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Research Article

Fairness-Aware and Energy Efficiency Resource Allocation in Multiuser OFDM Relaying System

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A fairness-aware resource allocation scheme in a cooperative orthogonal frequency division multiple (OFDM) network is proposed based on jointly optimizing the subcarrier pairing, power allocation, and channel-user assignment. Compared with traditional OFDM relaying networks, the source is permitted to retransfer the same data transmitted by it in the first time slot, further improving the system capacity performance. The problem which maximizes the energy efficiency (EE) of the system with total power constraint and minimal spectral efficiency constraint is formulated into a mixed-integer nonlinear programming (MINLP) problem which has an intractable complexity in general. The optimization model is simplified into a typical fractional programming problem which is testified to be quasiconcave. Thus we can adopt Dinkelbach method to deal with MINLP problem proposed to achieve the optimal solution. The simulation results show that the joint resource allocation method proposed can achieve an optimal EE performance under the minimum system service rate requirement with a good global convergence.

1. Introduction

Recently, orthogonal frequency division multiple (OFDM) cooperative communication systems have been widely used to overcome the limitations of the users' space constraints, because the relays can adopt the frequency diversity technique to deal with channel fading. In multiple frequency channels, subcarrier pairing was first devised independently for a single-user communication environment in [1, 2], by matching the subcarriers in OFDM relaying networks. Further in multiuser relaying networks [3, 4], both the relay and users are sharing all the channel. Owing to the complexities and drastic variations in the channel conditions for different users, appropriate channel-user assignments can potentially enable significant improvements in the spectral efficiency (SE). Recently, energy efficiency (EE) [5–9] has emerged as one of the most promising solutions to resolve issues such as the rapidly increasing energy consumption and the carbon emissions caused by the escalating growth of wireless data traffic in next-generation networks. The authors in [10–13] have conducted a preliminary research on EE multiuser relaying resource allocation (RA). In such OFDM relaying networks, an optimal system performance should take into account three problems jointly: the subcarrier pairing, channel-user assignment (the assignment of subcarrier pairs to users), and the power allocation that have a strong correlation among them. However, the combinatorial solution of these three problems entails the mixed-integer linear programming problem (MILP) which generally has an excessive computational complexity. Besides, if we further consider the energy efficiency resource allocation problem, the optimization problem will be a mixed-integer nonlinear programming (MINLP) problem that in general is computationally undesirable because of its combinatorial nature which could adopt branch-and-bound method to solve [14]. Previous attempts to optimize the performance of the multiple users OFDM relaying networks have usually considered only a subset of three problems regarding the SE [15–22] or a subset of three problems regarding the EE [5–12] or have adopted a suboptimal approach [13, 23].

Based on single-user amplify-and-forward (AF) OFDM relaying networks, [15] shows that the subcarrier pairing method according to the instantaneous channel gain that matches the incoming and outgoing subcarriers is sum-rate optimal. The authors in [16, 17] propose a joint power allocation and subcarrier pairing scheme in the same scenarios with [15] for the AF and the decode-and-forward (DF) networks, respectively. However, the works mentioned above only address the maximization of the end-to-end SE without jointly considering the direct passing path. For the AF and the DF, respectively, [18, 19] consider power allocation and subcarrier pairing scheme jointly, which could be obtained by the Lagrange means, in the single-user OFDM relaying network when the passing path directly is available. An equal power allocation policy in [23] exploits an optimal subcarrier-user allocation method which maximizes the system throughput. For DF relaying networks, [21] provides an asymptotically optimal scheme to jointly allocate power and assign subcarrier user. The same in DF relaying networks, [20] considers all the three problems with the total power constraint. However, this approach is suboptimal because of separately applying the power allocation, subcarrier pairing, and subcarrier-user allocation. The authors in [22] address a maximized throughput problem by joint considering power allocation, subcarrier pairing, and subcarrier pair-user allocation. Based on usual relaying strategies, the optimal resource allocation problem can be obtained by Lagrange means.

For a downlink OFDM system, [5] presents a bandwidth allocation scheme based on energy efficiency to maximize the number of bits per Joule energy consumption. Reference [6] offers a global optimal energy efficiency scheme to solve the optimal energy efficiency of the system that decomposes the joint optimization problem into three subproblems. However, [5, 6] do not consider the EE of the OFDM relaying networks which are traditional OFDM networks without relays. Considering a sum-rate constraint for a cooperative OFDM DF relaying network, [7] develops a sum-power minimized RA algorithm without the direct source-destination link. In [8], based on AF relaying networks with a frequency selective channel, a suboptimal two-step power allocation and subcarrier pairing strategy is raised to maximize the energy efficiency when the direct source-destination link is unavailable. In a downlink cooperative multiuser OFDM relaying network, the authors in [9] present a joint subcarrier pairing and power allocation scheme to maximize the EE of the system with the proportional fairness.

In [10–13], multiple users relaying networks are considered. Considering only the power allocation without considering the subcarrier pairing and the channel-user assignment, [10] presents a multiple users AF relaying model. Reference [11] formulates energy efficiency optimization problem for power allocation with fairness in cooperative multiple users fading channels. In [12, 13], maximizing the EE problem is proposed which is formulated as the ratio of the SE over the total power dissipation and joint power and subcarrier allocation in a multiple users OFDM relaying network. In [12], the optimization problem is solved under a constraint of providing the minimum required spectral efficiency in the OFDM relaying networks.

In [13], the objective function (OF) is proven to be quasiconcave and can adopt Dinkelbach method to obtain the optimal solution by solving a sequence of subtractive concave problems using the dual decomposition approach. However, [12, 13] jointly consider only power allocation and subcarrier pairing without considering channel-user assignment.

In this work, we focus on the design of a fairness-aware resource allocation scheme in a cooperative OFDM network. Compared with traditional OFDM relaying networks, the source is permitted to retransfer the same data transmitted by it in the first time slot, further improving the system capacity performance. The problem which maximizes the energy efficiency (EE) of the system with total power constraint and minimal spectral efficiency constraint is formulated into a mixed-integer nonlinear programming (MINLP) problem which has an intractable complexity in general. The optimization model is simplified into a typical fractional programming problem which is testified to be quasiconcave. Thus we can adopt Dinkelbach method to deal with MINLP problem proposed to achieve the optimal solution. The simulation results show that the joint resource allocation method proposed can achieve an optimal EE performance under the minimum system service rate requirement with a good global convergence.

The main contributions of the work are summarized as follows:

(i) We propose a new energy-efficient maximizing method in a multiple users relaying system with direct passing path and total power constraints which jointly optimizes the subcarrier pairing, the power allocation, and the channel-user assignment. We can also adopt Lagrangian method and continuity relaxation to solve the joint optimal problem. But the three-dimensional assignment problem is its key subproblem which is nondeterministic polynomial time (NP-hard) but has time complexity.

(ii) Compared with traditional OFDM relaying networks, the source is permitted to retransfer the same data transmitted by it in the first time slot, further improving the system capacity performance. Because of both the new relay cooperation protocol and the subcarrier pairs-user three-dimensional assignment algorithm, the proposed joint resource allocation method could achieve optimal EE performance under a minimum system data rate requirement with a good global convergence which can be proved by theoretical derivation and simulation analysis.

(iii) The optimization model is simplified into a typical fractional programming problem which is testified to be quasiconcave. Thus we can adopt Dinkelbach method to deal with MINLP problem proposed to achieve the optimal solution.

The remained of this paper is organized as follows. In Section 2, the system model and the resource allocation problem are described. In Section 3, the problem is formulated and reformulated by the convex optimization technique. In Section 4, a resource allocation iteration algorithm will be adopted and solved by a dual decomposition method.

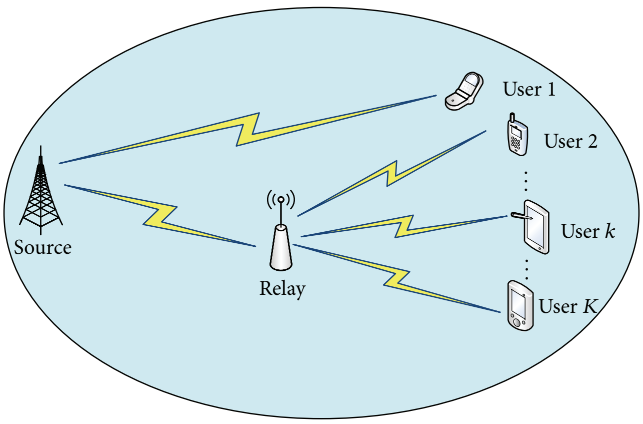

Figure 1: Model of the concerned single relay multiuser OFDM network.

In Section 5, both the analysis and the simulation results are presented to compare the performances of the different resource allocation schemes. Section 6 gives a conclusion for this paper.

2. System Model

In this section, we first introduce the adopted system model and the performance measure. Then, the design of the resource allocation and scheduling is formulated as an optimization problem.

2.1. System Model. Considering an OFDM single relay multiusers system as in Figure 1, source transfers the information to all the users with the help of one relay. In this paper, we focus on the joint resource allocation problem in a scenario including one source, one relay, and K users. N equal-bandwidth orthogonal channels haves been divided from the available frequency spectrum, accessible by the relay and all the users. Without loss of generality, we assume that all the channels occupy the same bandwidth and experience independent frequency selective fading. It is also assumed that all pieces of the channel state information (CSI) are available at the source, the relay, and the users [18]. The half-duplex transmission process can be divided into two phases. The source S transmits the information data to all the other nodes including the relay and all the users in the first phase. The relay decodes the received signals in the first phase and retransmits them to all the users in the second phase. Compared with traditional OFDM relaying networks [22], the source is permitted to retransfer the same data transmitted by it in the first time slot, further improving the system capacity performance [24].

From the discussion above, the state of channel i can denote that, for $1 \le i \le N$, h_i^{sr} and h_i^{sk1} represent the instantaneous channel gain from source to relay and from the source to the user k in the first phase and h_i^{rk} and h_i^{sk2} signify the instantaneous channel gain from the relay to the user k and from the source to the user k in the second phase. The AWGN (Additive Gaussian White Noise) at the kth user and the relay are zero mean with variances σ_r^2 and σ_k^2, respectively.

Since there are multiple users, for the sake of maximizing the system throughput when allocating the resources, we must also take the user fairness into account [9, 11]. The fairness factor ω_k for user k is expressed by

$$\sum_{k=1}^{K} \omega_k = 1. \tag{1}$$

It should be mentioned that the considered scenario is applicable in practice where the source, the relay, and the users may act as base station, the relay station, and the cellular users, respectively. Further, this system model is an example of a wireless sensor network transmission model, where the source, the relay, and the users are all considered as wireless sensor nodes. In our system model, adopting one relay instead of multiple relays can significantly reduce the energy consumption and the system overhead, in accordance with green communication and environmental protection.

2.2. Channel Assignment. The relay not only forwards the incoming signals to their intended users by a special relay process strategy but also conducts the subcarrier pairing and the channel-user assignments. Obviously, the solutions of the subcarrier pairing are closely related to the strategy of the channels assignments to all the users. Then, we refer to the joint assignment on subcarrier pairing and subcarrier pair-user allocation as the joint channel assignment problem.

Suppose that the path $P(m, n, k)$ is selected, if the first-hop channel m is paired with a second-hop channel n and the pair of channels (m, n) is assigned to user k. Further, we define the indicator functions given by [22]

$$\phi_{m,n,k} = \begin{cases} 1, & \text{if } P(m,n,k) \text{ is selected,} \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

A user can be assigned many subcarrier pairs, but a subcarrier pair must be allocated to a user exclusively. Hence

$$\begin{aligned} &\sum_{n=1}^{N} \sum_{k=1}^{K} \phi_{m,n,k} = 1, \quad \forall m, m \in \{1, 2, \ldots, N\} \\ &\sum_{m=1}^{N} \sum_{k=1}^{K} \phi_{m,n,k} = 1, \quad \forall n, n \in \{1, 2, \ldots, N\}. \end{aligned} \tag{3}$$

2.3. Relaying Strategy and Power Allocation. In the traditional DF relaying networks, each transmission cycle is divided into two time slots equally. In the first time slot, the source broadcasts a data block in every channel to both user and relay nodes. Then, in the second time slot the relay starts to decode and forward the data from source to the user. Meanwhile, if the channel strength of the source is sufficient in the second hop, the source will be assigned power to send the data again and then obtains a diversity gain. The user adopts the MRC in both two time slots on the received signals.

Along any path $P(m,n,k)$, the source in the first time slot, the source in the second time slot, and the relay transmission powers are denoted by P_{mnk}^{s1}, P_{mnk}^{s2}, and P_{mnk}^{r}, respectively. Then the total power allocated to path $P(m,n,k)$ is $P_{mnk} = P_{mnk}^{s1} + P_{mnk}^{s2} + P_{mnk}^{r}$. The total power P_{total} constraint can be given by

$$\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{k=1}^{K}\phi_{mnk}\left(P_{mnk}^{s1} + P_{mnk}^{s2} + P_{mnk}^{r}\right) \le P_{\text{total}}. \quad (4)$$

Based on DF relaying networks, the maximum source-destination achievable rate on path $P(m,n,k)$ is given by [22]

$$\begin{aligned} R(m,n,k) = \frac{1}{2}\min\left\{\log_2\left(1 + a_m P_{mnk}^{s1}\right),\right. \\ \left.\log_2\left(1 + b_{nk}P_{mnk}^{r} + c_{mk}P_{mnk}^{s1} + a_{nk}P_{mnk}^{s2}\right)\right\}, \end{aligned} \quad (5)$$

where $a_m = |h_m^{sr}|^2/\sigma_r^2$, $b_{nk} = |h_n^{rk}|^2/\sigma_k^2$, $c_{mk} = |h_m^{sk1}|^2/\sigma_k^2$, $a_{nk} = |h_n^{sk2}|^2/\sigma_k^2$, and 1/2 indicates that one data transmission is needed in two time slots.

3. Problem Formation and Convex Reformulation

In this section, we formulate the corresponding source allocation problem and reformulate the optimization problem.

3.1. Problem Formulation. Given a fixed total power P_{mnk} of path $P(m,n,k)$, (5) can be converted to [24]

$$R(m,n,k) = \frac{1}{2}\log_2\left(1 + a_{mnk}P_{mnk}\right). \quad (6)$$

a_{mnk} denotes the equivalent channel gain on the path $P(m, n,k)$, expressed as

$$a_{mnk} = \begin{cases} \dfrac{a_m a_{nk}}{a_m + a_{nk} - c_{mk}}, & \text{when } b_{nk} \le a_{nk} \\ \dfrac{a_m b_{nk}}{a_m + b_{nk} - c_{mk}}, & \text{when } b_{nk} > a_{nk}. \end{cases} \quad (7)$$

According to the fairness factor ω_k for every user k, the total end-to-end SE and the total transmit power on all the subcarriers by the source and the relay of the system can be expressed by

$$\begin{aligned} R_{\text{total}}(\mathbf{\Phi},\mathbf{P}) &= \frac{1}{2}\sum_{k=1}^{K}\omega_k\sum_{m=1}^{N}\sum_{n=1}^{N}\phi_{mnk}\log_2\left(1 + a_{mnk}P_{mnk}\right) \\ P_{\text{users}}(\mathbf{\Phi},\mathbf{P}) &= \sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{k=1}^{K}\phi_{mnk}P_{mnk}, \end{aligned} \quad (8)$$

where $\mathbf{P} = [P_{mnk}]_{N\times N\times K}$, $\mathbf{\Phi} = [\phi_{mnk}]_{N\times N\times K}$, and P_{mnk} and ϕ_{mnk} satisfy the constraints mentioned previously.

The total power consumed can therefore be expressed as [13]

$$P_{\text{total}}(\mathbf{\Phi},\mathbf{P}) = P_C + \varsigma P_{\text{users}}(\mathbf{\Phi},\mathbf{P}), \quad (9)$$

where P_C is the constant circuit power consumption which includes the power dissipations in the transmit filter, the mixer, the frequency synthesizer, and the digital-to-analog converter that are independent of the actual transmitted power [12]. $\varsigma > 1$ denotes the reciprocal of the drain efficiencies of the power amplifiers employed at the source and the relay. For example, an amplifier with a 50% drain efficiency has $\varsigma = 1/0.5 = 2$. R_{req} specifies the minimum SE requirement as a QoS constraint and satisfies that $R_{\text{total}}(\mathbf{\Phi}, \mathbf{P}) \ge R_{\text{req}}$.

Finally, the optimization problem to maximize the average system EE is formulated into

$$\begin{aligned} \max_{\mathbf{\Phi},\mathbf{P}} \quad & q(\mathbf{\Phi},\mathbf{P}) = \frac{R_{\text{total}}(\mathbf{\Phi},\mathbf{P})}{P_{\text{total}}(\mathbf{\Phi},\mathbf{P})} \\ \text{s.t.} \quad & (3) \text{ and } (4) \\ & \phi_{mnk} = \{0,1\}, \\ & P_{mnk} \ge 0, \\ & \forall m,n,k \\ & R_{\text{total}}(\mathbf{\Phi},\mathbf{P}) \ge R_{\text{req}}. \end{aligned} \quad (10)$$

3.2. Continuous Relaxation and Convex Reformulation. The optimization problem addressed in (10) is MINLP problem that in general is computationally undesirable because of its combinatorial nature which could adopt branch-and-bound method to solve [14]. However, in the following section, we will raise a method to find an optimal strategy that grows polynomial with the numbers of subcarriers available in the system.

First, ignoring the physical meaning of formula (2), we relax the constraints by allowing ϕ_{mnk} to take any value in the interval [0, 1], where

$$\phi_{mnk} \in [0,1], \quad \forall m,n,k. \quad (11)$$

Hence, we introduce a new variable

$$S_{mnk} = \phi_{mnk}P_{mnk}. \quad (12)$$

Second, the relaxed optimization problem of (10) according to $\mathbf{\Phi} = [\phi_{mnk}]_{N\times N\times K}$ and $\mathbf{S} = [S_{mnk}]_{N\times N\times K}$ can be reformulated as

$$\begin{aligned}
\max_{\boldsymbol{\Phi},\mathbf{S}} \quad & q(\boldsymbol{\Phi},\mathbf{S}) = \frac{(1/2)\sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\omega_k\phi_{mnk}\log_2\left(1+a_{mnk}\left(S_{mnk}/\phi_{mnk}\right)\right)}{P_C+\varsigma\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{k=1}^{K}S_{mnk}} \\
\text{s.t.} \quad & (3) \\
& \sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{k=1}^{K}S_{mnk} \le P_t \\
& 0 \le \phi_{mnk} \le 1, \\
& S_{mnk} \ge 0, \\
& \forall m,n,k \\
& R_{\text{total}}(\boldsymbol{\Phi},\mathbf{S}) \ge R_{\text{req}}.
\end{aligned} \tag{13}$$

Proposition 1. *The channel-user assignments and the power allocation matrices* $(\boldsymbol{\Phi}^*,\mathbf{S}^*)$ *found in the previous subsection are globally optimal solutions to the original problem of (10).*

Proof. Applying the Dinkelbach approach in [25], the objective functions of (10) and (13) are given as

$$F(q) = \max_{\boldsymbol{\Phi},\mathbf{P}}\left[R_{\text{total}}(\boldsymbol{\Phi},\mathbf{P}) - qP_{\text{total}}(\boldsymbol{\Phi},\mathbf{P})\right]$$

$$\begin{aligned}
F(q) &= \max_{\boldsymbol{\Phi},\mathbf{S}}\left[\frac{1}{2}\sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\omega_k\phi_{mnk}\log_2\left(1+a_{mnk}\frac{S_{mnk}}{\phi_{mnk}}\right)\right. \\
&\quad \left. - qP_C+\varsigma\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{k=1}^{K}S_{mnk}\right].
\end{aligned} \tag{14}$$

The optimization problem of (10) is not concave since $\phi_{mnk} = \{0,1\}$. The optimization problem of (13) is the slack form of optimization problem (10) by allowing ϕ_{mnk} to take any value in the interval $[0,1]$.

The objective function (13) is concave in $(\boldsymbol{\Phi},\mathbf{S})$ since $\phi_{mnk}\log_2(1+a_{mnk}(S_{mnk}/\phi_{mnk}))$ are perspectives of the concave function $\log_2(1+a_{mnk}S_{mnk})$. Further, since there are feasible points and all constraints are affine obviously, Slater's condition can be satisfied [17]. Hence, we can suggest that a globally optimal solution can be got in the Lagrange dual domain because convex optimization problem (13) has a zero duality gap. Therefore, relaxation problem (13) and original problem (10) have the same optimal solution. □

Note that adopting traditional convex optimization software packages cannot get the optimal solution in (10) because $\boldsymbol{\Phi}^*$ is not ensured to be a binary. In next section, we will present a three-dimensional joint subcarrier pairing and channel-user assignment scheme that can provide an optimal solution with the polynomial time.

4. Joint Resource Allocation Scheme for Multiuser OFDM Relaying System

Since solving the nonconvex problem in (13) is not standard approach in general, in this section, we transform the optimization problem with the Dinkelbach method and handle an iterative algorithm to obtain it.

4.1. Objective Function Transformation. Without loss of generality, we denote the optimal EE and the set of feasible solutions for the optimization proposed in (13) as q^* and $\mathbf{T}$; then we have

$$q^* = \max_{\boldsymbol{\Phi},\mathbf{S}}\frac{R_{\text{total}}(\boldsymbol{\Phi},\mathbf{S})}{P_{\text{total}}(\boldsymbol{\Phi},\mathbf{S})} = \frac{R_{\text{total}}(\boldsymbol{\Phi}^*,\mathbf{S}^*)}{P_{\text{total}}(\boldsymbol{\Phi}^*,\mathbf{S}^*)}, \quad \forall\{\boldsymbol{\Phi},\mathbf{S}\}\in\mathbf{T}. \tag{15}$$

We define

$$F(q) = \max_{\boldsymbol{\Phi},\mathbf{S}}\left[R_{\text{total}}(\boldsymbol{\Phi},\mathbf{S}) - qP_{\text{total}}(\boldsymbol{\Phi},\mathbf{S})\right]. \tag{16}$$

The optimal energy efficiency of the optimization problem proposed in (15) q^* is achieved if and only if

$$\begin{aligned}
F(q^*) &= \max_{\boldsymbol{\Phi},\mathbf{S}}\left[R_{\text{total}}(\boldsymbol{\Phi},\mathbf{S}) - q^*P_{\text{total}}(\boldsymbol{\Phi},\mathbf{S})\right] \\
&= R_{\text{total}}(\boldsymbol{\Phi}^*,\mathbf{S}^*) - q^*P_{\text{total}}(\boldsymbol{\Phi}^*,\mathbf{S}^*) = 0, \\
&\qquad \forall\{\boldsymbol{\Phi},\mathbf{S}\}\in\mathbf{T}.
\end{aligned} \tag{17}$$

We can prove (17) by following the Dinkelbach approach as in [25]. In other words, the optimal resource allocation policies $\{\boldsymbol{\Phi}^*,\mathbf{S}^*\}$ for the equivalent objective function are also the optimal resource allocation policies for the original objective function.

In summary, the optimization of the original objective function and the optimization of the equivalent objective function result in the same resource allocation policies. Equation (17) reveals that, for an optimization problem with

(1) Initial maximum number of iterations $L_{\max}$ and maximum tolerance ε.
(2) Set maximum energy efficiency $q = 0$ and iteration index $n = 0$.
(3) **repeat** {Main Loop}
(4) Solve the inner loop problem in (19) for a given q and channel assignment and power allocation policy $(\mathbf{\Phi}', \mathbf{S}')$
(5) **if** $R_{\text{total}}(\mathbf{\Phi}', \mathbf{S}') - qP_{\text{total}}(\mathbf{\Phi}', \mathbf{S}') < \varepsilon$ **then**
(6) Convergence = **true**
(7) **return** $(\mathbf{\Phi}^*, \mathbf{S}^*) = (\mathbf{\Phi}', \mathbf{S}')$ and $q^* = R_{\text{total}}(\mathbf{\Phi}', \mathbf{S}')/P_{\text{total}}(\mathbf{\Phi}', \mathbf{S}')$
(8) **else**
(9) Set $q = R_{\text{total}}(\mathbf{\Phi}', \mathbf{S}')/P_{\text{total}}(\mathbf{\Phi}', \mathbf{S}')$ and $n = n + 1$
(10) Convergence = **false**
(11) **end if**
(12) **until** Convergence = **true** or $n = L_{\max}$

ALGORITHM 1: Resource allocation iteration algorithm for EE maximization.

an objective function in the fractional form, there exists an equivalent objective function in a subtractive form, for example, $R_{\text{total}}(\mathbf{\Phi}^*, \mathbf{S}^*) - q^* P_{\text{total}}(\mathbf{\Phi}^*, \mathbf{S}^*)$ in the considered case. As a result, we can focus on the equivalent objective function further in this paper.

4.2. Resource Allocation Iteration Algorithm for EE Maximization. The iterative algorithm for EE maximization is described in Algorithm 1.

As shown in Algorithm 1, for each iteration in the main loop, that is, lines (3)–(12), we solve the following optimization problem for a given parameter q that can be expressed as

$$\max_{\mathbf{\Phi},\mathbf{S}} F(q) = \left[R_{\text{total}}(\mathbf{\Phi}, \mathbf{S}) - qP_{\text{total}}(\mathbf{\Phi}, \mathbf{S})\right]. \tag{18}$$

In combination with formula (13), (18) can be further converted to

$$\begin{aligned}
\max_{\mathbf{\Phi},\mathbf{S}} \quad & F(q) \\
& = \frac{1}{2}\sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\omega_k\phi_{mnk}\log_2\left(1 + a_{mnk}\frac{S_{mnk}}{\phi_{mnk}}\right) \\
& \quad - q\left(P_C + \varsigma\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{k=1}^{K}S_{mnk}\right) \\
\text{s.t.} \quad & (3) \\
& \sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{k=1}^{K}S_{mnk} \le P_t \\
& 0 \le \phi_{mnk} \le 1, \\
& S_{mnk} \ge 0, \\
& \forall m, n, k \\
& R_{\text{total}}(\mathbf{\Phi}, \mathbf{S}) \ge R_{\text{req}}.
\end{aligned} \tag{19}$$

According to (19) and setting $q = 0$, the optimization problem by solving $F(0)$ turns out to be an SE-oriented resource allocation scheme. $R_{\text{total}}(\mathbf{\Phi}, \mathbf{S})$ is concave, and S_{mnk} is affine. The optimization problem of $\text{OP}(q)$ is concave with respect to (ϕ_{mnk}, S_{mnk}). We assume that R_{req} is achievable under the constraints of (19) that indicates the existence of interior points. Then Slater's condition is satisfied [26].

Hence, it can be shown that the strong duality holds and the optimization problem (19) has a zero duality. In other words, solving the dual problem is equivalent to solving the primal problem, and a globally optimal solution can be found in the Lagrange dual domain. As mentioned in Section 3.2, by relaxing the constraints and introducing a continuous $\phi_{mnk} \in [0, 1]$, solving the dual problem will always provide an upper bound for the original optimization problem.

Specifically, the optimal solution for the dual problem does not always result in a binary $\phi_{mnk} \in \{0, 1\}$ that is desired as a necessary constraint in the original optimization problem. However, we will prove that a globally optimal solution always exists for the dual problem with a binary $\phi_{mnk} \in \{0, 1\}$, making the solution obtained available and optimal for the optimization problem in (10).

4.3. Dual Problem Formulation and Decomposition Solution. The Lagrangian of (19) is given by

$$\begin{aligned}
L(\mathbf{\Phi}, \mathbf{S}, \lambda, \mu, q) &= \frac{1}{2} \\
&\cdot \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\omega_k\phi_{mnk}\log_2\left(1 + a_{mnk}\frac{S_{mnk}}{\phi_{mnk}}\right) - q\Bigg(P_C \\
&+ \varsigma\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{k=1}^{K}S_{mnk}\Bigg) - \lambda\left(\sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{k=1}^{K}S_{mnk} - P_t\right) \\
&- \mu\Bigg(R_{\text{req}} \\
&- \frac{1}{2}\sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\omega_k\phi_{mnk}\log_2\left(1 + a_{mnk}\frac{S_{mnk}}{\phi_{mnk}}\right)\Bigg).
\end{aligned} \tag{20}$$

Associated with the total power constraint, $\lambda \geq 0$ and $\mu \geq 0$ denote the Lagrangian multipliers. The dual function is therefore given by

$$\begin{aligned} \min \quad & g(\lambda,\mu) = \min \max_{\mathbf{\Phi},\mathbf{S}} L(\mathbf{\Phi},\mathbf{S},\lambda,\mu,q) \\ \text{s.t.} \quad & (3) \\ & 0 \leq \phi_{mnk} \leq 1, \\ & S_{mnk} \geq 0, \\ & \forall m,n,k. \end{aligned} \tag{21}$$

To deal with (21), we resolve the dual problem into three subproblems and solve it iteratively.

(1) Power Allocation. First, with a given value of λ and μ, we will have

$$\begin{aligned} g(\lambda,\mu) &= \max_{\mathbf{\Phi},\mathbf{S}} L(\mathbf{\Phi},\mathbf{S},\lambda,\mu,q) \\ &= \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\left(\frac{1+\mu}{2}\omega_k\phi_{mnk}\log_2\left(1+a_{mnk}\frac{S_{mnk}}{\phi_{mnk}}\right) - q\varsigma S_{mnk} - \lambda S_{mnk} - \mu R_{\text{req}}\right) + \lambda P_t - qP_C. \end{aligned} \tag{22}$$

We take the partial derivative of (22) with respect to S_{mnk} and then make the derivative equal to zero. According to the Karush-Kuhn-Tucker (KKT) conditions [26], the optimal S_{mnk} for a given value of λ and μ can be obtained in a water-filling form as

$$S^{*}_{mnk}(\lambda,\mu) = \left[\frac{\omega_k(1+\mu)}{2\ln 2(\lambda+q\varsigma)} - \frac{1}{a_{mnk}}\right]^{+}\phi_{mnk}, \tag{23}$$

where $[x]^{+} = \max(x,0)$. Equation (23) is a type of multiplanar water-filling solution [12].

For any path $P(m,n,k)$, we maximize the equivalent channel gain a_{mnk} according to the instantaneous channel information and the Fibonacci method to obtain the optimal τ^{*}_{mnk}. For a given value of τ^{*}_{mnk}, according to (23) and (12), the source transmission power for the first time slot P^{s1}_{mnk}, the source transmission power for the second time slot P^{s2}_{mnk}, and relay node transmission power P^{r}_{mnk} can be given by

$$\begin{aligned} P^{s1}_{mnk} &= \frac{a_{nk}(1-\tau^{*}_{mnk}) + b_{nk}\tau^{*}_{mnk}}{a_m + a_{nk} - c_{mk}} P_{mnk} \\ P^{s2}_{mnk} &= \frac{(a_{mk}-c_{mk})(1-\tau^{*}_{mnk}) - b_{nk}\tau^{*}_{mnk}}{a_m + a_{nk} - c_{mk}} P_{mnk} \\ P^{r}_{mnk} &= \tau^{*}_{mnk} P_{mnk}. \end{aligned} \tag{24}$$

(2) Channel-User Assignment. Substituting S_{mnk} in (23) into (22), $g(\lambda,\mu)$ can therefore be reformulated as

$$\begin{aligned} g(\lambda,\mu) &= \max_{\mathbf{\Phi},\mathbf{S}} L(\mathbf{\Phi},\mathbf{S},\lambda,\mu,q) \\ &= \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\phi_{mnk}A_{mnk}(\lambda,\mu) + \lambda P_{\max} - qP_C \\ &\quad - \mu R_{\text{req}}, \end{aligned} \tag{25}$$

where $A_{mnk}(\lambda,\mu)$ can be given by

$$\begin{aligned} A_{mnk}(\lambda,\mu) &= \frac{1}{2}\omega_k \log\left(1 + a_{mnk}\left[\frac{\omega_k(1+\mu)}{2\ln 2(\lambda+q\varsigma)} - \frac{1}{a_{mnk}}\right]^{+}\right) \\ &\quad - (\lambda+\varsigma q)\left[\frac{\omega_k(1+\mu)}{2\ln 2(\lambda+q\varsigma)} - \frac{1}{a_{mnk}}\right]^{+}. \end{aligned} \tag{26}$$

Then we have

$$\begin{aligned} \max_{\mathbf{\Phi}} \quad & \sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\phi_{mnk}A_{mnk}(\lambda,\mu) \\ \text{s.t.} \quad & (3) \\ & 0 \leq \phi_{mnk} \leq 1, \quad \forall m,n,k. \end{aligned} \tag{27}$$

To calculate $\mathbf{\Phi} = [\phi_{mnk}]_{N\times N\times K}$ which turn into solving $(\mathbf{X},\{\mathbf{y}^{\mathbf{mn}}\})$, the model of (27) can be given by

$$\max_{\mathbf{X},\{\mathbf{y}^{\mathbf{mn}}\}} \sum_{m=1}^{N}\sum_{n=1}^{N} x_{mn}\sum_{k=1}^{K} y^{mn}_{k} A_{mnk}(\lambda,\mu). \tag{28}$$

We solve x_{mn} and y^{mn}_k in (28) over two stages. Firstly, we maximize the inner-sum term over y^{mn}_k for each subcarrier pair (m,n); that is,

$$\begin{aligned} A'_{mn}(\lambda,\mu) = \max_{\{\mathbf{y}^{\mathbf{mn}}\}} \quad & \sum_{k=1}^{K} y^{mn}_{k} A_{mnk}(\lambda,\mu) \\ \text{s.t.} \quad & \sum_{k=1}^{K} y^{mn}_{k} = 1, \\ & 0 \leq y^{mn}_{k} \leq 1, \quad \forall k. \end{aligned} \tag{29}$$

The optimal y^{mn}_k in (29) is readily gained by

$$y^{mn*}_{k} = \begin{cases} 1, & \text{if } k = \arg\max\limits_{1\leq l\leq K} A_{mnl}(\lambda,\mu) \\ 0, & \text{otherwise.} \end{cases} \tag{30}$$

Secondly, taking $A'_{mn}(\lambda,\mu)$ into (28), we reduce (28) to the following linear optimization problem:

$$\begin{aligned}\max_{\mathbf{X}} \quad & \sum_{m=1}^{N}\sum_{n=1}^{N} x_{mn}A'_{mn}(\lambda,\mu) \\ \text{s.t.} \quad & \sum_{n=1}^{N} x_{mn} = 1, \quad \forall m, \\ & \sum_{m=1}^{N} x_{mn} = 1, \quad \forall n \\ & 0 \le x_{mn} \le 1, \quad \forall m,n.\end{aligned} \tag{31}$$

It is easy to know that a binary solution $\mathbf{X}^* \in \{0,1\}^{N\times N}$ to this problem (31) will always exist. Further, with the binary constraints on $\mathbf{X}$, this is depicted as a two-dimensional assignment problem, such as the Hungarian Algorithm [27].

Finally, the optimal ϕ^*_{mnk} in (25) is gained as the product of x^*_{mn} and y_k^{mn*}. Since both x^*_{mn} and y_k^{mn*} are binary, ϕ^*_{mnk} is binary.

(3) Subgradient Updating. The previous subsection proposes the method to get the Lagrange function $g(\lambda,\mu)$ with a given value of the Lagrange multipliers λ and μ. Since the dual function is differentiable, we use the subgradient method to update λ and μ. The subgradient-updated equations of λ and μ are

$$\begin{aligned}\lambda(n+1) &= \left[\lambda(n) - \alpha_\lambda(n)\left(P_t - \sum_{m=1}^{N}\sum_{n=1}^{N}\sum_{k=1}^{K} S_{mnk}\right)\right]^+ \\ \mu(n+1) &= \Bigg[\mu(n) - \alpha_\mu(n) \\ &\quad \cdot \left(\frac{1}{2}\sum_{k=1}^{K}\sum_{m=1}^{N}\sum_{n=1}^{N}\omega_k\phi_{mnk}\log_2\left(1 + a_{mnk}\frac{S_{mnk}}{\phi_{mnk}}\right) \right. \\ &\quad \left. - R_{\text{req}}\right)\Bigg]^+,\end{aligned} \tag{32}$$

where n, $\alpha_\lambda(n)$, and $\alpha_\mu(n)$ denote the iteration index and the positive diminishing the nth inner iteration step sizes of the dual variables, respectively. The subgradient method above is guaranteed to converge to the optimal dual variables if the step sizes are chosen following the diminishing step size policy [26].

5. Simulation Results and Analysis

We have obtained the optimal solution of joint source allocation scheme in the previous sections. In this section, we compare the performances of the proposed joint EE resource allocation scheme with the other resource allocation schemes.

The multiusers OFDM channel gains are modeled as complex Gaussian distributions with a zero mean and the variance is $c \cdot d_{i,j}^{-v}$, indicating that $h_{i,j} \sim CN(0, c\cdot d_{i,j}^{-v})$ [19].

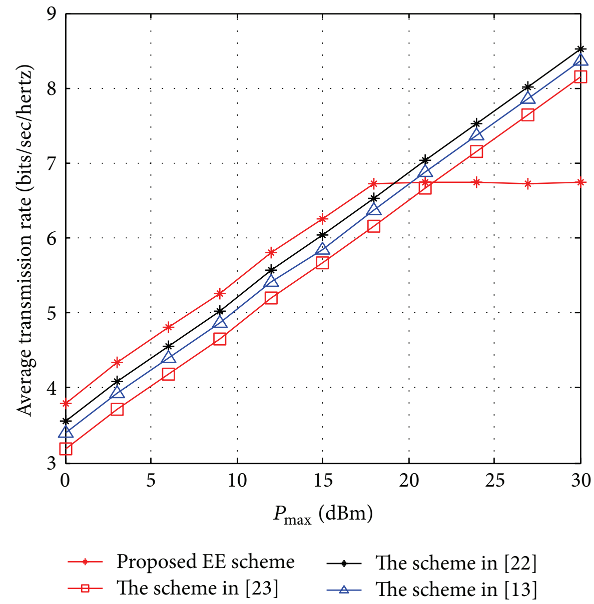

Figure 2: Average SE performance of different resource allocation schemes.

We assume that there is a circle which is centered in the relay node with a radius of 500 m. Users, as shown in Figure 1, are randomly distributed in the right half circle. Correspondingly, the source is randomly distributed in the left half circle. The number of users is set to $K = 4$ and the number of OFDM system subcarriers is set to $N = 16$. The fairness factors for every user are set to [0.15, 0.15, 0.35, 0.35]. The variances of the AWGNs are set to $\sigma_r^2 = \sigma_k^2 = N_0 = -131$ dBm and the power consumption of the constant circuit is set to $P_C = 30$ dbm.

5.1. Analysis of Average SE Performance. The average transmission rate of our proposed EE scheme is compared with the others schemes proposed in [13, 22, 23], as shown in Figure 2. The resource allocation schemes proposed in [13, 22, 23] are designed to maximize the total system SE. We can see from Figure 2 that the average SE performance of our proposed scheme monotonically increases when $P_{\max} \le 18$ dBm and then saturates when $P_{\max} > 18$ dBm. When $P_{\max} \le 18$ dBm, based on the analysis in previous section, the proposed algorithm by solving $F(0)$ is also aimed at maximizing the total system SE; hence the profile monotonically increases with respect to $P_{\max}$. However when $P_{\max} > 18$ dBm, the proposed algorithm stops consuming more power for transmitting the radio signals to maximize the system energy efficiency. In [13, 22, 23], the average SE of the other resource allocation schemes monotonically increases with respect to $P_{\max}$, as $F(0)$, by sacrificing the energy efficiency of the system. Moreover, as expected, our proposed scheme can provide a better SE performance compared to the other resource allocation schemes when $P_{\max} \le 18$ dBm; it can obtain a 3.0 dB, 2.0 dB, and 1.6 dB gain, approximately, compared with schemes proposed in [13], [23], and [22], respectively.

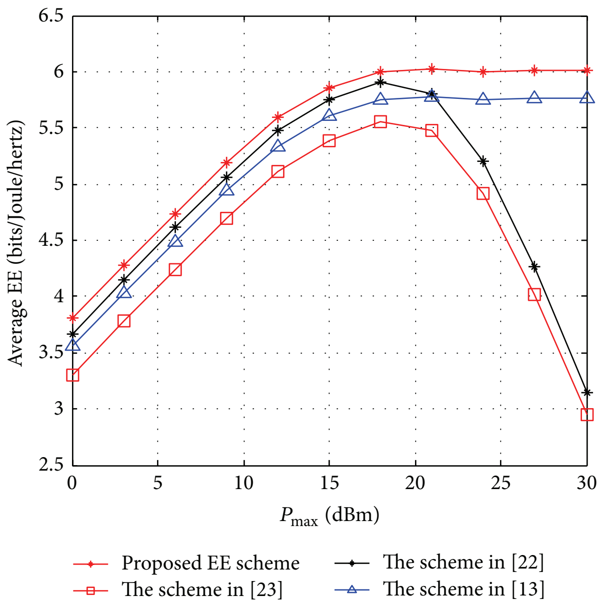

FIGURE 3: Average EE performance of different resource allocation schemes.

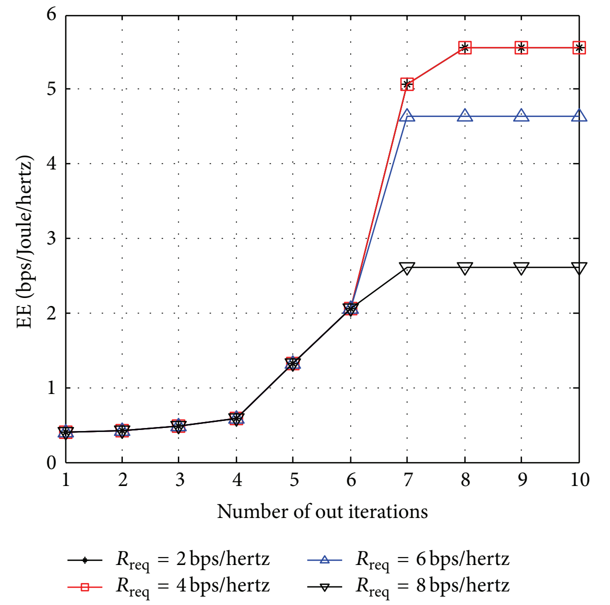

FIGURE 4: Convergence performance of the outer iteration algorithm for EE maximization.

In summary, [23] exploited an optimal subcarrier-user assignment with an equal power assignment policy and has the worst performance. Reference [13] jointly considers only the power allocation and the subcarrier pairing without considering the channel-user assignment; thus it has the second worst performance. Reference [22] considers the maximized SE problem of jointly optimizing the subcarrier pairing, the channel-user assignment, and the power allocation but the performance is still not as good as our scheme because we have adopted a new relaying strategy. In this paper, compared with traditional OFDM relaying networks [22], the source is permitted to retransfer the same data transmitted by it in the first time slot, further improving the system capacity performance.

5.2. Analysis of Average EE Performance. Figure 3 shows the comparison of our proposed resource allocation method and the other methods proposed in [13, 22, 23] in allusion to maximize the total average EE performance.

We can see from Figure 3 that schemes in [22, 23], aimed at maximizing the total system SE, monotonically increase when $P_{max} \leq 18$ dBm and monotonically decrease when $P_{max} > 18$ dBm. But the average EE performances of our method raised and [13] monotonically increase when $P_{max} \leq 18$ dBm and then saturate when $P_{max} > 18$ dBm. However, the average EE of our method raised remains constant while $P_{max} > 18$ dBm, after it attains an optimal EE of about 5.6 bit/J/Hz. This is because once the maximum EE of the system has been obtained, the source and relay will not take any energy to do useless transmission. It is also shown in Figures 2 and 3 that our proposed EE scheme provides both better EE and SE performances when $P_{max} \leq 18$ dBm, caused by the joint channel-user assignment and the new relaying strategy. Reference [13] also considers a joint channel-user

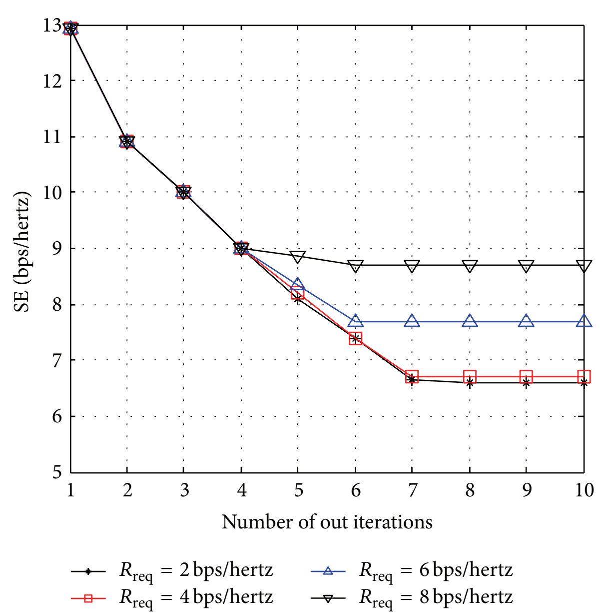

FIGURE 5: Convergence performance of SE under minimum QoS constrain.

assignment but continues to have lower EE performance than our scheme since we adopt a new relaying strategy.

5.3. Convergence of Iterative Algorithm. Figures 4 and 5 illustrate the evolution of the average system energy efficiency of the proposed iterative algorithm for different minimum system service rate requirements, based on the fractional programming method in [25].

Figures 4 and 5 display the convergence performances of the total EE and the total SE under different QoS constraints, respectively. As shown in Figure 5, EE q monotonically increases with the number of outer iterations and then saturates when the number of iterations exceeds eight. On the basis of the analysis in Section 3.2, q will achieve an optimal q^* when the outer cycle is convergent. Particularly in this paper, by setting $R_{\text{req}} = 0$, indicating that there is no QoS constraint, we will obtain the optimal $q^*_{R\text{req}=0} = 5.6\,\text{bit/s/Hz}$ and the corresponding SE will be $R_{R\text{req}=0} = 6.3\,\text{bit/s/Hz}$. According to the above-mentioned analysis, we can conclude that our resource allocation method raised could obtain an optimal EE performance under different QoS constraints with a good global astringency and a rapid convergence ability.

6. Conclusions

This paper discuss energy efficiency problem for multiple users OFDM relaying scenario. We investigate a joint resource allocation scheme including the power allocation, the subcarrier pairing, and the channel assignment to the user. We maximize the overall system EE guaranteeing the constraints of total power and a minimum SE. The optimization model is simplified into a typical fractional programming problem which is testified to be quasiconcave. Thus we can adopt Dinkelbach method to deal with MINLP problem proposed to achieve the optimal solution. The simulation results show that the joint resource allocation method proposed can achieve an optimal EE performance under the minimum system service rate requirement with a good global convergence.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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