A Joint Resource Allocation Scheme for Relay Enhanced Multi-cell Orthogonal Frequency Division Multiple Networks

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Abstract

This paper formulates resource allocation for decode-and-forward (DF) relay assisted multi-cell orthogonal frequency division multiple (OFDM) networks as an optimization problem taking into account of inter-cell interference and users fairness. To maximize the transmit rate of system we propose a joint interference coordination, subcarrier and power allocation algorithm. To reduce the complexity, this semi-distributed algorithm divides the primal optimization into three sub-optimization problems, which transforms the mixed binary nonlinear programming problem (BNLP) into standard convex optimization problems. The first layer optimization problem is used to get the optimal subcarrier distribution index. The second is to solve the problem that how to allocate power optimally in a certain subcarrier distribution order. Based on the concept of equivalent channel gain (ECG) we transform the max-min function into standard closed expression. Subsequently, with the aid of dual decomposition, water-filling theorem and iterative power allocation algorithm the optimal solution of the original problem can be got with acceptable complexity. The third sub-problem considers dynamic co-channel interference caused by adjacent cells and redistributes resources to achieve the goal of maximizing system throughput. Finally, simulation results are provided to corroborate the proposed algorithm.

Keywords: OFDM, DF relaying, inter-cell interference, multi-cell joint optimization, Equivalent channel gain

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1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a mature technique to mitigate frequency selective fading and inter-symbol interference by dividing the total bandwidth into several orthogonal subcarriers. The fading of each subcarrier can be seen as flat fading which can provide higher spectrum utilization. Cooperative relaying has been regarded as a promising candidate for next generation broadband wireless communication systems, and has been considered by the IEEE 802.16j standard [1] because it can provide an efficient way to overcome the disadvantages brought by wireless fading channel through exploiting multiuser diversity (MUD). According to the difference of the received signal, two main relay strategies have been identified: amplify-and-forward (AF) and decode-and-forward (DF) [1, 2]. A large number of works has been devoted to the resource allocation of OFDM and cooperative relaying systems [3-5]. However, the future wireless communication network needs to provide higher transmission rate and broader coverage that a single technology cannot satisfy these requirements. Thus, there emerges combination of OFDM and relay technology which can provide better customer service experiences, assure fairness of inside and the edge users in multi-cell mobile communication networks. However, the resource allocation for it is more challenging because three issues should be taken into account [6], they are, how to allocate power at source and relay nodes to the subcarriers, how to match subcarriers of first-hop and the second-hop, and which pair of subcarrier should be allocated to which user.

Although there is a rich literature consider the resource allocation for relay-enhanced OFDM networks, most of them focus on the single-cell scenario [6-10], in which inter-cell interference (ICI) is ignored. However, in reality ICI severely degrades system performance. Hence, for practical systems it should be considered in the resource allocation process. Undoubtedly, interference coordination and interference elimination will be a new trend in future communication networks since it can help to achieve a higher system capacity. In [11-15] multi-cell resource allocation scheduling are studied under different system configuration. However, [11, 13] have not consider the fairness of heterogeneous users. The authors of [12] use intermediate variable （interference constraint） to transform the max-min DF problem into standard closed expression which can only get a lower bound for the original problem instead of optimal solution. Reference [14] gives a two-stage resource allocation scheme: in the first stage, all of the users in each cell are selected sequentially and the joint subcarrier allocation and scheduling is conducted for the selected users, in the second stage, the optimal power control is performed by geometric programming method. However, [14, 15] only allow each user connect with one fixed relay, such kind of distribution method cannot make full use of space diversity, which will greatly reduce the flexibility of carrier allocation. In addition, the majority methods of the above researches are centralized or half-centralized solutions. Therefore, frequent and complex signaling interaction is indispensable among base stations of different cells which are difficult to apply in real large-scale wireless communication systems.

Also, there are some recent works on the space-time coding design in cooperative decode-and-forward relay systems [17] for the combination of space-time coding with cooperative relay can further improve the wireless transmission performance. The author of [17] proposed two O-DSTC (opportunistic distributed space-time coding) schemes for full-duplex and half-duplex relaying scenarios which provided a new direction for the application of cooperative relay. In addition, the research of relaying selection [18] can also be used in resource allocation of relay-enhanced OFDM systems.

To maximize system capacity, we propose a low complexity distributed algorithm which considers not only inter-cell interference but also heterogeneous users' fairness of DF relay enhanced OFDM systems in this paper. We deduce the optimization model under the power constraints of source and relay nodes and formulate resource allocation as a joint interference coordination, subcarrier and power distribution problem. Through dividing the original optimization into three sub-optimization problems, we transform the primal BNLP into convex optimization problem thus the optimal solutions of the objective function can get by using dual decomposition approach, water-filling theorem and iterative power allocation algorithm. Finally, the performance of our proposals is evaluated by extensive simulations.

The remainder of this paper is organized as follows. DF relay based multi-cell OFDM system model and problem formulation are introduced in Section 2. Section 3 introduces our proposed resource allocation algorithm. Performance results and analysis are presented in section 4. In the last section we give a brief summary of this paper.

2. System Model and Problem Formulation

2.1 System Model

Consider the downlink transmission of a relay-aided multi-cell OFDM system that consists of L cells. Each cell has one base station (BS) locates at the center of the hexagon area, K users, and M relay stations (RS) uniformly distribute on the circle around the BS. We assume universal frequency reuse which means that the L base stations share the total bandwidth. The intra-cell interference does not considered in this paper. Each subcarrier can be used by one user or relay at any time**.** All nodes hold only one antenna and can't transmit and receive simultaneously. And we assume that there is no direct transmission from source to relay, the destination can receive signals only from the relay because of high shadowing between source and destination. The TDD transmission protocol is adopted that the communication between source and destination covers two time slots. The source transmits an OFDM symbol through the source to relay channel (first-hop) during the first time slot. During the second time slot, the relay decodes and re-encodes the previously received signal, and retransmit it toward the corresponding destination over the relay-destination channel (second-hop). The destination decodes the signal based on the received signal from the relay. It is assumed that the base station knows all of the channel state information (CSI) at the transmitter in each cell. The relay enhanced multi-cell OFDM system model as is shown in **Fig. 1**.

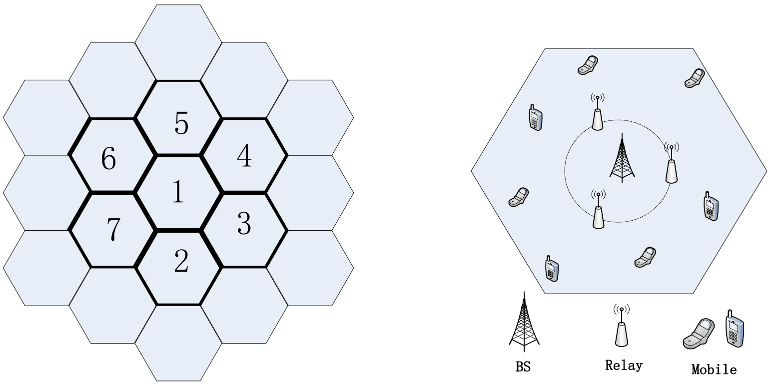

Fig. 1. Relay-enhanced multi-cell OFDM networks

This paper uses two different time slot allocation strategies to minimize the inter-cell interference. For example, if cell 1 uses time slot allocation strategy 1 for subcarrier n, the base station of cell 1 communicates with relay stations during the first time slot through subcarrier n and relay stations decodes and re-encodes the previously received signal, and retransmits it toward the corresponding user in the second phase; Meanwhile, the adjacent cell 2 may use the strategy 2 for subcarrier n, that is the base station communicate with relay stations in the second time slot and relay stations communicate with users during the next first time slot. Therefore, if one cell uses the strategy 1 for a subcarrier the adjacent cell may uses the strategy 2 for this subcarrier, and vice versa. **Table 1** is the time slot allocation scheme on subcarrier n of different cells in this paper.

Table 1. Time slot strategies of different cells

Slot Cell No.	Slot1	Slot2	Slot1	Slot2	Slot1	Slot2	Slot1	……
Cell 1, subcarrier n （strategy 1）	Bs-RS	Rs-Ms	Bs-RS	Rs-Ms	Bs-RS	Rs-Ms	Bs-RS	……
Cell 2, subcarrier n （strategy 2）		Bs-RS	Rs-Ms	Bs-RS	Rs-Ms	Bs-RS	Rs-Ms	……
Cell 3, subcarrier n （strategy 1）	Bs-RS	Rs-Ms	Bs-RS	Rs-Ms	Bs-RS	Rs-Ms	Bs-RS	……
Cell 4, subcarrier n （strategy 2）		Bs-RS	Rs-Ms	Bs-RS	Rs-Ms	Bs-RS	Rs-Ms	……
……	……	……	……	……	……	……	……	……
Cell$L$, subcarrier n （strategy 1）	Bs-RS	Rs-Ms	Bs-RS	Rs-Ms	Bs-RS	Rs-Ms	Bs-RS	……

2.2 Problem Formulation

For each cell l (suppose that l is an odd number), considering the downlink of OFDM system with N subcarriers. We assume the signal of user k transmitted on the n-th first-hop subcarrier is decoded and re-encoded by relay m and finally retransmitted on the n-th second-hop subcarrier. To express conveniently here we do not consider subcarrier pairing of two hops for the moment. The subcarrier matching strategy will be presented more detail in section 3.1. Thus the first-hop capacity and the second-hop capacity of subcarrier n, $R_{l,m}^{s}(n)$and $R_{l,m,k}^{r}(n)$can be expressed as

$$R_{l,m}^{s}(n) = log_2\left(1 + \frac{p_{l,m}^{s}(n)\left|H_{l,m}^{s}(n)\right|^2}{N_0 + I_{l,m}^{s}}\right) \tag{1}$$

$$R_{l,m,k}^{r}(n) = log_2\left(1 + \frac{p_{l,m,k}^{r}(n)\left|H_{l,m,k}^{r}(n)\right|^2}{N_0 + I_{l,m,k}^{r}}\right) \tag{2}$$

where

$$\begin{cases} I_{l,m}^{s} = I_{l,m}^{s,1} + I_{l,m}^{r,2} \\ I_{l,m}^{s,1} = \sum\limits_{l' \in \Omega_1} p_{l',m}^{s,1}(n)\left|H_{l',m}^{s,1}(n)\right|^2 \\ I_{l,m}^{r,2} = \sum\limits_{l' \in \Omega_2}\sum\limits_{m} p_{l',m}^{r,2}(n)\left|H_{l',m}^{r,2}(n)\right|^2 \end{cases} \tag{3}$$

The Additive White Gaussian Noise (AWGN) variance is denoted by N_0. $p_{l,m}^{s}(n)$ is the transmit power for subcarrier n during the source to relay channel that allocated by BS l; $p_{l,m,k}^{r}(n)$ is the transmit power of subcarrier n during the relay to destination channel; Ω_1 represents the set of adjacent cells which use the same time slot allocation strategy as l and Ω_2 the set of adjacent cells which use different time slot allocation strategy; $I_{l,m}^{s,1}$ and $I_{l,m}^{r,2}$ are the total interference that caused by the BSs of Ω_1 and relays of Ω_2 respectively. And $p_{l',m}^{s,1}(n)$ is the transmit power for subcarrier n during the first-hop that distributed by base station l', $p_{l',m}^{r,2}(n)$ indicates the transmit power of subcarrier n during second-hop; $\left|H_{l',m}^{s,1}(n)\right|^2$ and $\left|H_{l',m}^{r,2}(n)\right|^2$ are the channel gains of the two phases severally.

Using the similar analysis approach we can get the expression of $I_{l,m,k}^{r}$

$$\begin{cases} I^{r}_{l,m,k} = I^{r,1}_{l,m,k} + I^{s,2}_{l,m,k} \\ I^{r,1}_{l,m,k} = \sum_{l' \in \Omega_1} \sum_{m} p^{r,2}_{l',m}(n) \left| H^{r,2}_{l',m}(n) \right|^2 \\ I^{s,2}_{l,m} = \sum_{l' \in \Omega_2} p^{s,2}_{l',m}(n) \left| H^{s,2}_{l',m}(n) \right|^2 \end{cases} \tag{4}$$

where Ω_1 represents the set of adjacent cells that use the same time slot allocation strategy as l and Ω_2 the set of adjacent cells which use different time slot allocation strategy; $I^{r,1}_{l,m,k}$and$I^{s,2}_{l,m,k}$ are the total interference caused by the RSs of Ω_1 and BSs of Ω_2; $p^{r,2}_{l',m}(n)$ is the transmit power allocated by relay m in cell l' for n-th subcarrier of second-hop and $p^{s,2}_{l',m}(n)$ denotes the power allocated by BS l' for the n-th first-hop subcarrier. $\left| H^{r,2}_{l',m}(n) \right|^2$ and $\left| H^{s,2}_{l',m}(n) \right|^2$ are the channel gains of the two hops respectively.

We use DF relay in this paper and with the above definition, the achievable capacity of the n-th sub-channel $C_{l,m,k}(n)$ is

$$C_{l,m,k}(n) = \frac{1}{2} min\{R^{s}_{l,m}(n), R^{r}_{l,m,k}(n)\} \tag{5}$$

The 1/2 factor appears in (5) due to the two hops used for a complete transmission. Therefore, the joint interference coordination, subcarriers and power allocation algorithm with relay and BS power constraints can be formulated as follows

$$\max_{P_s, P_r, \rho} \sum_{l=1}^{L} \sum_{m=1}^{M} \sum_{k=1}^{K} \sum_{n=1}^{N} w_{l,k} \cdot \rho_{l,m,k}(n) \cdot C_{l,m,k}(n) \tag{6}$$

Subject to:

$$\begin{aligned} & C_1: \sum_{m=1}^{M} \sum_{k=1}^{K} \sum_{n=1}^{N} \rho_{l,m,k}(n) \cdot p^{s}_{l,m}(n) \le p_s \\ & C_2: \sum_{k=1}^{K} \sum_{n=1}^{N} \rho_{l,m,k}(n) \cdot p^{r}_{l,m,k}(n) \le p_r \\ & C_3: \sum_{m=1}^{M} \sum_{k=1}^{K} \rho_{l,m,k}(n) = 1 \ \forall \ n = 1,2,\cdots,N \\ & C_4: \sum_{k=1}^{K} \rho_{l,m,k}(n') = 1 \ \forall \ n' = 1,2,\cdots,N \end{aligned} \tag{7}$$

$$C_5: p^s_{l,m}(n) \geq 0 \ \forall \ l = 1,2,\cdots,L; \ n = 1,2,\cdots,N; m = 1,2,\cdots,M$$
$$C_6: p^r_{l,m,k}(n) \geq 0 \ \forall \ l,n,m,k$$
$$C_7: \rho_{l,m,k}(n) \in \{0,1\} \ \forall \ n = 1,2,\cdots,N$$

where $w_{l,k}$ is the priority value of user k in cell l; $\mathrm{p_s}$ and p_r are the transmit power constraints of BS and relay nodes respectively. $\rho_{l,m,k}(n)$ is the subcarrier allocation index which can be 0 or 1, $\rho_{l,m,k}(n) = 1$ means that the signal of user k transmitted on the n-th first-hop subcarrier is decoded and re-encoded by relay m and finally retransmitted on the n-th second-hop subcarrier. Constraints C_1 (C_2) indicates the individual power constraint for each BS (relay) with maximum transmit power p_s (p_r). C_3 and C_4 are imposed to guarantee each subcarrier can only be used by one relay or user for any time. C_5 and C_6 are the positive power constraints.

3. The Proposed Resource Allocation Algorithm

The optimization problem in (6) is a mixed binary nonlinear programming problem, which is generally hard to solve. In this section, we divide the original problem into three sub-problems thus transform (6) into convex optimization problem based on the concepts of semi-distributed resource allocation method. This method optimizes resource allocation of single-cell firstly then coordinate inter-cell interference to achieve higher system capacity.

The first layer optimization problem is used to seek optimal subcarrier distribution index, and can be expressed as

$$\mathbb{Q}\left(\rho_{l,m,k}(n)\right) = \left\{\max_{P_s,P_r} \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N} w_{l,k}\cdot C_{l,m,k}(n) \middle| p^r_{l,m,k}(n), p^s_{l,m}(n), I^s_{l,m}, I^r_{l,m,k}\right\} \quad (8)$$

The second is to solve the problem—how to optimization power allocation in a certain subcarriers distribution order and can be formulated as

$$\mathbb{Q}\left(p^r_{l,m,k}(n), p^s_{l,m}(n)\right) = \left\{\max_{\rho} \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N} w_{l,k}\cdot C_{l,m,k}(n) \middle| \rho_{l,m,k}(n), I^s_{l,m}, I^r_{l,m,k}\right\} \quad (9)$$

The last sub-problem takes into account of the dynamic inter-cell interference caused by adjacent cells and redistributes resources to further improve system performance which can be expressed as

$$\mathbb{Q}\left(p^r_{l,m,k}(n), p^s_{l,m}(n), \rho_{l,m,k}(n), I^s_{l,m}, I^r_{l,m,k}\right) = \left\{\max_{P_s,P_r,\rho} \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N} w_{l,k}\cdot C_{l,m,k}(n)\right\} \quad (10)$$

3.1 Subcarrier Allocation and Matching

The first layer optimization problem can be reformulated as

$$\mathbb{Q}(\rho_{l,m,k}(n)) = \left\{ \max_{P_s,P_r} \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N} w_{l,k}\cdot C_{l,m,k}(n) \,\middle|\, p^{r}_{l,m,k}(n), p^{s}_{l,m}(n), I^{s}_{l,m}, I^{r}_{l,m,k} \right\}$$

Subject to：

$$C_1\colon \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N} p^{s}_{l,m}(n) \le p_s$$

$$C_2\colon \sum_{k=1}^{K}\sum_{n=1}^{N} p^{r}_{l,m,k}(n) \le p_r$$

$$C_3, C_4, C_5, C_6, C_7$$

For given $p^{s}_{l,m}(n)$ and $p^{r}_{l,m,k}(n)$ values the transmit rate $C_{l,m,k}(n)$ is constant and independent of $\rho_{l,m,k}(n)$. Additionally, each subcarrier has the same constraints C_3 and C_4. Thus, problem (8) can be divided into per-subcarrier problem in each cell as

$$\mathbb{T}_l(\rho) = \max \sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N} w_{l,k}\cdot C_{l,m,k}(n) \quad l = 1,2,\cdots,L$$

Obviously

$$(m,k,n) = ar\widehat{gmax}\; C_{l,m,k}(n)\,, l = 1,2,\cdots,L \tag{11}$$

That is, each subcarrier should be allocated to the relay or user that can maximize its instantaneous transmit rate and this theory is the same as the single-hop systems.

In the previous sections, we have assumed the symbols that the BS transmitted over the n-th first-hop subcarrier are encoded by the relay and retransmitted over the n-th subcarrier of the second-hop to destination without considering subcarrier matching. A higher performance will be achieved if the subcarriers of the two hops are matched according to their actual strength—the source to relay channel with the highest channel gain is matched with the relay to destination channel with the highest channel gain [1].

3.2 Power Allocation

After subcarrier allocation, each sub-channel is associated with a specific destination through a certain relay. We use the subcarrier pairing method mentioned in section 3.1 to further increase the system throughput. This subsection focuses on power distribution of sub-channels at BS and relay nodes separately. Due to the interference item contains power variables, we suppose that power variables in the interference are static values. Accurately, resource allocation optimization problem in a single-cell scenario need not consider the adjacent interference. Therefore, basing on the above hypothesis the non-convex problem can be thought as standard convex problem that can be solved by using optimization theory. We use equivalent channel gain (ECG) transform the max-min problem into closed expression. Meanwhile, to reduce the complexity without sacrificing performance we use power constraints instead of binary subcarrier distribution index constraints that can make the power allocation process easily to operate.

By using the Lagrange decomposition method we can get the Lagrangian function of the primal optimization problem (6). After rearranging the same terms, the Lagrangian is given by

$$\begin{aligned}
&\boldsymbol{\mathcal{L}}\left(\boldsymbol{P_s},\boldsymbol{P_r},\rho,\boldsymbol{\lambda},\boldsymbol{\mu},\boldsymbol{\delta},\boldsymbol{\eta}\right)\\
&=\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{l,m,k}(n)\left\{w_{l,k}C_{l,m,k}(n)-\lambda_l p_{l,m}^{s}(n)-\mu_{l,m}p_{l,m,k}^{r}(n)\right\}\\
&+\sum_{l=1}^{L}\lambda_l p_s+\sum_{l=1}^{L}\sum_{m=1}^{M}\mu_{l,m}-\sum_{l=1}^{L}\delta_l\sum_{m=1}^{M}\sum_{k=1}^{K}\left[\left(\rho_{l,m,k}(n)-1\right)\right]\\
&-\sum_{l=1}^{L}\sum_{m=1}^{M}\eta_{l,m}\sum_{k=1}^{K}\left[\left(\rho_{l,m,k}(n)-1\right]\right.
\end{aligned}\tag{12}$$

where $\boldsymbol{P_s},\boldsymbol{P_r}$corresponding to the allocated power vector of first-hop and second-hop. $\boldsymbol{\lambda}$ is the Lagrange multiple vector associated with the individual BS power constraints. $\boldsymbol{\mu}$ is the Lagrange multiple vector corresponding to the relay power constraints. Lagrange multiple vector $\boldsymbol{\delta}$ and $\boldsymbol{\eta}$ are connected with the subcarrier usage constraints C_3 and C_4.

Lemma 1: Through power transformation the Lagrangian $\boldsymbol{\mathcal{L}}\left(\boldsymbol{P_s},\boldsymbol{P_r},\rho,\boldsymbol{\lambda},\boldsymbol{\mu},\boldsymbol{\delta},\boldsymbol{\eta}\right)$can be equivalent to $\mathbb{L}\left(\boldsymbol{P_s},\boldsymbol{P_r},\boldsymbol{\rho},\boldsymbol{\lambda},\boldsymbol{\mu}\right)$, which can be formulated as

$$\begin{aligned}
&\mathbb{L}\left(\boldsymbol{P_s},\boldsymbol{P_r},\boldsymbol{\rho},\boldsymbol{\lambda},\boldsymbol{\mu}\right)\\
&=\sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{l,m,k}(n)\left\{w_{l,k}C_{l,m,k}(n)-\lambda_l p_{l,m}^{s}(n)-\mu_{l,m}p_{l,m,k}^{r}(n)\right\}\\
&+\sum_{l=1}^{L}\lambda_l p_s+\sum_{l=1}^{L}\sum_{m=1}^{M}\mu_{l,m}
\end{aligned}\tag{13}$$

Proof: The re-arranged Lagrangian function (13) does not consider the constraints $C_3{\sim}C_6$. However, through the processing (14) (15) for power transformation, (13) can achieve the same solution of the objective function as (12).

$$\begin{cases}p_{l,m}^{s}(n)=p_{l,m}^{s*}(n) & \rho_{l,m,k}(n)=1\\ p_{l,m'}^{s}(n)=0\ \ \forall m'\neq m\,;l=1,2,\cdots,L\end{cases}\tag{14}$$

$$\begin{cases}p_{l,m,k}^{r}(n)=p_{l,m,k}^{r*}(n) & \rho_{l,m,k}(n)=1\\ p_{l,m,k'}^{r}(n)=0\ \ \forall k'\neq k;\ l=1,2,\cdots,L\end{cases}\tag{15}$$

where $p_{l,m}^{s*}(n)$, $p_{l,m,k}^{r*}(n)$ denotes the optimal power allocation for n-th sub-channel pair. The superscripts and subscripts have the same definition as previous sections. Obviously this approach in the process of achieving optimal solution of power allocation is suitable.

The dual problem is：

$$\mathcal{D}(\boldsymbol{\lambda}, \boldsymbol{\mu}) = \min_{\lambda \geq 0, \mu \geq 0} \left\{ \max_{\boldsymbol{P_s}, \boldsymbol{P_r}, \boldsymbol{\rho}} \mathbb{L}\left(\boldsymbol{P_s}, \boldsymbol{P_r}, \boldsymbol{\rho}, \boldsymbol{\lambda}, \boldsymbol{\mu}\right) \right\}$$

where

$$\max_{\boldsymbol{P_s}, \boldsymbol{P_r}, \boldsymbol{\rho}} \mathbb{L}\left(\boldsymbol{P_s}, \boldsymbol{P_r}, \boldsymbol{\rho}, \boldsymbol{\lambda}, \boldsymbol{\mu}\right)$$

$$= \max_{\boldsymbol{P_s}, \boldsymbol{P_r}, \boldsymbol{\rho}} \sum_{l=1}^{L} \rho_{l,m,k}(n) \sum_{m=1}^{M} \sum_{k=1}^{K} \sum_{n=1}^{N} \{ w_{l,k} C_{l,m,k}(n) - \lambda_l p_{l,m}^{s}(n)$$

$$- \mu_{l,m} p_{l,m,k}^{r}(n) \} + \sum_{l=1}^{L} \lambda_l p_s + \sum_{l=1}^{L} \sum_{m=1}^{M} \mu_{l,m} \tag{16}$$

It is obvious that the innermost maximization in (16) can be regarded as optimization problem in single-cell scenario. Therefore, the assumption about interference we do at the beginning of this section is reasonable. In addition, the power optimization of single-cell can be divided into N independent per-subcarrier problems. By using the concept of equivalent channel gain we can get a simple closed-form expression for the optimal power values.

Lemma 2： To assist mathematical discussion, we let $\widehat{H_{l,m,k}}(n)$ denote the equivalent channel gain of subcarrier pair n that can be expressed as

$$\widehat{H_{l,m,k}}(n) = \frac{\left|H_{l,m}^{s}(n)\right|^2 \left|H_{l,m,k}^{r}(n)\right|^2}{\left|H_{l,m}^{s}(n)\right|^2 \left(N_0 + I_{l,m,k}^{r}\right) + \left|H_{l,m,k}^{r}(n)\right|^2 \left(N_0 + I_{l,m}^{s}\right)} \tag{17}$$

Proof：

For DF relay it is obvious that only when both capacities are equated can the end-to-end capacity be maximized which means

$$\begin{cases} \dfrac{p_{l,m}^{s}(n)\left|H_{l,m}^{s}(n)\right|^2}{N_0 + I_{l,m}^{s}} = \dfrac{p_{l,m,k}^{r}(n)\left|H_{l,m,k}^{r}(n)\right|^2}{N_0 + I_{l,m,k}^{r}} \\ \dfrac{p_{l,m}^{s}(n)\left|H_{l,m}^{s}(n)\right|^2}{N_0 + I_{l,m}^{s}} = p(n)\widehat{H_{l,m,k}}(n) \end{cases} \tag{18}$$

where $p(n)$ is the equivalent power of subcarrier pair n, we assume that $p(n) = p_{l,m}^{s}(n) + p_{l,m,k}^{r}(n)$, (18) can be re-expressed as

$$\frac{p_{l,m}^{s}(n)\left|H_{l,m}^{s}(n)\right|^2}{N_0 + I_{l,m}^{s}} = \frac{\left[p(n) - p_{l,m}^{s}(n)\right]\left|H_{l,m,k}^{r}(n)\right|^2}{N_0 + I_{l,m,k}^{r}} \tag{19}$$

Thus we can get $p_{l,m}^{s}(n) = p(n)\frac{\left|H_{l,m,k}^{r}(n)\right|^2 (N_0 + I_{l,m}^{s})}{\left|H_{l,m}^{s}(n)\right|^2 (N_0 + I_{l,m,k}^{r}) + \left|H_{l,m,k}^{r}(n)\right|^2 (N_0 + I_{l,m}^{s})}$, substituting this into (18) the corresponding ECG $\widehat{H_{l,m,k}}(n)$ is given by

$$\widehat{H_{l,m,k}}(n)=\frac{\left|H_{l,m}^{s}(n)\right|^{2}\left|H_{l,m,k}^{r}(n)\right|^{2}}{\left|H_{l,m}^{s}(n)\right|^{2}\left(N_0+I_{l,m,k}^{r}\right)+\left|H_{l,m,k}^{r}(n)\right|^{2}\left(N_0+I_{l,m}^{s}\right)}$$

The achievable capacity on the n-th subcarrier pair (5) can be formulated as a simple close-form expression

$$C_{l,m,k}(n)=\frac{1}{2}log_2\left\{1+\left[p_{l,m}^{s}(n)+p_{l,m,k}^{r}(n)\right]\cdot\frac{\left|H_{l,m}^{s}(n)\right|^{2}\left|H_{l,m,k}^{r}(n)\right|^{2}}{\left|H_{l,m}^{s}(n)\right|^{2}\left(N_0+I_{l,m,k}^{r}\right)+\left|H_{l,m,k}^{r}(n)\right|^{2}\left(N_0+I_{l,m}^{s}\right)}\right\} \tag{20}$$

Substituting the capacity expression (20) to (13), the considered problem becomes a convex optimization problem. The derivative of (13) with respect to $p_{l,m}^{s}(n)$ is given by

$$\frac{\partial\mathbb{L}\left(\boldsymbol{P_s},\boldsymbol{P_r},\boldsymbol{\rho},\boldsymbol{\lambda},\boldsymbol{\mu}\right)}{\partial p_{l,m}^{s}(n)}=\frac{w_{l,k}}{2\lambda_l ln2}-\frac{1}{\widehat{H_{l,m,k}}(n)}-p_{l,m,k}^{r}(n) \tag{21}$$

If $p_{l,m}^{s}(n)=p_{l,m}^{s*}(n)$, then $\left.\frac{\partial\mathbb{L}\left(\boldsymbol{P_s},\boldsymbol{P_r},\boldsymbol{\rho},\boldsymbol{\lambda},\boldsymbol{\mu}\right)}{\partial p_{l,m}^{s}(n)}\right|_{p_{l,m}^{s}(n)=p_{l,m}^{s*}(n)}$ =0, where $p_{l,m}^{s*}(n)$ is the optimal solution which is given by

$$p_{l,m}^{s*}(n)=\left[\frac{w_{l,k}\left|H_{l,m,k}^{r}(n)\right|^{2}\left(N_0+I_{l,m}^{s}\right)}{2\lambda_l ln2\left[\left|H_{l,m}^{s}(n)\right|^{2}\left(N_0+I_{l,m,k}^{r}\right)+\left|H_{l,m,k}^{r}(n)\right|^{2}\left(N_0+I_{l,m}^{s}\right)\right]}-\frac{N_0+I_{l,m}^{s}}{\left|H_{l,m}^{s}(n)\right|^{2}}\right]^{+} \tag{22}$$

Using a similar approach we can get the optimal $p_{l,m,k}^{r*}(n)$ that should satisfy

$$p_{l,m,k}^{r*}(n)=\left[\frac{w_{l,k}\left|H_{l,m}^{s}(n)\right|^{2}\left(N_0+I_{l,m,k}^{r}\right)}{2\mu_{l,m} ln2\left[\left|H_{l,m}^{s}(n)\right|^{2}\left(N_0+I_{l,m,k}^{r}\right)+\left|H_{l,m,k}^{r}(n)\right|^{2}\left(N_0+I_{l,m}^{s}\right)\right]}-\frac{N_0+I_{l,m,k}^{r}}{\left|H_{l,m,k}^{r}(n)\right|^{2}}\right]^{+} \tag{23}$$

The power allocation (22), (23) can be regarded as a multi-level water-filling scheme as the water levels of different users can be different. And the water levels of (22) (23) are determined by $w_{l,k},\lambda_l$ and $w_{l,k},\mu_{l,m}$ respectively.

After the optimal transmit power value is derived, the problem (6) is a function of $\boldsymbol{\lambda},\boldsymbol{\mu}$. Parameters $\boldsymbol{\lambda}$ and $\boldsymbol{\mu}$ can be obtained by sub-gradient method iteratively.

$$\Delta\lambda=p_s-\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N}\rho_{l,m,k}(n)\cdot p_{l,m}^{s}(n) \tag{24}$$

$$\Delta\mu_{l,m} = p_r - \sum_{k=1}^{K}\sum_{n=1}^{N} \rho_{l,m,k}(n) \cdot p_{l,m,k}^{r}(n) \tag{25}$$

$$\lambda(t+1) = [\lambda(t) - \Theta(t)\,\Delta\lambda]^{+} \tag{26}$$

$$\mu_{l,m}(t+1) = \left[\mu_{l,m}(t) - \theta(t)\,\Delta\mu_{l,m}\right]^{+} \tag{27}$$

where t is the iterative times, $\theta(t)$ and $\Theta(t)$ represent the step size which are equal to a small positive real number or update as $\theta(t) = \frac{\alpha}{t}$, $\Theta(t) = \frac{\beta}{t}$ [7] where α, β are constants. $\Delta\lambda$ and $\Delta\mu_{l,m}$ are gradients stated in (26) and (27).

The first and second layer sub-problems can be interpreted as the optimal resource allocation of single-cell scenario. The optimal resource allocation processing is summarized as follows.

```
Algorithm I: Optimal resource allocation
$\mathbb{s}_1$. Initialize $p_{l,m}^{s}(n) = p_s/N, p_{l,m,k}^{r}(n) = p_r/N$ , $\rho_{l,m,k}(n) = 0\ \forall l,m,n,k$
●Find the optimal $\rho_{l,m,k}(n)$
  For $l = 1: L$
    For $n = 1: N$
    $(m,k,n) = \widehat{argmax}\ C_{l,m,k}(n)$
    End
  End
$\mathbb{s}_2$. Initialize loop number, $\boldsymbol{\lambda}, \boldsymbol{\mu}$;
●Find the optimal $p_{l,m,k}^{r}(n), p_{l,m}^{s}(n)$
  For $j = 1$: loop number
  Calculate $p_{l,m}^{s}(n)$ and $p_{l,m,k}^{r}(n)$ by using (22), (23) respectively $\forall l,m,n,k$
  Update $\lambda, \mu$ base on (25) and (26) separately;
  Until convergence or $j =$ loop number
  End
```

3.3 Semi-Distribution Solution

The resource allocation of relay-enhanced multi-cell OFDM systems can be classified into two categories [16]: centralized resource allocation and distributed resource allocation. Centralized means that there exists a central controller gathers all the information and feedback required from all the BSs and performs global resource allocation. Meanwhile, a scheme may be considered as distributed if each cell individually performs its own resource allocation based on local information and perhaps aided with some inter-cell information. Distributed resources allocation can avoid frequent and complex signaling interaction among different cells, which can help to solve the difficulty of implementation for centralized in the large-scale communication network. However, there seems to be no agreement in the literature on the use of the terms “centralized” and “distributed”. This paper uses a semi-distributed resources allocation scheme, for we regard the co-channel interference caused by adjacent cells as noise in the previous section. This can help prevent frequent and complex signaling interaction to realizing distributed processing. However, it also makes power information of each cell lost at the same time. As a result BSs can’t coordinate to reduce the influence of inter-cell interference. So this section will concentrates on the solving of the third level problem——taking into account of the dynamic inter-cell interference caused by adjacent cells and redistributing resources to further improve system performance. The mathematical expression is given by

$$\max_{\boldsymbol{P}_s^*,\boldsymbol{P}_r^*,I_{l,m}^s,I_{l,m,k}^r} \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N} w_{l,k}\cdot C_{l,m,k}(n) \tag{28}$$

where $\boldsymbol{P}_s^*, \boldsymbol{P}_r^*$ are the transmit power allocation vectors for subcarriers at BS and relay nodes which can get from the analysis of Algorithm I.

In a word, the third sub-optimization problem combines Algorithm I with inter-cell interference coordination process to reduce the influence of interference. Based on the analysis of the previous sections the resource allocation algorithm of this paper can be summarized as Algorithm II.

```
Algorithm II: A semi-distribution resource allocation for relay assisted multi-cell OFDM networks
$\mathbb{s}_1$. Initialize $w_{l,k}$, the maximum inter-cell loop number $\mathbb{N}$
$\mathbb{s}_2$. Repeat inter-cell loop
$\mathbb{s}_3$. Initialize $p_{l,m}^s(n) = p_s/N, p_{l,m,k}^r(n) = p_r/N$ , $\rho_{l,m,k}(n) = 0\ \forall l,m,n,k$
●Find the optimal $\rho_{l,m,k}(n)$
  For $l = 1: L$
    For $n = 1: N$
    $(m,k,n)$= $ar\widehat{gm}ax\ C_{l,m,k}(n)$
    End
  End
$\mathbb{s}_4$. Initialize intra-cell loop number $\mathbb{m}$, $\lambda, \mu$;
●Find the optimal $p_{l,m,k}^r(n), p_{l,m}^s(n)$
```

```
    For $j = 1$: loop number
    Calculate $p^{s}_{l,m}(n)$ and $p^{r}_{l,m,k}(n)$ using (22), (23) respectively $\forall l, m, n, k$;
    Update $\lambda, \mu$ base on (25) and (26) separately;
    Until convergence or $j = \mathbb{m}$
    End
$\mathbb{s}_5$. Each cell takes into account of the dynamic inter-cell interference caused by adjacent cells and redistributes resources. Until convergence or inter-cell loop number equals $\mathbb{N}$.
```

4. Simulation Results and Analysis

We use simulation results to show the performance of the proposed semi-distributed resource allocation. In our simulations we use the Okumura-Hata model: $L(d) = 137.74 + 35.22\ dB$ to measure path loss where d (km) is the distance between two nodes. We consider frequency-selective channels which can be defined in the time domain by $h(t) = \sum_{p=0}^{P-1} \alpha(p)\delta(t - pT/N)$, where $\alpha(p)$ is the complex amplitude of the p-th path, P the number of channel taps and T the OFDM symbol interval. We assume that all taps are subject to Rayleigh fading $\alpha(p) \sim CN(0,1/P)$. The additive white Gaussian noise (AWGN) variance N_0 of each subcarrier is the same.

4.1 System Throughput Analysis

The number one to seven cells in **Fig. 1** compose a system names cluster, this subsection using the weighted rate of this cluster as the basis for comparison. Simulation parameters for system capacity analysis are given in **Table 2**.

Table 2. Simulation parameters for system capacity analysis

Parameters	Values	Parameters	Values
Transmit power of BS p_s (dbm)	35	Transmit power of RS p_r (dbm)	35/2
Radius of each cell (Km)	1	Radius of each relay circle (Km)	0.5
Cell number of every cluster	7	Relay number/cell	3
Number of subcarrier	128,64	User number K /cell	[3 4 5 6 7 8]
Priority value of users	1	N_0 (dbm)	-128

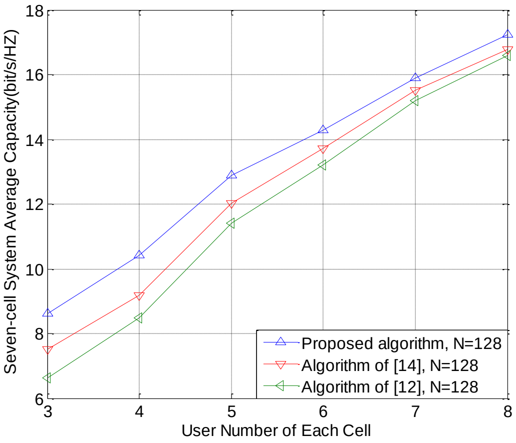

Fig. 2. System throughput versus user number K of each cell, the total subcarrier number $N = 128$

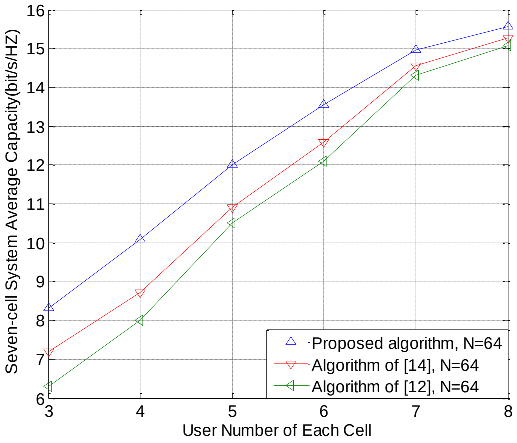

Fig. 3. System throughput versus user number K of each cell, the total subcarrier number $N = 64$

Fig. 2 and **Fig. 3** illustrate the cluster system (seven cells) capacity versus different user number of each cell. We compare our resource allocation algorithm with resource allocation method of [12] and [14] under different subcarrier number N and different user number K of each cell. It is clearly show that the method we propose in this paper can provide a significant performance improvements compared with the scheme of [12], about 15% when the use number of each cell is 4 or 5, because the method of [12] can only give a lower bound for the original problem and the proposed algorithm uses optimal power allocation solution which can utilize limited resources more effectively under the power constraints of base stations and relay nodes. The performance of our algorithm is still better than [14], for [14] only allow each user connect with one fixed relay which cannot make full use of space diversity.

On one hand, seven-cell system capacity is increasing with the increase of total user number in every single cell. On the other hand, increasing the total subcarrier number can help enhance system capacity to some extent for the three different algorithms, which can be conclude by comparing simulation results **Fig. 2** and **Fig. 3**.

4.2 Convergence Performance Analysis

The proposed power allocation algorithm can be divided into multi-level water-filling and cyclic iteration two parts. Through the analysis of λ, μ we can get system iterative convergence performance. **Fig. 4** to **Fig. 6** are system convergence performance versus number of iterations. The decision conditions for convergence are as follows

$$|\lambda(t) - \lambda(t-1)| \leq \Delta \tag{29}$$

$$\left|\mu_{l,m}(t) - \mu_{l,m}(t-1)\right| \leq \Delta \tag{30}$$

where Δ is a nonnegative constant; $\lambda(t)$ and $\mu_{l,m}(t)$ have the same meaning as previous introduction. **Table 3** gives the related simulation parameters for convergence analysis.

Table 3. Simulation parameters for convergence analysis

Parameters	Values	Parameters	Values
Transmit power of BS p_s (dbm)	30	Transmit power of RS p_r (dbm)	$p_s/2$
Radius of each cell (Km)	2	Radius of each relay circle (Km)	1
Cell number of every cluster	7	Relay number/cell	3
Number of subcarrier	128	User number K /cell	[3 4 5 6 7 8]
Priority value of users	1	N_0 (dbm)	-128

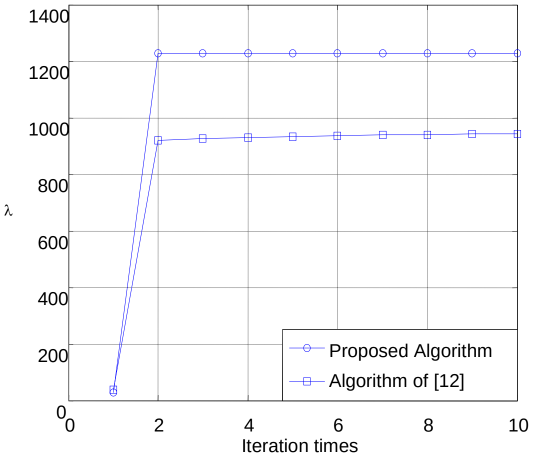

Fig. 4. Lagrange multiplier λ versus iterations

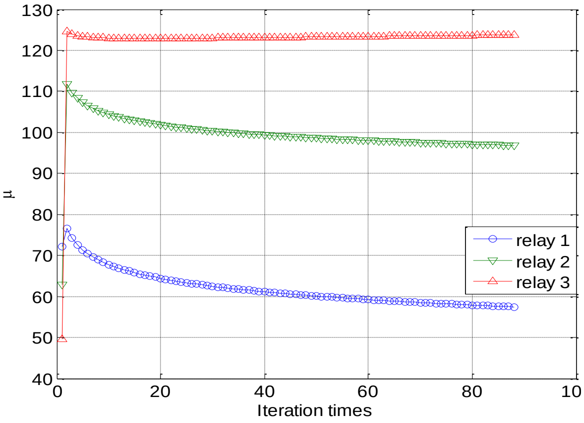

Fig. 5. Lagrange multiplier μ versus iterations in algorithm of [12]

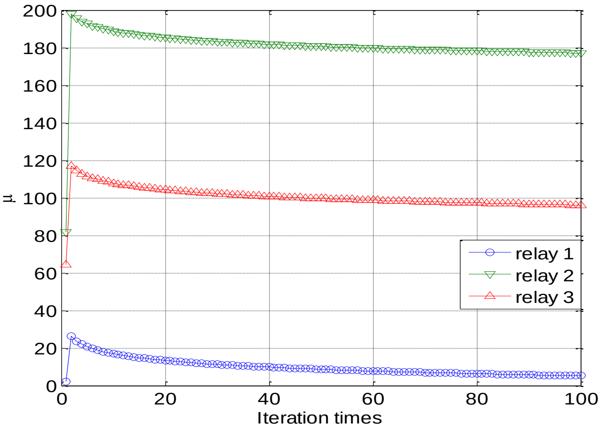

Fig. 6. Lagrange multiplier μ versus iterations in proposed algorithm

Fig. 4, **Fig. 5** and **Fig. 6** are different system convergence performance versus number of iteration times. λ is the Lagrange multiple vector associated with the individual BS power constraints. μ is the Lagrange multiple vector corresponding to the relay power constraints. By changing the nonnegative constant Δ in convergence conditions (29) (30) reasonably, the convergence time of system can be reduced. In addition, convergence can represent system time delay to some extent which means that when the algorithm convergence is good, the delay of system is relatively small. Carefully analysis the trends of the curves in the three pictures, we can find that the convergence performance of the proposed algorithm is slightly better than the algorithm of [12] for our curves tend to be gentle faster. Convergence performance analysis indicates the realizability of the resource algorithm we proposed in this paper. That is, convergence speed will not bring troubles to the process of system resource allocation.

4.3 Fairness Performance Analysis

This part we will give an analysis for system fairness performance, according to the author's acknowledge that most of the existing research works have taken into account of user fairness by using the following two schemes: ①Proportional fairness scheduling, that is in the process of subcarrier allocation not only consider system capacity maximization but also consider the edge users requirements; ②QOS (Quality of system) constraints which adds the minimum rate requirements for specific users in the original target function. We use a more concise way to achieve system fairness by regulating the priority values of different users. The related simulation parameters for fairness performance analysis are given in **Table 4**. **Table 5** represents the different user weights schemes.

Table 4. Simulation parameters for fairness performance analysis

Parameters	**Values**	**Parameters**	**Values**
Transmit power of BS p_s (dbm)	30	Transmit power of RS p_r (dbm)	$p_s/2$
Radius of each cell (Km)	1	Radius of each relay circle (Km)	0.5
Cell number of every cluster	7	Relay number/cell	3
Number of subcarrier	128	User number K /cell	5
Priority value of users	**Table 5**	N_0 (dbm)	-128

Table 5. Users weights schemes

Weights schemes	$w_{l,k}$, subcarrier matching
Algorithm 1	[0.8 ,0.8 ,1.4 ,1.4 ,1.4], with subcarrier matching
Algorithm 2	[0.8 ,0.8 ,1.4 ,1.4 ,1.4], without subcarrier matching
Algorithm 3	[1.4 ,1.4, 0.8 ,0.8 ,0.8], with subcarrier matching
Algorithm 4	[1.4 ,1.4, 0.8 ,0.8 ,0.8], without subcarrier matching
Algorithm 5	[1 ,1 ,1 ,1 ,1], with subcarrier matching
Algorithm 6	[1 ,1 ,1 ,1 ,1], without subcarrier matching

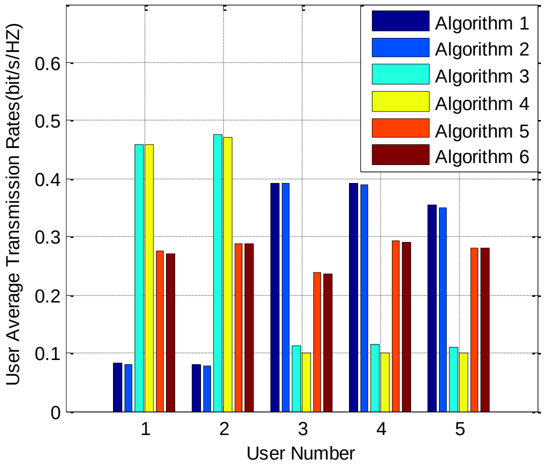

Fig. 7. User average transmission rates under different weight schemes.

Fig. 7 depicts user average transmission rates under different weight schemes, there are five users in each single cell. Ordinate illustrates average transmission rate of users with the same weight coefficient of the seven-cell system. Abscissa indicates different user number. It is shown that algorithms with subcarriers matching performance better than schemes without subcarriers pairing. However, capacity increasing that the subcarriers matching can bring is limited because power allocation algorithm of this paper is the optimal scheme. At the same time users with heavier weights coefficient have higher capacity than these with lighter weights. When all user weights are 1, the average transmission rates of different users are almost the same. Therefore, it can be concluded that by regulating the priority values of different users reasonably the fairness of system can be achieved.

5. Conclusion

In this paper, we present a study on resource allocation for relay assisted multi-cell OFDM networks, deduce an optimization model under the power constraints of source and relay nodes, formulate resource allocation as a joint interference coordination and carrier, power distribution problem and propose a semi-distributed resource allocation algorithm. Through dividing the original optimization into three sub-optimization problems, we transform the original BNLP into standard convex optimization problem. By the application of dual decomposition approach, water-filling theorem and iterative power allocation algorithm we get the optimal solution of the primal problem finally. Meanwhile, by regulating the priority values of different users reasonably the fairness of system can be achieved. The proposed scheme is easy to operate which can help to solve the difficulty of implementation for centralized algorithms in the large-scale communication network.

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