An Auction Approach to Resource Allocation in OFDM-Based Cognitive Radio Networks

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***Abstract*—We study a repeated auction for the resource allocation problem in OFDM-based cognitive radio networks (CRNs), in which secondary users (SUs) share the primary spectrum under the interference constraints of primary users (PUs). With the inter-cell interference and mutual interference between PUs and SUs, the resource allocation problem is formulated as a non-convex optimization problem. Auction performs well in solving non-convex problems, therefore the interference auction with cooperative bidding is proposed. Moreover, with the theoretical analysis of equilibrium, an implementation algorithm for the auction is developed and the convergence is proved. Simulation results show that the interference auction obtains a good spectrum efficiency improvement and a rapid convergence rate.**

***Keyword*- Auction, cognitive radio network, OFDM, spectrum sharing**

I. Introduction

Currently, the survey shows that the authorized spectrum is underutilized by PUs in time and location [1]. Since traditional fixed spectrum sharing policy leads to the low utilization problem of the wireless spectrum, dynamic spectrum access uses spectrum holes to improve spectrum efficiency. Cognitive radio technology [2], which has the ability to observe, learn and decide, enables dynamic spectrum access. In CRN, the SUs communicate with each other through dynamically accessing the primary spectrum in underlay and overlay methods, while for the PUs, it is also an opportunity to get some revenue by selling the resource to the SUs .

Recently, economic theory has been extensively applied to deal with the resource allocation problem. For example, spectrum trading [3], which applies pricing incentive to stimulate PUs to sell and lease spectrum to the SUs, is an efficient way to share spectrum. Auction ([4]-[5]) as a particular form of trading is performed by bidders who submit their bids to auctioneers. The auctioneers decide the price and sell the resource to bidders.

Related work on spectrum sharing based on auction has appeared in [6], [7] and [8]. Authors in [6] study the spectrum auction with multiple auctioneers and multiple bidders, and solve the spectrum assignment problem in CRN. In [7], a real-time spectrum auction framework is proposed to distribute spectrum among a large number of users under interference constraints. A spectrum-management policy framework based on the Vickrey auction is proposed in [8], in which CR base stations (CBSs) compete for the primary spectrum bands available for overlay access. However, auction is seldom applied in OFDM-based CRN and lots of existed work focuses on subcarrier allocation. We intend to study the joint power and subcarrier allocation problem in OFDM-based CRN with the auction theory.

In this paper, a repeated auction model involving selling and buying processes is introduced. Further, the tolerable interference of PUs is the sharing resource for auction in CRN. In selling process, PUs (auctioneers) sell the tolerable interference resource to all SUs under their interference temperature constraints. And in buying process, SUs (bidders) buy the resource and access the spectrum while causing co-channel interference to other SUs. In the repeated auction, auctioneers dynamically adjust the trading prices according to their received interference and bidders' reaction changes with the price. The proposed interference auction can effectively improve spectrum efficiency with a fast convergence rate.

The rest of this paper is organized as follows. System model and problem formulation are described in Section II. In Section III, the interference auction model with cooperative bidding is proposed. Besides, a dynamic auction algorithm is proposed to get the solution, along with the analysis of equilibrium and convergence. Section IV presents the numerical performance analysis. In the end, conclusions are stated in Section V.

II. System Model and Problem Formulation

A. System Model

We consider a CRN with a bandwidth of W Hz consisting of M subcarriers, and K CR cells coexisting with L active PUs. There are S SUs in each cell trying to access the unlicensed primary spectrum in hybrid method. To guarantee that the performance of each PU is not significantly degraded by the SUs, the total interference to PU l should be limited by I_l^{th} where $I_l^{th} = T_l^{th} w_l$ denotes the maximum interference power threshold of PU l, T_l^{th} is the interference temperature limit for PU l and w_l is the bandwidth of PU l. We are interested in the OFDM-based downlink transmission. As shown in Figure 1,

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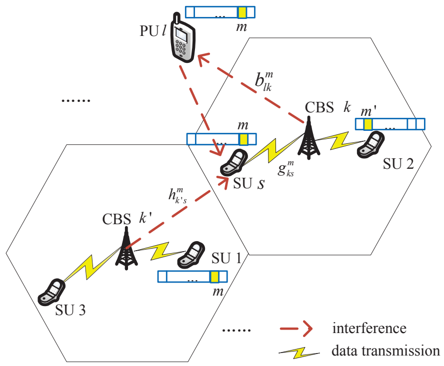

Fig. 1. System model

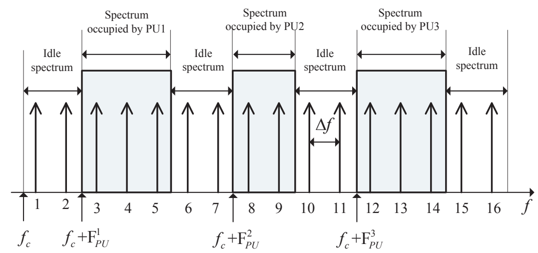

Fig. 2. Frequency distribution of the primary bands and spectrum holes

the mth subcarrier is occupied and CBS k uses it to transmit data to SU s with co-channel interference from CBS k'. The mth subcarrier channel gain from CBS k to SU s is g^m_{ks}. b^m_{lk} is the mth subcarrier interference channel gain from CBS k to PU l. $h^m_{k's}$ denotes the interference channel gain of the mth subcarrier from CBS k' to SU s. The distribution of active PU frequency bands and spectrum holes are illustrated in Figure 2. Assuming the signal on the subcarrier is Sa-shape [9], I^m_{lk} is the interference introduced by the signal of the mth subcarrier from CBS k to PU l's frequency band, and can be expressed as

$$\begin{aligned} I^m_{lk} &= P^m_{ks} b^m_{lk} T_s \int_{F^l_{PU}-(m-\frac{1}{2})\Delta f}^{F^l_{PU}-(m-\frac{1}{2})\Delta f+w_l} \left(\frac{\sin \pi f T_s}{\pi f T_s}\right)^2 df \\ &= P^m_{ks}\Omega^m_{lk} \end{aligned} \tag{1}$$

where P^m_{ks} is the transmitted power across the mth subcarrier of CBS k to SU s, F^l_{PU} is the start frequency of PU l in CRN bandwidth, Δf is the OFDM subcarrier spacing, T_s is the symbol duration and Ω^m_{lk} denotes the interference factor of the mth subcarrier from CBS k to PU l.

B. Problem Formulation

The SUs coexist with the PUs in CRN and try to access the primary spectrum. We denote the subcarrier allocation indicator as follows

$$\rho^m_{ks} = \begin{cases} 1, & \text{if the } m\text{th subcarrier is assigned to } s \text{ in cell } k \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

The arrival rate of SU s in cell k on the mth subcarrier can be expressed as

$$\begin{aligned} u^m_{ks} &= \rho^m_{ks}\log_2(1+\gamma^m_{ks}) \\ &= \rho^m_{ks}\log_2\Big(1+\frac{g^m_{ks}P^m_{ks}}{N_0+\sum\limits_{j\neq k} h^m_{js}P^m_{js}+\sum\limits_{l} I_{ls}}\Big) \end{aligned} \tag{3}$$

where γ^m_{ks} is the SINR on the mth subcarrier of SU s in cell k, N_0 is the noise power, $\sum\limits_{j\neq k} h^m_{js}P^m_{js}$ is the interference from other CBSs to SU s in cell k and I_{ls} is the interference from PU l to SU s.

In this paper, it is assumed that each subcarrier is allocated to at most one SU and we focus on maximizing the total rate of SUs subject to the constraints of the total interference introduced to the PUs and the total transmitted power. The optimization problem can be formulated as

$$\begin{aligned} &\max_{\rho,P} \frac{1}{K}\frac{1}{M}\sum_{k\in\mathcal{K}}\sum_{s\in\mathcal{S}}\sum_{m\in\mathcal{M}} \rho^m_{ks}\log_2(1+\gamma^m_{ks}) \\ &s.t. \begin{cases} \sum\limits_{s\in\mathcal{S}} \rho^m_{ks} \le 1, \forall m\in\mathcal{M}, k\in\mathcal{K} \\ \sum\limits_{k\in\mathcal{K}}\sum\limits_{s\in\mathcal{S}}\sum\limits_{m\in\mathcal{M}} \rho^m_{ks}\Omega^m_{lk}P^m_{ks} \le I^{th}_l, \forall l\in\mathcal{L} \\ \sum\limits_{s\in\mathcal{S}}\sum\limits_{m\in\mathcal{M}} \rho^m_{ks}P^m_{ks} \le P_{k,max}, \forall k\in\mathcal{K} \\ 0\le P^m_{ks}, \forall k\in\mathcal{K}, s\in\mathcal{S}, m\in\mathcal{M} \end{cases} \end{aligned} \tag{4}$$

where the set of CBS, subcarrier, PU and SU is denoted by $\mathcal{K}, \mathcal{M}, \mathcal{L}$ and $\mathcal{S}$ respectively. $P_{k,max}$ is the maximum transmitted power of CBS k. The subcarrier and power allocation scheme can be obtained by solving this problem.

III. Interference Auction

The optimization problem in (4) is a non-convex optimization problem and to solve this problem is a very tough issue. We introduce the auction model which has been recognized as an effective way to obtain resource allocation scheme.

A. Auction Modeling

As stated before, the SUs share the primary spectrum under the constraints of PUs' interference power thresholds. To obtain greater throughput, the SUs intend to transmit more power, while causing more harmful interference to the PUs. Then the tolerable interference of PUs becomes the limited sharing resource and SUs compete for more power. We call the PU is in interference temperature surplus (denoted by *state* ϑ) if the PU's interference is below its interference power threshold.

We build an interference auction model to allocate PUs' tolerable interference to the SUs. The SUs as bidders buy the interference from the PUs (auctioneers). From a market perspective, we define the demand vector $\mathbf{d}_{kl}$ as the demand of cell k for PU l's interference, which can be written as

$$\mathbf{d}_{kl} = \Big(\sum_{s\in\mathcal{S}}\rho^1_{ks}d^1_{ksl}, ..., \sum_{s\in\mathcal{S}}\rho^M_{ks}d^M_{ksl}\Big)^T \tag{5}$$

where $\sum\limits_{s\in\mathcal{S}}\rho^m_{ks}\le 1$ and d^m_{ksl} denotes the demand of SU s in cell k for PU l's interference on the mth subcarrier. If PU l sell the interference to SU s with a demand of d^m_{ksl} in the auction, then SU s accesses the primary spectrum and transmits data with the power which satisfies $P^m_{ks} = d^m_{ksl}/\Omega^m_{lk}$.

The sum demand for PU l's interference is D_l and can be written as

$$D_l = \sum_{k\in\mathcal{K}} \sum_{s\in\mathcal{S}} \sum_{m\in\mathcal{M}} \rho_{ks}^m d_{ksl}^m \tag{6}$$

The interference supply of PU l is defined as the interference power threshold I_l^{th}. We have $D_l < I_l^{th}$ if PU l is in *state* ϑ.

As mentioned previously, maximizing the total rate of SUs is our object. To achieve this aim, it's very significant to design the benefit function. If SU s succeeds in the auction, then it acquires the benefit and pays the PU a given monetary payment for the demand, or else acquires no benefit in a failed bid. We have the benefit function as follows

$$U_{ks}^m = u_{ks}^m - \sum_{l\in\mathcal{L}} d_{ksl}^m \rho_{ks}^m \mathcal{P}_l \tag{7}$$

where $\mathcal{P}_l$ is the trade price of PU l. If PU l is in *state* ϑ, it can obtain a profit denoted by π_l by selling the tolerable interference. To protect the performance of PUs, we design the profit function π_l which discourages the PU to sell more interference when it is not in *state* ϑ. We can write π_l as follows

$$\pi_l = \begin{cases} D_l(\mathcal{P}_l - c_l), & \text{if } D_l \le I_l^{th} \\ -D_l c_l, & \text{otherwise} \end{cases} \tag{8}$$

where c_l is the cost of PU l for selling interference.

In repeated auction [10], bidders submit their bids repeatedly with the dynamically changed trade price. The interference auction is modeled as a repeated auction, in which the PU adjusts the trade price according to its received interference. If PU l is in *state* ϑ, we have

$$\mathcal{P}_l^{(t+1)} = \mathcal{P}_l^{(t)} - \varepsilon \cdot \delta_l \tag{9}$$

where ε is the small step and $\delta_l = I_l^{th} - D_l$.

The auction process is described as follows.

1) The SUs of each cell submit the interference demand vector $\mathbf{d}_{kl}$ to each PU;

2) Each PU judges whether it is in *state* ϑ or not, then adjusts its trading price, and announces the new price to the SUs in CRN;

3) For each subcarrier, the CBS allocates the subcarrier to the SU who has the maximum benefit and allocates the power under the constraints caused by the interference demands;

4) The process continues until PUs are just not in *state* ϑ.

B. Cooperative Bidding Model

In the auction, the SUs cause co-channel interference to other SUs and reduce their benefits. In order to get more benefits with appropriate interference demands, CBSs can choose a cooperative bidding in which case CBSs adjust SUs' bids through exchanging bidding information. Since the benefits obtained on different subcarriers are independent, we decompose the optimization problem with cooperative bidding into M subproblems. For the mth subcarrier, the problem can be formulated as follows

$$\max_{\{\rho_{ks}^m\},\{d_{ks}^m\}} \sum_{k\in\mathcal{K}} U_{ks}^m$$
$$s.t. \begin{cases} \sum\limits_{s\in\mathcal{S}} \sum\limits_{m\in\mathcal{M}} \rho_{ks}^m P_{ks}^m \le P_{k,\max}, \forall k \in \mathcal{K} \\ 0 \le P_{ks}^m, \forall k \in \mathcal{K} \end{cases} \tag{10}$$

The Lagrangian can be expressed as follows

$$\begin{aligned} L = \sum_{k\in\mathcal{K}} U_{ks}^m \quad & - \sum_{k\in\mathcal{K}} \lambda_k \Big(\sum_{s\in\mathcal{S}} \sum_{m\in\mathcal{M}} \rho_{ks}^m P_{ks}^m - P_{k,\max}\Big) \\ & - \sum_{k\in\mathcal{K}} \beta_k (-P_{ks}^m) \end{aligned} \tag{11}$$

where λ_k and β_k are Lagrange multipliers for the constraints in (10) respectively.

C. Equilibrium and Convergence

As stated before, the optimization problem in (4) is a complex non-convex problem. We model the problem as a repeated auction and then solve for the joint subcarrier and power allocation scheme through the analysis of one-shot auction solution and convergence of the repeated auction.

1) One-shot Auction with Given Price

In one-shot auction, the SUs submit their bids only once and pay the trade price given by the PU. For the price, each CBS chooses its demand vector to maximize its benefit function. Note that the benefit of CBS k is $U_k = \sum_{s\in\mathcal{S}} \sum_{m\in\mathcal{M}} U_{ks}^m$. The non-cooperative auction game can be defined formally as

$$\mathbf{G}(K, \{\mathbf{d_k}\}, \{U_k\}) = \max_{\mathbf{d_k}} U_k(\mathbf{d_k}, \mathbf{d_{-k}}), \forall k \in \mathcal{K} \tag{12}$$

Nash equilibrium (NE) [11] is a solution of demand vectors, which satisfies

$$U_k(\mathbf{d_k^*}, \mathbf{d_{-k}^*}) \ge U_k(\mathbf{d_k}, \mathbf{d_{-k}^*}) \tag{13}$$

In the case, each CBS maximizes its benefit in a distributed way, then the demand vector constitutes a *best response* to the demand vectors chosen by other CBSs. Best response function is defined as follows

$$\mathbf{r}_k(\mathbf{d}_{-k}) = \arg\max_{\mathbf{d}_k} U_k(\mathbf{d}_k, \mathbf{d}_{-k}) \tag{14}$$

The problem of maximizing U_k can be decomposed into maximizing U_{ks}^m for each m. For each SU, we have the vector (ρ_{ks}^m, d_{ks}^m) representing whether the mth subcarrier is allocated to SU s in cell k or not and how much interference is allocated. Let $N_{ks} = N_0 + \sum\limits_l I_{ls}$, $G_{ks}^m = g_{ks}^m/\Omega_{lk}^m$, $H_{ks}^m = h_{ks}^m/\Omega_{lk}^m$. If the mth subcarrier is allocated to SU s, then we have

$$\frac{\partial U_{ks}^m}{\partial d_{ks}^m} = \frac{G_{ks}^m}{(\ln 2)(N_{ks} + \sum\limits_{j\neq k} H_{js}^m d_{js} + G_{ks}^m d_{ks}^m)} - \mathcal{P} \tag{15}$$

According to (14), d_{ks}^m can be obtained by $\frac{\partial U_{ks}^m}{\partial d_{ks}^m} = 0$, that is

$$d_{ks}^m = [\frac{1}{\mathcal{P}\ln 2} - \frac{N_{ks} + \sum_{j\neq k} H_{js}^m d_{js}^m}{G_{ks}^m}]^+ \tag{16}$$

where $[x]^+$ is equal to x if $x > 0$, otherwise equal to 0. Denoted $a_{ks}^m = \frac{G_{ks}^m}{(N_{ks} + \sum\limits_{j\neq k} H_{js}^m d_{js}^m)}$. If $d_{ks}^m = \frac{1}{\mathcal{P}\ln 2} - \frac{1}{a_{ks}^m}$, we have

$$\max U_{ks}^m = \log_2 \frac{a_{ks}^m}{\mathcal{P}\ln 2} - \frac{1}{\ln 2} + \frac{\mathcal{P}}{a_{ks}^m} \tag{17}$$

We know $d_{ks}^m \ge 0$, i.e. $a_{ks}^m > \mathcal{P}\ln 2$, otherwise $d_{ks}^m = 0$. We can get $\frac{\partial U_{ks}^m}{\partial a_{ks}^m} \ge 0$, so the function in (17) is non-decreasing with a_{ks}^m. We allocate the subcarrier to the SU who has the maximum a_{ks}^m, set $\rho_{ks}^m = 1$, and get (16). Then the best response is

$$\{\{\arg\max_{d_{ks'}^m} U_{ks'}^m | s' = \arg\max_s a_{ks}^m \wedge \rho_{ks'}^m = 1\}, m \in \mathcal{M}\} \tag{18}$$

If co-channel interference among SUs is weak, we assume that subcarrier allocation strategies are independent. The SU who has the highest ratio of data channel gain to interference channel gain to PU will win the auction. Therefore, the resource allocation problem can be simplified to power allocation problem. Since the strategy space of each SU is a compact, convex set and the benefit function is quasi-concave in d_{ks}^m, an Nash equilibrium exists under certain conditions [12].

2) Repeated Auction with Dynamically Changed Price

As mentioned above, the interference auction is a repeated auction. The equilibrium of the auction is obtained when the supply of auctioneer and the sum demand of bidders balance.

Theorem 1. If ε is small enough, the interference auction will get convergence to equilibrium.

Proof: According to (16), then we get

$$\frac{1}{\mathcal{P}\ln 2} = \frac{N_{ks} + \sum\limits_{j\neq k} H_{js}^m d_{ks}^m}{G_{ks}^m} + d_{ks}^m \tag{19}$$

Update the price $\mathcal{P}' = \mathcal{P} - \varepsilon\delta$ and set ${\rho_{ks'}^m}' = 1$, we have

$$\frac{1}{\mathcal{P}'\ln 2} = \frac{N_{ks'} + \sum\limits_{j\neq k} H_{js'}^m {d_{js'}^m}'}{G_{ks'}^m} + {d_{ks'}^m}' \tag{20}$$

As stated before, $a_{ks'}^m > a_{ks}^m$. We have

$$\frac{1}{\mathcal{P}'\ln 2} \leq \frac{N_{ks} + \sum\limits_{j\neq k} H_{js}^m {d_{js}^m}'}{G_{ks}^m} + {d_{ks}^m}' \tag{21}$$

Note that the demand vector on the mth subcarrier is $({d_1^m}', ..., {d_K^m}') = (d_1^m + \Delta d_1^m, ..., d_K^m + \Delta d_K^m)$, where d_K^m is the interference demand of cell K on the mth subcarrier. Subtracting (19) from (21), for $k \in \mathcal{K}$, we get K equations, which can be written as

$$\begin{bmatrix} 1 & ... & \frac{\mathcal{H}_{1K}^m}{\mathcal{G}_1^m} \\ & 1 & \\ \frac{\mathcal{H}_{K1}^m}{\mathcal{G}_K^m} & ... & 1 \end{bmatrix} \begin{bmatrix} \Delta d_1^m \\ .. \\ \Delta d_K^m \end{bmatrix} \geq \begin{bmatrix} \frac{\varepsilon\delta}{(\ln 2)\mathcal{P}(\mathcal{P}-\varepsilon\delta)} \\ .. \\ \frac{\varepsilon\delta}{(\ln 2)\mathcal{P}(\mathcal{P}-\varepsilon\delta)} \end{bmatrix} \tag{22}$$

where $\mathcal{H}_{kk'}^m$ is $\{H_{k's}^m | \rho_{ks}^m = 1 \wedge s \in \mathcal{S}\}$ and $\mathcal{G}_k^m$ is $\{G_{ks}^m | \rho_{ks}^m = 1 \wedge s \in \mathcal{S}\}$. Assuming $\frac{\mathcal{H}_{kk'}^m}{\mathcal{G}_k^m} \ll 1$, then we obtain $\Delta d_k^m > 0$. If ε is small enough, we have

$$\sum_{k\in\mathcal{K}}\sum_{s\in\mathcal{S}}\sum_{m\in\mathcal{M}} \rho_{ks}^m d_{ks}^m < \sum_{k\in\mathcal{K}}\sum_{s\in\mathcal{S}}\sum_{m\in\mathcal{M}} {\rho_{ks}^m}' {d_{ks}^m}' \leq I^{th} \tag{23}$$

In the auction process, the sum demand of bidders approaches the supply of auctioneer gradually. Only when they balance, the demands of bidders remain unchanged. Then auction can reach the equilibrium.

TABLE I
INTERFERENCE AUCTION ALGORITHM

(i) **Initialization**
for each SU, set $d_{ks}^m = 0$;
for each PU, set $\mathcal{P}_l = \mathcal{P}_0$;
(ii) **Selling**
if PU is in *state* ϑ
for each PU
calculate δ_l;
according to (9), decrease the trade price;
else
action end;
(iii) **Buying**
for each m,
for each CBS k,
get $s = \arg\max_s a_{ks}^m$;
set $\rho_{ks}^m = 1$;
get $d_{ks}^m = \arg\max_d (u_{ks}^m - d * \mathcal{P}_l)$;
go to (ii);

3) Interference Auction Algorithm

To obtain the equilibrium solution, the interference auction algorithm is developed. Formally, we present the detailed algorithm steps in Table 1, where $\mathcal{P}_0$ is the initial price of the interference auction.

IV. SIMULATION RESULTS

In this section, simulations are performed for the downlink of an OFDM-based CRN consisting of seven cells with the radius of 0.289km [15]. In each cell, there is a CBS located at the center and eight SUs uniformly distributed. Three PUs occupy 3,2,3 continuous subcarriers respectively. The SUs share 16 subcarriers, each with the noise power of 10^{-16} W and interference power of 10^{-15} W from PUs. The value of Δf and T_s is assumed to be $0.3125MHz$ and $4\mu s$ respectively. The PUs have the equal interference power threshold $I_l^{th} = 8\times10^{-14}$ W. The total power for each CBS is 28 dBm. All the results are obtained from 10000 simulation realizations.

Firstly, we consider the one-PU scenario to illustrate the performance of the multi-cell algorithm compared with the single-cell optimal algorithm. To evaluate the performance, the adaptive power allocation algorithm [13] for single-cell and equal interference algorithm are considered as the comparison schemes. With equal interference algorithm, each SU has the same interference to PUs. We assume the CBSs assign the subcarriers to the SUs with the highest data channel gain. Figure 3 shows the rate as a function of the PUs' interference power threshold. We can see that the rate of the proposed auction algorithm is about 0.50 and 0.95 bit more than that of the adaptive power allocation algorithm and equal interference algorithm respectively regardless of difference interference power thresholds. This is because the proposed algorithm optimizes the resource distribution among cells with the coordination of inter-cell interference. The rates of three

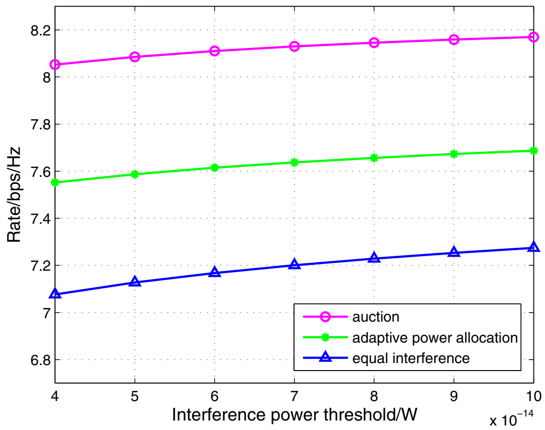

Fig. 3. Rate with different interference power threshold

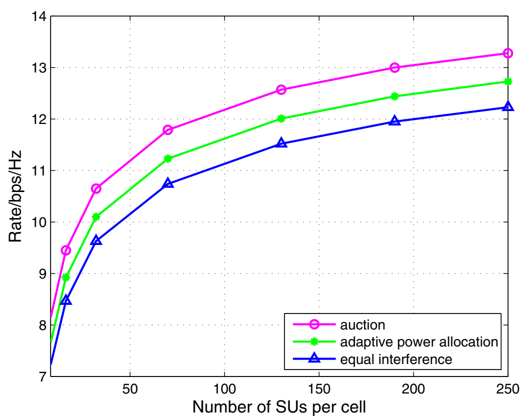

Fig. 4. Rate with different number of SUs per cell

schemes increase with the interference power threshold, for the SUs can obtain more transmitted power.

Figure 4 shows the rates of the three algorithms mentioned above with different number of SUs. The improvement of the proposed algorithm increases and reaches 0.55 and 1.05 bit more than the adaptive power allocation algorithm and equal interference algorithm respectively when the number of SUs is 250. The three algorithms are shown to achieve higher rates with a gradually decreasing trend. That is because the subcarrier channel gain changes in a certain range and becomes larger statistically with more SUs.

Finally, the multi-PU scenario is extended to evaluate the convergence. It is shown in Figure 5 that the Max-Min algorithm [14] which gets convergence after about 1000 iterations, is 30 times slower than the proposed algorithm. Moreover, the performance of the interference auction is better than max-min algorithm and equal interference algorithm.

V. Conclusion

An effective interference auction has been proposed to solve the joint power and subcarrier allocation problem with co-channel interference as well as mutual interference between SUs and PUs. In the auction, SUs bid for PUs' interference repeatedly. A theoretic analysis of one-shot auction solution

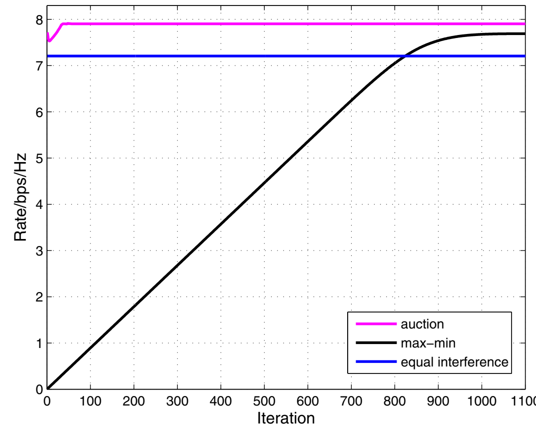

Fig. 5. Convergence behavior

is given and the convergence of the interference auction is proved. Besides, the interference auction algorithm is developed to obtain the resource allocation scheme. Simulation results show that the interference auction achieves higher rate than the single-cell optimal algorithm and obtains a good convergence.

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