Frequency Saving OFDMA Resource Allocation with QoS Provision*

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Abstract. With the increasing wireless communication demands, frequency spectrum has become more and more limited and expensive. This paper proposes a novel optimization objective: minimizing the required frequency resource, on the premise that both the power constraints and users' quality of service (QoS) demands can be met. With the frequency saving objective, the primary system can release the unnecessary frequencies for other applications, such as subordinate or cognitive networks. In this paper, we formulate the number of subcarriers minimization problem for both uplink and downlink OFDMA-based networks, which is a mixed NP-hard problem. For the downlink case, we propose an efficient near-optimal algorithm to solve the problem. For the uplink case, we derive low complexity greedy algorithms to obtain tight lower bound and upper bound. Simulation results show that our algorithms can significantly save the system's frequency resource.

Keywords: Frequency adapting, OFDMA, QoS, resource allocation.

1 Introduction

Due to the increasing communication demands, multiple wireless network (multi-radio) coexistence [1] has become an inevitable trend. Meanwhile, how to improve the resource (frequency and power) utilization efficiency has always been a hot research topic. Under the context of multi-network co-existence, the existing resource allocation methods can be classified into three categories:

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1) Single network dynamic resource allocation. It assumes each network independently allocates its resource without considering the other co-existed networks. The resource allocation within this category mainly consists of margin adaptive (MA) and rate adaptive (RA) approaches [2] [3]. The objective of MA is to minimize the total transmit power with the constraints of bandwidth and individual user's QoS requirement, and the objective of RA is to maximize the system throughput under the available power and bandwidth constraints.

2) Spectrum sharing in cognitive radio (CR) [1]. It allows the secondary users to share the spectrum in an opportunistic way when the primary users are silent. The success of CR requires fast and sufficient spectrum sensing.

3) Joint resource allocation with inter-network cooperation. In this approach multiple networks jointly allocate the shared resources to achieve mutual benefits. For example, our recent work [4] proposed a collaborative hybrid network that supports both TV broadcasting and cellular data access on a single-frequency platform that can greatly enhance the aggregate capacity.

Intuitively, we expect the combination of the above three approaches can further improve the resource utilization efficiency. However, under the context of multi-network co-existence, most existing optimization objectives are either too selfish or unrealistic. For example, let's consider a cellular (primary) and ad-hoc (cognitive) coexisting networks. With dynamic resource allocation, the primary cellular users tend to use all the frequency resource to maximize their performance according to MA or RA optimization objective. As a result, the performance of the CR network can be jeopardized due to an insufficient amount of available frequencies. Meanwhile, these two coexisting networks can't be cast into the collaborative hybrid structure in [5] because they don't share the same transmitter. In this case, if the primary network is aware of the existence of the cognitive network and the latter agreed to somehow share the cost, at least some limited coordination can be done between the two networks. As is well known, the scarcest resource in wireless communications is the radio spectrum. A fundamental question in multi-radio coexistence is: how to minimize the required frequency resource of any single network without sacrificing its performance (i.e., guaranteed QoS to its users)?

On the other hand, the orthogonal frequency division multiple access (OFDMA) has been widely used as the prime multiple access scheme in many wireless standards (IEEE 802.16, IEEE 802.22, LTE, etc.). One prominent advantage of OFDMA is that it can exploit the multi-user diversity embedded in diverse frequency-selective channels through intelligent resource allocation. To date, most existing research on OFDMA resource allocation focuses on either cellular networks (see [3-6] and references therein) or on CR systems [1] [7] [8], without inter-network coordination. In this paper, we *propose a new resource allocation objective that minimizes the required number of subcarriers in an OFDMA based network, on the premise that both the power constraints and the users' QoS requirements can be met.* The motivation of such a frequency saving objective can be found in many applications. In addition to the aforementioned CR application where the subcarriers saved by the primary network can be used by the secondary users, the cellular system itself can also benefit from the frequency savings (For example, the saved frequencies can be used by other cellular applications such as mobile TV broadcasting).

The main contributions of this paper are summarized as follows:

1) In contrast to the existing RA and MA optimization objectives, we formulate a new frequency saving optimization problem for both uplink and downlink cellular systems.

2) In downlink case, we propose the decoupled bisection search and feasibility test algorithm for multi-user frequency adaptive optimization" (BF-MUFA), which has near optimal performance.

3) For uplink, we derive low complexity greedy methods to obtain very tight upper bound and lower bound for multi-user frequency adaptive optimization. The proposed greedy methods can also be easily adapted to downlink case to eliminate the bisection searching scope.

2 System Model and Problem Formulation

Consider an OFDMA cellular network with K users, and N subcarriers. The subcarrier bandwidth is W. Assume this network has some other co-existing subordinate network(s), which can be a cognitive radio network or a network that shares the same frequency with a lower priority. In such a configuration, the frequency saving scheme in the primary network can benefit others without affecting its own users. Let $P_{k,n}$ denote the power allocated to the k-th user. Then the maximum achievable data rate of the k-th user on channel n is:

$$C_{k,n} = W \cdot log_2\left(1 + P_{k,n} \cdot \frac{\left|H_{k,n}\right|^2}{\sigma_{k,n}^2}\right) \tag{1}$$

where $H_{k,n}$ is the instantaneous frequency response of user k on subcarrier n and is assumed to be known at both the transmitter and receiver; and $\sigma_{k,n}^2$ is the corresponding noise power which is assumed the same for all users on all subcarriers. Define channel signal to noise ratio (SNR) $\left|H_{k,n}\right|^2 / \sigma_{k,n}^2$ as $e_{k,n}$. Denote matrix $\mathbf{X}$ as the subcarrier allocation schedule, i.e. the (k, n)-th element of $\mathbf{X}$ is:

$$X_{k,n} = \begin{cases} 1 & \text{subcarrier } n \text{ is assigned to user } k \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

Hence, the overall maximum rate for user k in this system is:

$$C_k = \sum_{n=1}^{N} X_{k,n} C_{k,n} \tag{3}$$

Correspondingly, the total power allocated to user k in this system is: $\sum_{n=1}^{N} X_{k,n} P_{k,n}$.

Since the transmission delay is small in the cellular system, we assume user k's QoS requirement is specified by its transmission rate R_k. Thus, the frequency minimization problem can be formulated as follows:

$$P0:\ f = \min \sum_{k=1}^{K} \sum_{n=1}^{N} X_{k,n} \quad (4)$$

$$\text{Subject to: } \sum_{k=1}^{K} X_{k,n} \le 1,\ \forall n;\ X_{k,n} = 0 \text{ or } 1,\ \forall n,k \quad (4a)$$

$$C_k \ge R_k, \forall k \quad (4b)$$

$$P_{k,n} \ge 0, \forall n,k \quad (4c)$$

$$\text{Downlink: } \sum_{k=1}^{K} \sum_{n=1}^{N} X_{k,n} P_{k,n} \le P_T \quad (4d)$$

$$\text{Uplink: } \sum_{n=1}^{N} X_{k,n} P_{k,n} \le P_k,\ \forall k \quad (4e)$$

where (4) is our optimization objective. The OFDMA constraints (4a) indicate each subcarrier can be used by no more than one user at any time slot to avoid multi-user interference. Inequalities (4b) make sure each user's QoS demand is met; inequalities (4c) restrict the power cannot be negative. For downlink, the total transmission power constraint is shown in (4d); for uplink, each user is subject to an individual power constraint as shown in (4e).

P0 is a mixed integer and continuous optimization problem, because the optimization variables contain both the discrete variables $\{X_{k,n}\}$ and continuous variables $\{P_{k,n}\}$. Also, P0 is a NP-hard question [9]; to find its optimal solution needs a brutal search which has $\sum_{i=1}^{N} \binom{N}{i} K^i$ possible combinations.

Notice that for downlink optimization, the base station's sensitivity towards the transmission power is less than the cellular users' sensitivity towards the battery life in uplink optimization. However, for uplink optimization, this model is still useful when the cellular users are less sensitive to their battery life. Moreover, when the operator charges users according to their data rates, users will prefer MA algorithm which, however, affects the operators' benefits by taking too much radio frequency. One way to solve this problem is to prioritize users. For high priority users, the system carries out MA resource allocation to save users' transmission power; for low priority users, the system applies subcarrier minimization algorithm to save the frequency resource. In the next section, the optimization algorithms for both downlink and uplink are introduced.

3 Frequency Saving Algorithms

In this section, we propose near optimal algorithms for downlink and uplink OFDMA, respectively. In the downlink case, the bisection and feasibility test combined algorithm for multi-user frequency adapting optimization (BF-MUFA) has been proposed, and the original problem is decomposed into two sub-problems. In the uplink, we propose low complexity greedy algorithms to obtain both a tight lower bound and a tight upper bound.

3.1 The Optimal Solution for Single User System

If the OFDM system has only one user, then problem P0 is trivial. Obviously, with the given power, user rate is a mono increasing function of the number of subcarriers. Hence, the optimal solution can be easily obtained by the bisection method combined with the traditional single user waterfilling algorithm [10]. We first introduce a single user frequency adapting algorithm (SUFA) as follows (Table 1). Let **e** be the channel SNR matrix with $(1, n)$-th element as $e_{1,n}$, other parameters are defined in Section 2. Note that in Step 3, the waterfilling algorithm we use was proposed in [10] which can easily obtain the global optimal for single user resource allocation.

Table 1. Single user frequency adapting algorithm (SUFA)

Input: P_T, R, **e**; Output $f, \mathbf{X}$
Step 1: Initialize $f_{\min}$=1 and $f_{\max}$=N. $E \leftarrow$ sort subcarriers according to their SNR **e** in the descending order.
Step 2: $f = \mathrm{int}\left((f_{\min} + f_{\max})/2\right)$;
Step 3: $[C, \mathbf{X}] \leftarrow waterfill(P_T, E(1:f))$;
Step 4: If $C > R$, then set $f_{\max} = f$;
else set $f_{\min} = f$;
Step 5: If $f_{\min} = f_{\max}$, stop; otherwise $\downarrow$ step 2.

3.2 Downlink OFDMA Frequency Optimization (Multi-User System)

From Section 3.1, we can see that the bisection method can be used to derive the optimal solution for the single user OFDM system. However, in the multi-user case, the optimization problem of P0 is NP-hard [9], to solve this problem optimally we need a brutal forth search. Hence, we need a low complexity optimization algorithm. Inspired by the single user case, we now consider can a similar method be used for the multi-user case? Can this similar method obtain the optimal solution? To answer these questions, we first introduce Lemma 1.

Lemma 1: In a given OFDMA system with K users and N possible subcarriers, the minimum total power required to satisfy all users' QoS requirements is the mono decreasing function of f , where f is the number of subcarriers allowed to use.

Proof: Firstly, in the single user case, this lemma was proved in the Appendix A of literature [11]. In a multi-user system, it's safe to assume two cases with $f = f_1$ and $f = f_2$, while $f_2 = f_1 + 1$. Denote the total minimum power required when $f = f_1$ and $f = f_2$ as P_{T1} and P_{T2}, respectively. By the contradiction method, suppose the Lemma 1 is not true, which means $P_{T2} > P_{T1}$. For $f = f_2$, assume all users maintain their subcarrier schedule as when $f = f_1$, except for user k who has one more subcarrier to use. Therefore, to meet all users' QoS, user k 's power requirement decreases, while other users' power requirements remain the same; hence, $P_{T2} \le P_{T1}$ which results in a contradiction of this assumption. Above all, Lemma 1 is proved. ■

Note that the number of subcarriers f is in one-dimensional space, and the total power constraint is obviously in one dimensional space. Supported by Lemma 1, we propose the following bisection feasibility test combined method to solve the optimization problem P0 (Table 2). The BF-MUFA contains mainly an outer loop and inner loop. The outer loop adjusts the number of subcarriers by bisection method, and chooses the best subcarriers from the subcarrier pool (Step 2 and Step 3); the inner loop tests the feasibility of meeting users' QoS with the given power constraint for the chosen subcarrier group of outer loop by comparing the minimum power required to meet QoS demands with the available total power (Step 4 and Step 5). Let $\mathbf{R}$ be the set that contains all users' rate requirements, and f_{opt} be the optimal number of subcarriers.

Table 2. Bisection and feasibility test combined algorithm for multi-user frequency adapting Optimization (BF-MUFA)

Input: $P_T, \mathbf{R}, \mathbf{e}$; Output $f, \mathbf{X}$
Step 1: Initialize $f_{\min} = 0$ and $f_{\max} = N$,
Step 2: $f = \mathrm{int}((f_{\min} + f_{\max})/2)$
Step 3: Find best f number of subcarriers E_f, such that
if $f \ge f_{opt}$, $E_f \supseteq E_{opt}$.
Step 4: $[P_{\min}, \mathbf{X}] \leftarrow \min power(\mathbf{R}, E_f)$;
Step 5: If $P_{\min} \le P_T$, then set $f_{\max} = f$;
else set $f_{\min} = f$
Step 6: If $f_{\min} = f_{\max}$, stop; otherwise $\downarrow$ Step 2

The above procedure contains two sub-problems (S1 and S2) which take up most of the computational complexity.

S1: Find best f number of subcarriers set E_f, such that if $f \geq f_{opt}$, $E_f \supseteq E_{opt}$, where E_{opt} represents the optimal set of subcarriers.

To meet S1's requirement, an exhaustive search is required. So we propose a suboptimal method. Among all possible N subcarriers, we select f number of subcarriers with the highest weight. We weigh each subcarrier s by $\sum_{k=1}^{K} \alpha_{k,s} e_{k,s}$. The parameter $\alpha_{k,s}$ is determined by possibility that it will be used by user k. In this paper, we assume $\alpha_{k,s} = R_k / |\mathbf{R}|$, where $|\mathbf{R}|$ is the norm-1 of the vector $\mathbf{R}$.

S2: Total power minimization:

$$\min \sum_{k=1}^{K} \sum_{n=1}^{N} P_{k,n} \tag{5}$$

$$\text{Subject to } : \sum_{n=1}^{N} X_{k,n} \cdot W \cdot \log_2 (1 + P_{k,n} e_{k,n}) \geq R_k , \forall k \tag{5a}$$

$$P_{k,n} \geq 0, \forall k, n \tag{5b}$$

$$\sum_{k=1}^{K} X_{k,n} \leq 1, \forall n, \text{ where } X_{k,n} = 1 \text{ or } 0 \tag{5c}$$

Sub-problem S2 is the traditional MA optimization. Among all the existing algorithms for MA optimization, the dynamic programming based resource allocation (DPRA) [11] is a recent method with low complexity and good performance. However, the DPRA method is a single loop method, and we cannot refine it simply by repeating it. Inspired by [11] and [12], we propose a new algorithm based on the Lagrangian dual decomposition method, which uses the DPRA's result as the initial solution and achieves better performance with low complexity.

The Lagrangian expression of (5) is as follows:

$$L(\mathbf{P}, \boldsymbol{\lambda}) = \sum_{k=1}^{K} \sum_{n=1}^{N} P_{k,n} + \sum_{k=1}^{K} \lambda_k \left(R_k - \sum_{n=1}^{N} W \log_2 (1 + P_{k,n} e_{k,n}) \right)$$

$$\text{Subject to : } P_{k,n} \geq 0, \forall k, n \tag{6}$$

$$\sum_{k=1}^{K} X_{k,n} \leq 1, \forall n, \text{ where} X_{k,n} = 1 \text{ or } 0.$$

Then the Lagrangian dual function is:

$$g(\boldsymbol{\lambda}) = \min_{\mathbf{P},\mathbf{X}} \{L(\mathbf{P},\mathbf{X},\boldsymbol{\lambda})\} = \sum_{n=1}^{N} g_n(\boldsymbol{\lambda}) + \sum_{k=1}^{K} \lambda_k R_k \tag{7}$$

In the OFDMA system, each subcarrier can be only used by at most one user; hence,

$$g_n(\boldsymbol{\lambda}) = \min_k \{P_{k,n} - \lambda_k W \log_2(1 + P_{k,n} e_{k,n})\} \tag{8}$$

The subcarrier n is allocated only to user k^* such that:

$$k^* = \arg\min_k \{P_{k,n} - \lambda_k W \log_2(1 + P_{k,n} e_{k,n})\} \tag{9}$$

With fixed $\boldsymbol{\lambda}$, the problem (8) is a convex function of $P_{k,n}$. So we let the derivation of (8) over $P_{k,n}$ equal to 0, and obtain:

$$P^*_{k,n} = \left(\lambda_k W \ln 2 - \frac{1}{e_{k,n}}\right)^+ \tag{10}$$

Finally, the Lagrangian dual variable λ_k can be obtained from:

$$\sum_{n \in S_k} W \log_2\left(1 + \left(\lambda_k W \ln 2 - \frac{1}{e_{k,n}}\right)^+ e_{k,n}\right) = R_k \tag{11}$$

in which S_k represents the set of subcarriers given to user k with $P_{k,n} > 0$. Hence:

$$\lambda_k = 2^{t/(W|S_k|)} \Big/ (W \ln 2), \text{ where } t = \left(R_k - \sum_{n \in S_k} W \log_2 e_{k,n}\right) \tag{12}$$

To optimally update this dual variable is nontrivial. Because of the discontinuity in the power allocation by (8), the existing methods, e.g. the ellipsoid method and subgradient based method, will result in slow convergence or even no convergence. Hence, by observing the above equations' structures, we propose an efficient algorithm as is shown in Table 3.

Table 3. Lagrangian dual decomposition based margin adaptive optimization (LDD-MA)

Input: $\mathbf{R}, \mathbf{e}$; Output $P_{\min}, \mathbf{X}$

Step 1: Initialization. Assume iteration i=0, assign subcarriers according to the DPRA solution.

Step 2: For n=1 to N

Step 3: Let $X_{k,n} = 1, \ \forall k$;

Step 4: Apply (12) and derive λ_k ;

then plug λ_k in (10), and obtain $P^*_{k,n}, \ \forall k$.

Step 5: $k^* \leftarrow \arg\min_k \left\{P^*_{k,n} - \lambda_k W \log_2\left(1 + P^*_{k,n} e_{k,n}\right)\right\}$

Step 6: Let $X_{k,n} = 0$, and update λ_k and $P_{k,n}, \ \forall k \neq k^*$

Step 7: $i = i + 1$; $P^{(i)}_{\min} \leftarrow sum\left(P_{k,n}\right)$

Step 8: If $P^{(i)}_{\min} - P^{(i-1)}_{\min} \geq \xi$, then $\downarrow$ step 2; otherwise, stop.

3.3 Uplink OFDMA Frequency Optimization (Multi-User System)

In uplink OFDMA system, each user has an individual power constraint; hence, the former BF-MUFA with the total power constraint for the feasibility test is not applicable to the uplink case. However, we propose low complexity greedy algorithms to find the upper bound and lower bound of the minimum number of required subcarriers for uplink cases. The general idea of the greedy algorithm is: rank users in the descending order according to their QoS requirements, and then minimize the number occupied subcarriers for each subscriber using SUFA from the first user to the last one, until all users' QoS demands have been met. To obtain the upper bound, each subcarrier can only be used by one user at most; on the other hand, we allow subcarrier sharing among multiple users to get the lower bound. The detail to attain the upper bound is presented in Table 4.

Table 4. Upper bound for multi-user frequency adapting optimization (UB-MUFA)

Input: $\mathbf{P}, \mathbf{R}, \mathbf{e}$; Output $f_{UB}, \mathbf{X}_{UB}$

Step 1: $\{k^*\} \leftarrow sort\,(QoS)$;

Step 2: For $k^* = 1{:}\ K$

$\mathbf{X}_{k*} \leftarrow$ SUFA (P_{k*}, R_{k*}, e_{k*}),

if $X_{k*,n} = 1$, rule out subcarrier n; $\forall k \neq k^*, \forall n$

Step 3: $f_{UB} \leftarrow \text{count}\left(X_{k,n} = 1\right)$

Step 4: If all users' QoS requirements are satisfied,

output $f_{UB}, \mathbf{X}_{UB}$; otherwise, perform multi-user access control.

Note that in this greedy algorithm, whenever multiple users contend for the same subcarrier, the user with the highest QoS requirement is selected. What's more important, the selected subcarriers is a sufficient subcarriers set E_f for the optimal solution, i.e. $E_f \supseteq E_{opt}$. The reason is that: if no subcarrier has been ruled out in Step 2, which means all users need distinct subcarriers to minimize the required frequency, then the greedy solution is the optimal solution; however, if some subcarriers are ruled out in Step 2, these subcarriers actually have already been given to the current user which means they are already included as candidates for optimal solution.

Similar as the UB-MUFA, we propose a greedy algorithm in Table 5 to obtain the lower bound. LB-MUFA differs from UB-MUFA in the following manner: we give all frequency resource to each user, and no subcarrier is ruled out even if multiple users occupy the same subcarrier; what's more, multi-user interference is not considered. Owing to the way to choose subcarriers for each user, the subcarriers selected from this approach are the necessary subcarriers to meet the users' requirements.

In the simulation section, we can see the lower bound and the upper bound of uplink OFDMA are very close which indicates their tightness.

Furthermore, for the uplink and downlink case, we can also apply the UB-MUFA and LB-MUFA to eliminate the searching scope. For simplicity, we assume each user has the equal power constraint as P_T/K in UB-MUFA algorithm to obtain the upper bound; also, we assume each user has P_T in LB-MUFA as the power constraint to obtain a rough lower bound of minimum number of subcarriers. With the lower bound and upper bound being considered, the searching scope of bisection in BF-MUFA searching scope can be reduced greatly.

Table 5. Lower bound for multi-user frequency adapting (LB-MUFA)

Input: $\mathbf{P}, \mathbf{R}, \mathbf{e}$; Output $f_{LB}, \mathbf{X}_{LB}$

Step 1: For $k = 1 : K$

$\mathbf{X}_k \leftarrow \text{SUFA}(P_k, R_k, e_k)$,

Step 2: $f_{LB} \leftarrow \text{count}\left(X_{k,n} = 1\right)$

Step 3: If all users' QoS requirements are satisfied, output $f_{LB}, \mathbf{X}_{LB}$; otherwise, perform multi-user access control.

4 Experimental Results

This section provides simulation results to validate the proposed algorithms in Section 3. For an OFDMA system with 20 users and 128 subcarriers, Fig. 1 compares our new LDD-MA algorithm and the DPRA algorithm proposed by [11]. After extensive simulations, we observe that whenever the system has more users, higher QoS requirements, or less subcarriers, the performance gap between LDD-MA and DPRA algorithm increases.

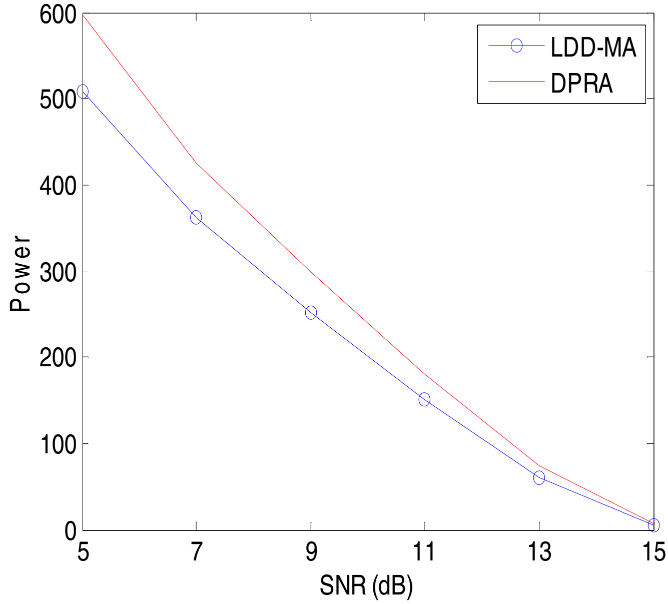

Fig. 1. Comparison between LDD-MA and DPRA

Fig. 2 and 3 are the typical numerical results of downlink OFDMA, which show the number of required subcarriers as a function of SNR and K respectively. In Fig. 2 and 3, “Random” represents the results obtained by first predefining each user has equal total available power and then randomly assign subcarriers to users till their QoS demands are met; “BF-MUFA” is our aforementioned algorithm using bisection search and feasibility test. In Fig. 2, we assume the 128 subcarriers are shared between 20 users, and each user has a random rate requirement. In Fig. 3, we assume each user has the same rate requirement, and SNR=10.

For uplink, extensive simulations have shown that the upper bound and lower bound are extremely close so that our algorithm for upper bound is almost always optimal, as shown by Fig. 4 and 5. Fig. 4 and 5 show the relationship between SNR and the number of required subcarriers, as well as number of users vs. the number of required subcarriers, respectively. In all cases, our proposed algorithms can significantly save the number of required subcarriers.

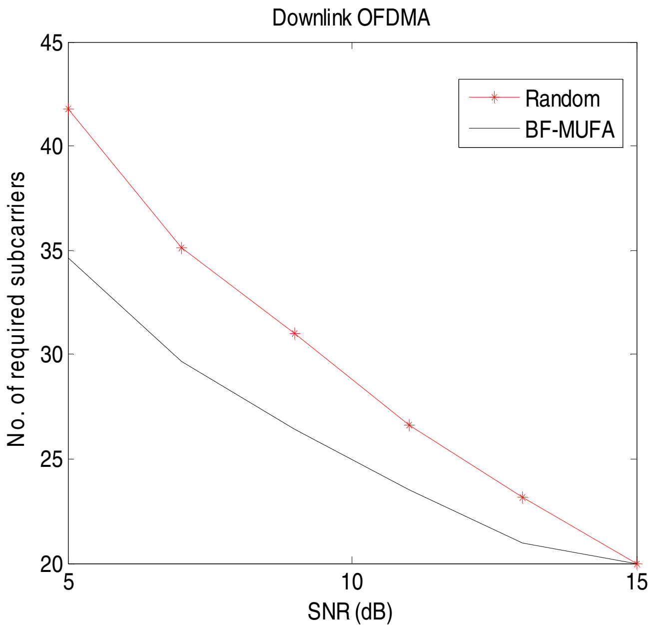

Fig. 2. SNR vs. No. of required subcarriers in downlink OFDMA

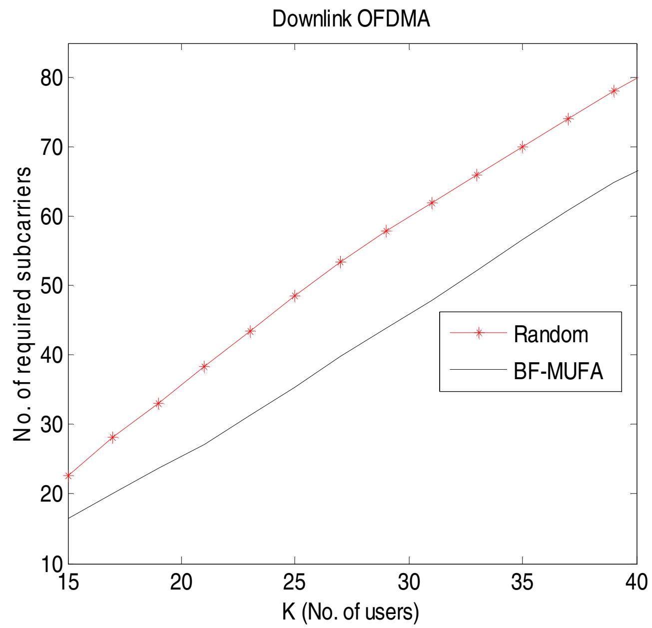

Fig. 3. K vs. No. of required subcarriers in downlink OFDMA

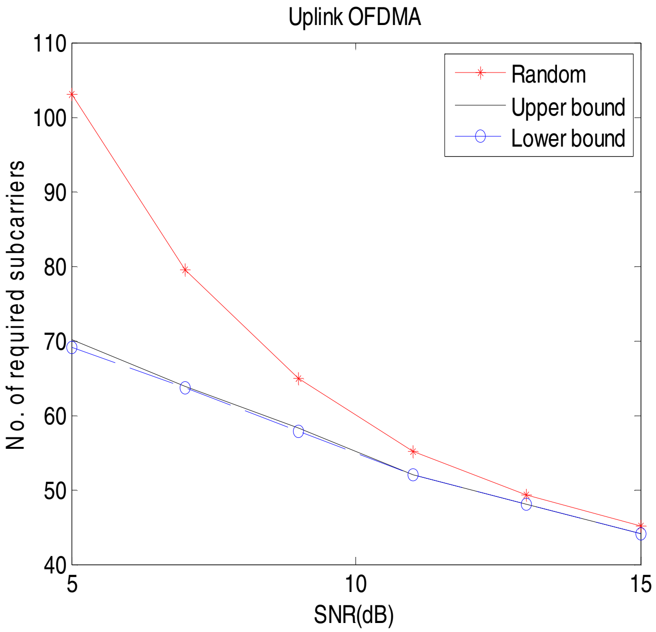

Fig. 4. SNR vs. No. of required subcarriers in uplink OFDMA

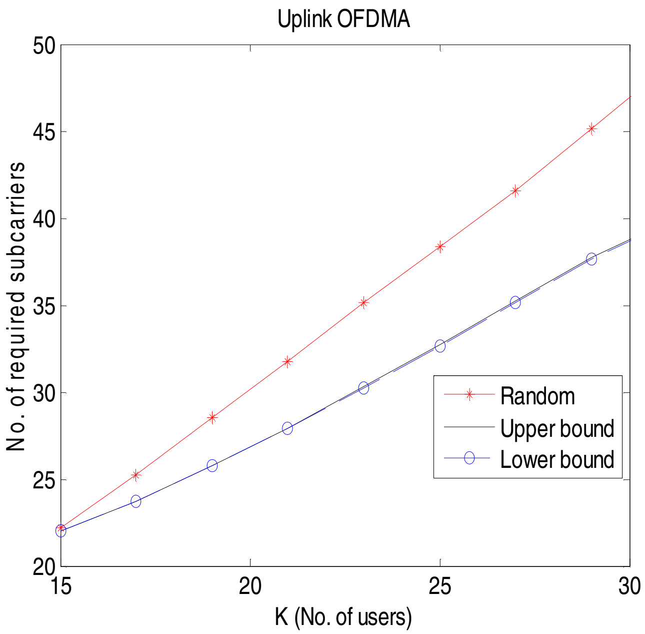

Fig. 5. K vs. No. of required subcarriers in uplink OFDMA

5 Conclusion

In this paper, we present a novel spectrum optimization model in OFDMA-based systems to minimize the required number of subcarriers under the individual user's QoS constraint and the power constraint(s). To solve this NP-hard mixed optimization problem efficiently, we propose BF-MUFA algorithm for downlink OFDMA and greedy algorithms for uplink OFDMA algorithms. Simulation results show our proposed algorithms can significantly save the number of required subcarriers. The LDD-MA algorithm proposed to solve the MA optimization greatly improves the existing DPRA algorithm, which guarantees the performance of BF-MUFA algorithm for downlink OFDMA systems. The simulation results of UB-MUFA and LB-MUFA for uplink OFDMA systems show the tightness of both bounds. Hence, the UB-MUFA algorithm can be used to obtain the near optimal results for uplink OFDMA systems.

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