 (initialization):
1. ∀ K, allocate equal power at each subcarrier l, l = 1, 2, · · ·, L
2. Initially \( \Psi^0 = \pi/2 \);

Stage 2 (iterative refinement):
3. Optimize \( \Psi \) while given \( F_{b,l} \);
4. \( A_l = (G_{l}^{H} \otimes H_{b,l}^{H})(G_{l}^{H} \otimes H_{b,l}^{H})^{H} \)
5. Compute \( y_l = \text{vec}((\Psi)^{-1}) \);
6. Update \( y_l \) as in (20)
7. \( y_l(m+1) = \text{reshape}(y_l) \)
8. if \( (\|\Psi_{l}(m+1)\Psi_{l}(m)\|^2 < \epsilon) \);
   break,
9. else
10. \( m \leftarrow m + 1; \)
11. return \( \Psi_l \)

K users with single-antennas, R RISs with N reflecting elements, and L subcarriers. It is worth pointing out that the previous work such as [29] is a special case of our work. For instance, by fixing several subcarriers L, R RISs, B BSs, to a reasonable integer value our presented model can be decomposed to a special case to maximize the energy efficiency. To be more specific, if we set parameters L, R, and B as 1, the considered RIS-aided CF network model will be simplified to the system model discussed in [30].

IV. SIMULATION RESULTS

In this section, we verify the effectiveness of the proposed SF-based scheme under different simulation settings for the wideband RIS-aided CF wireless network. The simulated 3-D network configuration of the considered CF framework is shown in Fig. 2. The CF network configuration is composed of four BSs, two RISs, and four single-antenna users. It shows that the service quality of the BSs to users is weakened by the obstruction from a green belt and high-rise buildings. To improve the network performance, two RISs are installed on two distant buildings to establish an extra link between the BSs and users. We assume that the b-th BS is located at \((40(b-1)) m, -50 m, 3 m)\), while the r-th RIS is located at \((20 + 40r) m, 10 m, 6 m)\). Besides, the users are located in a uniform circular region with a radius of 1 m, and the center of the region is located as \((D, 0, 1.5 m)\), where D is the distance between the BS 1 to the uniform circular region.

A. SIMULATION SETUP

In our simulation, we consider the number of antenna elements M at the b-th BS as 2, and the number of configure elements at the individual RIS is set as N = 50. We further set the number of users as K = 4, and we set the total number of sub-
Algorithm 2 Dinkelbach Algorithm

**Input:** Number of users $K$; Number of basestations $B$; Number of subcarriers $L$; Number of RISs $R$; Power dissipated by a basestation $P_{BS}$; Power dissipated by $N$ RIS elements $P_{RIS}$; Power dissipated by a mobile equipment $P_{ME}$; Power dissipated by backhaul $P_{bh}$; Transmit power efficiency $\gamma$; Noise power $\sigma^2$; Tolerance $\epsilon > 0$; $\lambda_0 = 0$.

**Output:** Power allocation matrix $P_{b,l}$

**Stage 1 (iterative refinement):**

1. for $b = 1, 2, \ldots, B$ do
2. for $l = 1, 2, \ldots, L$ do
3. for $i = 1, 2, \ldots, K$ do
4. Solve the subproblem for $P_{b,l}$ as:
   $$ P_{b,l}(i) = \arg \max_{P_{b,l}} \sum_{k=1}^{K} \log_2(1 + \sum_{b=1}^{B} P_{b,l,i} \sigma^{-2}) - \lambda_{i-1} \left( \sum_{k=1}^{K} \left( \sum_{b=1}^{B} P_{b,l,k} \right)^2 + P_{BS} + R_{P_RIS} + K P_{ME} + P_{bh} \right) $$
5. Compute
   $$ \lambda_i = \frac{\sum_{k=1}^{K} \log_2(1 + \sum_{b=1}^{B} P_{b,l,k} \sigma^{-2}) \lambda_{i-1}}{\sum_{k=1}^{K} \sum_{b=1}^{B} P_{b,l,k} \sigma^{-2}(i)} $$
6. if $(|\lambda_i - \lambda_{i-1}| < \epsilon)$ break;
7. end for
8. return $P_{b,l}$
9. end for
10. end for

Carriers as $L = 6$. To ensure the same QoS for all users, we set the minimum QoS constraint to $R_{\min} = 0.5 \text{ bit/s/Hz}$. Finally, the convergence parameter, channel attenuation parameter in (3), and noise power is set as $\epsilon = 10^{-3}$, $\beta_i = 1$, and $\sigma^2 = -120 \text{ dBm}$, respectively.

In our work, we adopt the same large-scale channel model which has comprehensively been discussed in [33]. Let us define the distance from the BS to RIS as $d_{BS,RIS}$, and the distance from an RIS to an individual $k$-th user as $d_{RIS,k}$. Hence, based on these settings, the path loss (PL) accompanied by the distance for a complete BS-RIS-user link is given by

$$ PL(d) = PL_0 \left( \frac{d}{d_0} \right)^\zeta, \quad d \in \{d_{BS,RIS}, d_{RIS,k}\} $$

where $PL_0$ denotes the PL at the reference point $d_0 = 1 \text{ m}$. Moreover, $PL_0$ depends on the wavelength, channel quality, antenna gain, effective aperture of the antennas and other parameters [33]. The PL exponent is represented by $\zeta$. In simulations, we assume $PL_0 = -30 $ dB, and the PL exponents for the link between BS to RIS and RIS to users are considered as $\zeta_{BS,RIS} = 2.2$ and $\zeta_{RIS,k} = 2.8$, respectively.

On the other hand, to take small-scale fading into account, we further adopt a Rician fading model and the BS to RIS link channel $H_{BS,RIS}$ can be expressed as

$$ H_{BS,RIS} = \sqrt{\frac{\alpha_{BS,RIS}}{1 + \alpha_{BS,RIS}}} H^{LoS}_{BS,RIS} + \sqrt{\frac{1}{1 + \alpha_{BS,RIS}}} H^{NLoS}_{BS,RIS} $$

where $\alpha_{BS,RIS}$ represents the Rician factor, and the LoS and NLoS components are denoted by $H^{LoS}$ and $H^{NLoS}$, respectively. In the same way, we can generate the RIS-user channel by using the above model, and the corresponding Rician factor can be denoted as $\alpha_{RIS, user}$ for the RIS-user link [29], [33].

B. ENERGY EFFICIENCY PERFORMANCE OF CELL-FREE NETWORK

We have discussed the power consumption model for the considered wideband RIS-aided CF network in Section II. To get more insight into the developed model (9), we further investigate the energy efficiency performance of the proposed SP solution with the existing scheme [33]. In our work, we consider the same simulation setup as provided in [29]. We set the efficiency of the transmit power $\zeta$ as 1.2; Power dissipation by the circuit blocks of BS $P_{BS}$ and mobile equipment $P_{ME}$ to operate the communication link are set as 9 dBW and 10 dBm, respectively; Moreover, the power dissipation of the $n$-th passive element of $r$-th BS $P_n$ is kept as $P_n = 10 \text{ mW}$, while the backhaul power $P_{bh}$ is set as 0 dBW. Then, by jointly exploiting the Algorithm 1 and Algorithm 2, we can examine the energy efficiency performance of the proposed SP and existing schemes [33] against different parameters such as distance $D$, BSs power budget, and the number of RISs elements. The energy efficiency performance gives us the vision to establish a useful conclusion regarding the trade-off between energy efficiency and spectral efficiency for the considered wideband RIS-aided CF network.

C. CONVERGENCE BEHAVIOUR OF PROPOSED METHOD

We plot the convergence graph of the proposed SP method in Fig. 3. We obtain this result by alternating optimizing the active beamforming at BSs and passive beamforming at RISs using Algorithms 1 and 2. The result is obtained by fixing $D = 80 \text{ m}$. The result shows that the proposed algorithm converges speedily in 15 iterations.
D. IMPACT OF RISs LOCATION AT ENERGY EFFICIENCY

Fig. 4 shows the energy efficiency performance in terms of different ranges of $D$. From Fig. 4, we can observe some interesting facts. First, with the deployment of RISs between users and BSs, we observe two noticeable peaks at $D = 60$ and $D = 100$ m. These sharp peaks indicate that the energy efficiency performance of both schemes reaches its maximum peak when users approach closer to any of the installed RISs. The reason is that when the users approach the RISs, they receive high-quality signals reflected by RISs. Hence, we can infer that the energy efficiency performance can be significantly improved by installing more RISs in the CF network while minimizing the large-scale fading caused by obstacles or high-rise buildings. Second important observation is that the performance gain of the existing scheme [33] is lower than the proposed SP-scheme over the entire range of $D$ under the same simulation setup, which indicates the significance of the proposed scheme over the existing benchmark scheme [33].

E. ENERGY EFFICIENCY VS. BS TRANSMIT POWER

We further explore the impact of BS transmit power on the presented wideband RIS-aided CF network model, and plot the energy efficiency performance at various available power budgets in Fig. 5. From this Fig., we can see that both schemes exhibit a similar energy efficiency performance at lower transmit power ranges. However, as the transmit power increases, i.e. 5 dBW or beyond, the energy efficiency performance of the existing solution drastically changes and drops to 0.18 (bit/s/Hz/W) when the transmit power exceeds 20 dBW, while the performance of the proposed solution remains stable. This shows that our proposed scheme is more stable than the existing benchmark scheme [33] and achieves higher energy efficiency performance at higher transmit power ranges.

F. ENERGY EFFICIENCY VS. RIS ELEMENTS

Fig. 6 demonstrates the energy efficiency performance with respect to the number of reflecting elements $N$. We can observe from Fig. 6 that the energy efficiency performance gain of both schemes increases with the increase of passive elements $N$. The reason is that, for all $R$ RISs, the huge number of passive elements coherently generate the beam to reflect the signals with high array gain, which improves the network performance. Since the RIS elements are of low-cost, we can also conclude that enlarging passive elements on the RIS metasurface could be the most economical way to maximize the energy efficiency of the wideband RIS-aided CF network. Moreover, we also observe that with the increase of RIS elements, the performance gap between the existing benchmark method [33] and the proposed scheme is quite large. This implies that our proposed scheme is an effective passive beamforming scheme to maximize the energy efficiency of the wideband RIS-aided CF network.

G. ENERGY EFFICIENCY TRADE-OFF BETWEEN BSs AND RISs

To investigate the performance of the proposed SP algorithm under different B and R settings, we plot energy efficiency at different ranges of $D$. We install multiple RISs and BSs to analyze the energy efficiency performance of the wideband RIS-aided CF network. The number of RISs are located at ...
different positions which jointly transmit the information with BSs to ensure high energy efficiency. Fig. 7 explains the significance of the RISs in traditional cooperative communication to realize the high energy efficiency with low-hardware cost. As you can see from Fig. that if we introduce just one RIS in the conventional cooperative BS system (here we consider 4-BSs and 1 RIS), we obtain a sharp rise in energy efficiency at the location of a RIS (which is indicated by a blue curve in the Fig.). However, an extraordinary performance of the considered wideband RIS-aided CF network is observed when we use multiple RISs along with a fewer number of BSs, which indicates that by replacing some of the BSs with RISs the energy efficiency performance of the CF network can be improved significantly. Thus, the trade-off between BS and RIS is cost-effective.

H. ENERGY EFFICIENCY VS NUMBER OF USERS

To explore the energy efficiency performance against the number of users, we further plot a graph of energy efficiency with the number of users $K$ in Fig. 8. The result is realized by fixing $D = 80$ m. The result shows that the proposed SP method outclasses the existing method [33] over the entire range of $K$, and the energy efficiency gap between the two methods is too large to cover, which shows the significance of the proposed SP method in the considered CF network.

I. SUM-RATE MAXIMIZATION

In previous subsections, we have explicitly discussed the energy efficiency maximization problem for the wideband multi-RIS-aided CF network. However, there is always a trade-off between energy efficiency and spectral efficiency. Thus, our original energy efficiency maximization problem (12) can easily be extended to sum-rate maximization problem by setting the parameter $\zeta = 0$. With this setting, the denominator of the OF in (12a) simplifies to a fixed quantity. Consequently, such a sum-rate maximization problem can be solved with a few iterations of Algorithm 2.

J. SPECTRAL EFFICIENCY VS. TRANSMIT POWER

The spectral efficiency of the different schemes versus the total BS power budget is exhibited in Fig. 9. It is observed from Fig. 9 that the spectral efficiency increases in all cases by rising the power budget. This gives us a basic conclusion that the network capacity of the wideband RIS-aided CF communication system could further be improved by proliferating the power budgets of all the $B$ BSs. Additionally, we also find that the performance gain of both schemes is significant even at a low transmit power of 0 dBm. This is because the quality of the reflected signal from RISs is quite good to serve multiple users. However, with the increase of the transmit power, the performance gap between the proposed SP-algorithm and the existing solution [33] also increases,
which proves the trade-off relation between the energy- and spectral efficiency.

K. SPECTRAL EFFICIENCY VS. REFLECTING ELEMENTS

Fig. 10 shows the spectral efficiency versus the number of reflecting elements $N$ for RISs in wideband CF network. We can observe from Fig. 10 that the spectral efficiency is directly proportional to passive reflecting elements $N$ for RISs. This implies that if we extend the number passive elements to a larger value, this gives rise in spectral efficiency of both schemes and exhibit the same trend as we observed in Fig. 6, but in a reverse manner.

V. CONCLUSION

In this paper, we investigate the energy efficiency maximization problem for the wideband RIS-aided CF network. To be more specific, we formulate a joint active and passive beamforming problem with power allocation to maximize the energy efficiency of the wideband RIS-aided CF network under the per subcarrier constraint at the BSs and unit modulus hardware constraints at the RISs. To solve this problem, we first decompose the original energy efficiency maximization problem into multiple subproblems, and then solve them alternately. Specifically, we adopt Dinkelbach’s solution to optimize the active beamforming at BSs, while the sequential programming method is adopted to optimize the passive beamforming at RISs. Simulation results indicate that our proposed solution achieves higher energy efficiency performance than the existing benchmark scheme.

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