Interference-limited Resource Allocation Algorithm in Cognitive Heterogeneous Networks

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Abstract

Interference mitigation is a significant issue in the cognitive heterogeneous networks, this paper studied how to reduce the interference to macrocell users (MU) and improve system throughput. Establish the interference model with imperfect spectrum sensing by analyzing the source of interference complexity. Based on the user topology, the optimize problem was built to maximize the downlink throughput under given interference constraint and the total power constraint. We decompose the resource allocation problem into subcarrier allocation and power allocation. In the subcarrier assignment step, the allocated number of subcarriers satisfies the requirement of the femtocell users (FU).Then, we designed the power allocation algorithm based on the Lagrange multiplier method and the improved water filling method. Simulation results and performance analyses show that the proposed algorithm causes less interference to MU than the algorithm without considering imperfect spectrum sensing, and the system achieves better throughput performance.

Keywords: Interference mitigation, cognitive heterogeneous networks, spectrum sensing, resource allocation, Lagrange multiplier method

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1. Introduction

With the rapid increase in wireless data rates, the demand in the new generation of wireless devices at the transport level grows sharply. However, radio spectrum scarcity crisis exists for many wireless applications, which is becoming a bottleneck to develop them. A practical solution is heterogeneous networks (HetNets), which consists of various communication nodes with different capacities and operating functions. Such as macrocell base station (MBS), microcell base station, picocell base station, femtocell base station (FBS) and relay base station. These nodes can potentially improve spectrum efficiency significantly by enhancing area spectrum reuse. As a new generation of HetNets, macro/femtocell has great advantages in improving network performance in hotspot area, reducing service latency, improving system throughput and guaranteeing quality of service (QoS).Convergence of heterogeneous wireless access techniques has emerged as one of the key solutions for fifth-generation(5G) mobile networks[1]. Hence, femtocells have attracted a lot of interests in the last few years in both industry and academia. In order to fully reap their potential gains, many critical issues should be solved, such as resource allocation, interference mitigation, spectrum access, and QoS guaranteeing. HetNets bring many advantages, but also bring interference problems. There is a lack of coordination between macrocells and femtocells, which can cause serious cross-tier interference when using the same channel. When the same channel is used between femtocells, there may be co-tier interference.

Cognitive radio (CR) is considered as a promising method to solve the spectrum efficiency problem, it is also considered as the most effective interference management scheme in HetNets [2]. The femtocell combined with CR can dynamically identify the radio environment of the cellular system and choose to access subchannel that produces minimal interference to MU. The cognitive capability can further improve the spectrum efficiency, wireless resource utilization, and we can carry out interference mitigation by effective spectrum sensing, interference sensing and adaptive transmission. Therefore, femtocell combined with CR can further improve the system performance [3]. The introduction of multicarrier technology in CR networks can meet the needs of flexible access in its physical layer setup. Owing to the inherent significant advantages of flexibly allocating radio resource, orthogonal frequency division multiple access (OFDMA) is deemed as a promising air interface for long term evolution (LTE) femtocells [4]. With OFDMA modulation, the co-tier interference can be eliminated by exploiting orthogonal radio resources among femtocells.

The study of resource allocation in cognitive HetNets is attracting more and more attention. Cognitive HetNets can improve cellular coverage and offload traffic from existing macrocells via resource allocation and interference mitigation. In [5], the issues on spectrum sensing and interference mitigation were investigated, where interference coordination approach was applied. In[6],to solve the comprehensive spectrum management problem,the author proposed a new protocol for carrier sensing and interference avoidance for HetNets. The author of [7] proposed a practical low complexity solution to the problem for bandwidth and power allocation in hybrid access cognitive HetNets networks. An optimal energy-efficient power allocation problem of uplink cognitive FU in spectrum sharing mode is analyzed in [8]. In [9], considering the signal noise ratio (SNR) and channel capacity, the algorithm solves the multi-channel scheduling problem in three steps to achieve equalization of spectrum access opportunity, performance and energy efficiency, but it has a high complexity. According to [10], a dynamic spectrum allocation scheme in mixed access mode was proposed, which maximizes the system utility function under the total power and the transmission rate of FU constraints. But the source of interference is not comprehensive enough. All above literatures studied are based on the assumption that the spectrum sensing is perfect. However, due to propagation loss, shadow fading, multi-path fading, CR receiver sensitivity and other factors, imperfect spectrum sensing (spectrum sensing errors) always exist in realistic communication scenarios. In [11], considering the imperfect channel sensing and QoS requirement, a discrete stochastic algorithm with low complexity of joint power and channel allocation was proposed. However, it does not take interference constraints to MU into account and has a strict limitation of the number of access users. The authour of [12] proposed a fast resource allocation algorithm based on imperfect spectrum sensing and uncertain channel state was proposed. In the literature [13-14] subcarrier allocation and power allocation schemes are all based on a complete integral algorithm, but the algorithm has high computational complexity due to the inner loop and outer loop. In [15], the dual decomposition method was used to optimize the resource allocation in the cognitive femtocell system. The interference introduced to MU which is caused by out-of-band emissions and spectrum sensing errors. Ignoring the spectrum sensing errors means aggravating the interference to MU.

In order to reduce the interference to MU, to improve the system throughput and to reduce the algorithm complexity, we propose a resource allocation method considering imperfect spectrum sensing based on OFDMA multi-carrier technology. First, we express the interference which is considering imperfect spectrum sensing. Then we implement the resource allocation, the interference expression will be used in this step. We divide resource allocation into subcarrier allocation and power allocation. The remainder of this paper is outlined as follows. Section 2 introduces the system model and formulates the problem. The resource allocation algorithm is developed in Section 3. Simulation results are provided in Section 4, followed by the conclusions in Section 5.

2. System Model and Problem Formulation

2.1 System Model

The 3GPP standard specifies seven macrocells in the urban deployment scenario [16]. The MBS is located at the center of the macrocell and each macrocell is divided into three sectors. This paper analyzes the downlink scenario with only one macrocell, including one MBS and F FBS, as shown in **Fig. 1**. Femtocells are deployed within the MBS coverage, and the OFDMA system bandwidth is B_H, divided into N_{total} subchannels. The channel model for each subchannel includes path loss and Rayleigh fading. The FU opportunistically access the spectrum licensed to the macrocells via cognitive FBS. In each spectrum sensing period, the cognitive FBS senses subchannels licensed to the macrocell network and determine available vacant subchannels.

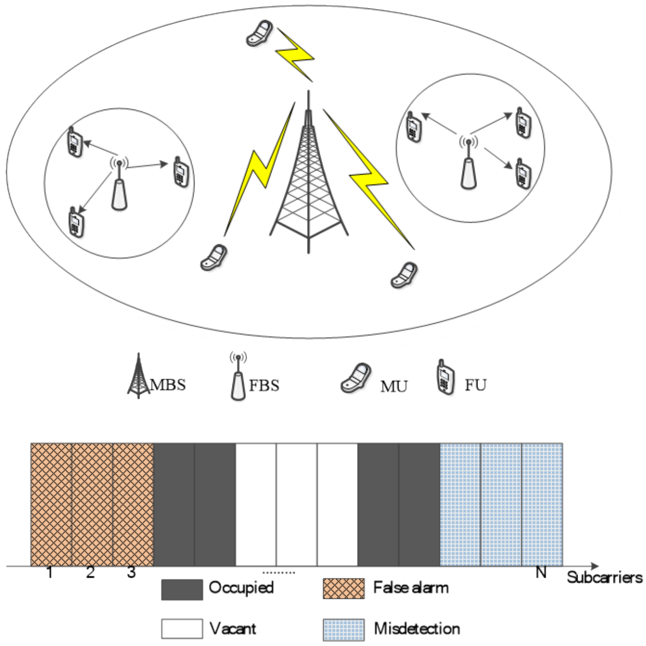

Fig. 1. Cognitive macro/femtocell network model

2.2 Interference Model with Imperfect Spectrum Sensing

With the interference induced by the cognitive femtocell networks to macrocell network derives from two aspects: out-of-band emissions and spectrum sensing errors. When the cognitive FU transmits information over the subcarrier *n* with unit transmit power, the interference introduced to the lth MU can be expressed as

$$I_{l,n} = \int_{|f_n - f_l| - B_l/2}^{|f_n - f_l| + B_l/2} \left| g_{n,l} \right|^2 \Phi_n(f) df \tag{1}$$

where f_n is the center frequency of subcarrier *n*. B_l denotes the MU bandwidth. f_l is the center frequency of MU. $g_{n,l}$ is the channel gain between the subcarrier *n* and the *l*th MU. $\Phi_n(f)$ is the power spectrum density (PSD) of subcarrier *n* used by a cognitive FU and can be denoted as $\Phi_n(f) = T_s(\sin \pi f T_s / \pi f T_s)$, where T_s is the sampling interval.

In cognitive macro/femtocell networks, imperfect spectrum sensing usually causes severe co-channel interference to MU and degrades the performance of the cognitive heterogeneous networks. There are four possible cases for the cognitive FBS that determines if a subchannel is occupied by MBS or not, which are listed as follows. (1) Subcarrier *n* is vacant in a macrocell network, and it is identified vacant through spectrum sensing. (2) Subcarrier *n* is vacant in a macrocell network, but it is identified occupied through spectrum sensing. (3) Subcarrier *n* is occupied in a macrocell network, and it is identified vacant through spectrum sensing. (4) Subcarrier *n* is occupied in a macrocell network, and it is identified occupied through spectrum sensing. For the first and fourth cases, the spectrum sensing made the correct decisions. The second case is a misdetection, and the third case is a false alarm. Denote q_n^f and q_n^m as the probabilities of the false alarm and misdetection. Denote H_n^o and $\tilde{H}_n^o$ as the subcarrier *n* is occupied by MU and the sensing result of subcarrier *n* is occupied by MU respectively. H_n^v and $\tilde{H}_n^v$ are the events of subcarrier n is vacant and the sensing result of subcarrier n is vacant respectively. Therefore, we can get the condition probabilities for the four cases as follows.

$$\begin{aligned}\omega_{1,n} &= \Pr\{H_n^v \mid \tilde{H}_n^v\} \\ &= \frac{\Pr\{\tilde{H}_n^v \mid H_n^v\}\Pr\{H_n^v\}}{\Pr\{\tilde{H}_n^v \mid H_n^v\}\Pr\{H_n^v\}+\Pr\{\tilde{H}_n^v \mid H_n^o\}\Pr\{H_n^o\}} \\ &= \frac{(1-q_n^f)(1-q_n^p)}{(1-q_n^f)(1-q_n^p)+q_n^m q_n^p}\end{aligned} \tag{2}$$

$$\begin{aligned}\omega_{2,n} &= \Pr\{H_n^v \mid \tilde{H}_n^0\} \\ &= \frac{\Pr\{\tilde{H}_n^o \mid H_n^v\}\Pr\{H_n^v\}}{\Pr\{\tilde{H}_n^o \mid H_n^v\}\Pr\{H_n^v\}+\Pr\{\tilde{H}_n^o \mid H_n^o\}\Pr\{H_n^o\}} \\ &= \frac{(1-q_n^p)q_n^f}{(1-q_n^p)q_n^f+(1-q_n^m)q_n^p}\end{aligned} \tag{3}$$

$$\begin{aligned}\omega_{3,n} &= \Pr\{H_n^o \mid \tilde{H}_n^v\} \\ &= \frac{\Pr\{\tilde{H}_n^v \mid H_n^o\}\Pr\{H_n^o\}}{\Pr\{\tilde{H}_n^v \mid H_n^v\}\Pr\{H_n^v\}+\Pr\{\tilde{H}_n^v \mid H_n^o\}\Pr\{H_n^o\}} \\ &= \frac{q_n^m q_n^p}{(1-q_n^f)(1-q_n^p)+q_n^m q_n^p}\end{aligned} \tag{4}$$

$$\begin{aligned}\omega_{4,n} &= \Pr\{H_n^o \mid \tilde{H}_n^0\} \\ &= \frac{\Pr\{\tilde{H}_n^o \mid H_n^o\}\Pr\{H_n^o\}}{\Pr\{\tilde{H}_n^o \mid H_n^v\}\Pr\{H_n^v\}+\Pr\{\tilde{H}_n^o \mid H_n^o\}\Pr\{H_n^o\}} \\ &= \frac{(1-q_n^m)q_n^p}{(1-q_n^p)q_n^f+(1-q_n^m)q_n^p}\end{aligned} \tag{5}$$

where q_n^p is the probability of subcarrier n is occupied by MU, $\omega_{1,n}$ is the probability of subcarrier n is actually vacant, and it will be used when we establish the objective function of the resource allocation problem. We use ω_n instead of $\omega_{1,n}$.

Based on the above analyses, the downlink cross-tier interference from the cognitive femtocell to the MU can be expressed as

$$I_{kn} = p_{n,k}\left(\sum_{n\in N_v}\omega_{3,n}I_{l,n} + \sum_{n\in N_o}\omega_{4,n}I_{l,n}\right) = p_{n,k}\tilde{I}_n \tag{6}$$

where N_v and N_o are the sets of vacant and occupied subcarriers respectively. $\sum_{n\in N_v}\omega_{3,n}I_{l,n}$ is the interference caused by out-of-band emissions. $\sum_{n\in N_o}\omega_{4,n}I_{l,n}$ is the interference caused by spectrum sensing errors.

2.3 Problem Formulation

First, we define a binary variable $a_{n,k}$ as subcarrier assignment index,

$$a_{n,k}=\begin{cases}1, \text{subcarrier } n \text{ is allocated to user } k\\ 0, \text{otherwise}\end{cases} \tag{7}$$

According to the Shannon capacity formula, the transmission rate of user *k* served by the *n*th subcarrier can be written as

$$R_{n,k}=\Delta f\log_2(1+\frac{r_{n,k}p_{n,k}}{\Gamma}) \tag{8}$$

where Δf is the subcarrier bandwidth, and Γ is a constant that depends on the bit error ratio (BER),the coding gain and the modulation scheme, $\Gamma=\frac{-\ln(5BER)}{1.5}$ in MQAM. We assume Γ =1 for the study of modulation is out of scope of this work. $r_{n,k}$ is the signal to interference plus noise ratio (SINR), it can be written as

$$r_{n,k}=\frac{\left|g_{n,k}\right|^2}{\sum_{l=1}^{L}J_n^l+\sigma_{AWGN}^2}=\frac{\left|g_{n,k}\right|^2}{\sigma_n^2} \tag{9}$$

where σ_{AWGN}^2 is the white Gaussian noise variance, J_n^l is the interference to subcarrier *n* when the *l*th user transmits date. Assuming σ_n^2 is all same on each subcarrier, that is $\sigma_n^2=\sigma^2$, therefore, the user rate R_k can be expressed as

$$R_k=\sum_{n\in N_v}a_{n,k}\Delta fR_{n,k}=\sum_{n\in N_v}a_{n,k}\Delta f\log\left(1+\frac{\left|g_{n,k}\right|^2p_{n,k}}{\sigma^2}\right) \tag{10}$$

We assume that each subcarrier goes under frequency flat fading gains and the instantaneous fading gains are perfectly known at the CR system. The objective of the optimization problem is to maximize the system throughput, while the transmit power and the interference to MU are under corresponding threshold value. The resource allocation problem can be formulated as follows

$$\text{R1:}\max\sum_{k=1}^{K}\sum_{n\in N_v}a_{n,k}\omega_n\Delta f\log\left(1+\frac{\left|g_{n,k}\right|^2p_{n,k}}{\sigma^2}\right) \tag{11}$$

s.t.

$$\sum_{k=1}^{K}a_{n,k}\le 1, n\in N_v \tag{12}$$

$$a_{n,k} \in \{0,1\}, \forall n \in N_v, \forall k \tag{13}$$

$$\sum_{k=1}^{K} \sum_{n \in N_v} a_{n,k} p_{n,k} \le P_T \tag{14}$$

$$\sum_{k=1}^{K} \sum_{n \in N_v} a_{n,k} I_{kn} \le I_{th}^{l} \tag{15}$$

$$p_{n,k} \ge 0, \forall n \in N_v, \forall k \tag{16}$$

where P_T is the total power constraint, I_{th}^{l} is the interference threshold of the lth MU.

3. The Proposed Resource Allocation Algorithm

The optimal problem is a mixed-integer nonlinear programming. The computational complexity increases exponentially with the increase of the data. It is not feasible to solve it directly in actual cellular system. To find the global optimal solution, we need to search all available power allocation spaces and all possible subchannel allocation combinations. In this paper, the problem is solved in two steps to reduce the computational complexity: subcarriers assignment and power assignment. Once the subcarriers assignment is determined, the system can be viewed virtually as a single user system which makes the problem computationally simpler.

3.1 Subcarriers Allocation

According to [17], the macro/femtocell system can obtain the maximum transmission rate in downlink if the subcarriers are assigned to FU with the best channel gain. With the best channel gain criterion, if the number of subcarriers assigned to the FU satisfies the subcarrier requirement of this FU, then the assignation of subcarriers to the user is ceased. The remaining subcarriers continue to be assigned with the best channel gain, and the process continues until the subcarrier requirement is met for each FU.

The number of subcarriers required for the kth FU is estimated as follows

$$\tilde{N}_k = \left\lceil R_{th}^{k} \Big/ \Delta f \log_2\left(1 + \left|\overline{g_k}\right|^2 \overline{p_k} \Big/ \sigma^2\right) \right\rceil \tag{17}$$

where $\lceil \bullet \rceil$ is the upward rounding function, $\overline{p_k} = P_T / N$ is the average power allocated to each subcarrier of kth FU, $\overline{g_k} = \sum_{n=1}^{N} g_{n,k} / N$ is the average channel gain on each subcarrier for the kth FU. The implementation of the subcarriers allocation algorithm is described in **Table 1**.

Table 1. Subcarriers allocation algorithm

Subcarriers allocation algorithm
1. Initialization: set $a_{n,k} = 0, \ \forall n \in N_v, \forall k$
2. Compute $\tilde{N}_k, \ \forall k$
3. for n=1 to $n = \sum_{k=1}^{K} \tilde{N}_k$ **do**
$k^* = \arg\max_k g_{n,k}, a_{n,k^*} = 1, N'_{k^*} = N'_{k^*} + 1$

if $N'_{k^*} = \tilde{N}_{k^*}$

let $g_n^{k^*} = 0,\ \forall n \in N_v, \forall k$

end if

end for

4. **for** $n = \sum_{k=1}^{K} \tilde{N}_k + 1$ to $n=N$ **do**

$k^* = \arg\max_k g_{n,k}$, $a_{n,k^*} = 1$

end for

3.2 Power Allocation

By subcarrier assignment, the values of the subcarrier allocation indicator $a_{n,k}$ are determined. And hence the optimization problem R1 can be reformulated as follows:

$$\text{R2: } \max \sum_{n \in N_v} \omega_n \Delta f \log\left(1 + \frac{|g_n|^2 p_n}{\sigma^2}\right) \tag{18}$$

$s.t.$

$$\sum_{n=1}^{N} p_n \le P_T \tag{19}$$

$$\sum_{n=1}^{N} p_n \tilde{I}_n \le I_{th}^l, \forall l \tag{20}$$

$$p_n \ge 0, \forall n \in N_v \tag{21}$$

R2 is a nonlinear convex problem and the optimal solution can be obtained by the Lagrange multiplier. The Lagrange function can be written as

$$L = -\sum_{n=1}^{N} \Delta f \log_2\left(1 + \frac{p_n |g_n|^2}{\sigma^2}\right) + \alpha\left(\sum_{n=1}^{N} p_n - P_T\right) + \sum_{l=1}^{L} \gamma_l \left(\sum_{n \in N_l} p_n \tilde{I}_n - I_{th}^l\right) - \sum_{n=1}^{N} \beta_n p_n \tag{22}$$

$$\alpha \ge 0,\ \beta_n \ge 0,\ \gamma_l \ge 0$$

where α 、 β_n 、 and γ_l are the Lagrange multipliers. For any given user scheduling and user selection, the corresponding power allocation must satisfy the Karush-Kuhn-Tucker (KKT) conditions. According to the KKT conditions, the solution to the optimization problem R2 is given by

$$p_n^* = \left[\frac{\omega_n \Delta f}{\alpha + \gamma_l \tilde{I}_n} - \frac{\sigma^2}{|g_n|^2}\right]^+ \tag{23}$$

Proof The details of the proof is given in Appendix.

where $[x]^+ = \max(0, x)$, the solution for optimization problem R2 has a high computational complexity which makes it unsuitable for the practical wireless system. In order to reduce the complexity, the interference-limited resource allocation algorithm (ILRA) is proposed. So continue to break down the problem. Ignoring the total power constraint in R2, the solution of the problem can be written as

$$p_n = \left[\frac{\omega_n \Delta f}{\gamma_l \tilde{I}_n} - \frac{\sigma^2}{|g_n|^2} \right]^+ .. \tag{24}$$

This solution ensures that the interference introduced to MU is below the interference threshold. The power assigned to each subcarrier cannot exceed p_n, this is the maximum power which subcarriers can be obtained $p_n^{\max} = p_n$. Substitute Eq.(24) into Eq.(20), the Lagrange multiplier γ_l can be get as follows

$$\gamma_l = \frac{|N_v|}{I_{th}^l + \sum_{n \in N_v} (\sigma^2 \tilde{I}_n / |g_n|^2)} \tag{25}$$

The total power is tested once the maximum power $p_n^{\max}$ is determined. The solution is equal to the maximum power if the total power constraint is satisfied, that is $p_n^{\max} = p_n$. The available power budget should be distributed among subcarriers assures that the power allocated to each subcarrier is lower than or equal to the maximum power $p_n^{\max}$, so the followed problem should be solved

$$\text{R3:} \max_{p_n^{WF}} \sum_{n \in N_v} \omega_n \Delta f \log_2 \left(1 + \frac{p_n^{WF} |g_n|^2}{\sigma^2} \right) \tag{26}$$

$$s.t.$$

$$\sum_{n=1}^{N} p_n^{WF} \le P_T \tag{27}$$

$$0 \le p_n^{WF} \le p_n^{max}, \quad \forall n \in N_v \tag{28}$$

Note that the objective function in R1, R2 and R3 contains the weight factor ω_n. Since it is assumed that $p_n^{WF} \le p_n^{max}$, the sum of power allocated to each subcarrier satisfies the total power constraints of cognitive femtocell system. This will make the interference introduce to MU below the threshold I_{th}^l. In the process of power allocation, we implement the power allocation to subcarrier according to its weight factor ω_n. Then we execute the 'Geometric Water-Filling with Peak Power constraints (GWFPP) [18]' to allocate power to subcarriers in R3. The solution will be the final power allocated to subcarriers. The implementation of power allocation algorithm is described in **Table 2** and the GWFPP algorithm is described in **Table 3**.

Table 2. ILRA algorithm

ILRA algorithm
Initialize $O = N$
Find the $p_n^{\max}$ as follows:
1) $\forall n \in O$, sort $\{T_n = \sigma^2 \tilde{I}_n / \lvert g_n \rvert^2\}$ in decreasing order with i being the sorted index.
2)Compute $T_{sum} = \sum_{n \in O} T_n$, $\gamma_l = \lvert O \rvert / I_{th} + T_{sum}$, m=1;
3)**While** $\gamma_l > T_{i(m)}^{-1}$ **do**
$T_{sum} = T_{sum} - T_{i(m)}$, $O = O - \{i(m)\}$, $\gamma_l = \lvert O \rvert / (I_{th} + T_{sum})$, m=m+1
end while
4)Set $p_n^{max} = \omega_n \Delta f / \gamma_l \tilde{I}_n - \sigma^2 / \lvert g_n \rvert^2$, $\forall n \in O$, $p_n^{max} = 0$, $\forall n \notin O$
Execute the GWFPP algorithm.

Table 3. GWFPP algorithm

GWFPP algorithm
1. Initialize $n = 1, 2, ..., N$, $\{d_n\}$, $\{\omega_n\}$, $\{p_n^{\max}\}$, $W_s = 0$, $O(N^3)$, i=1, i=1, $E = \{1, 2, ..., N\}$
2. Sort $\{d_n = 1/\alpha_n \omega_n\}$ in increasing order with k being the sorted index, compute $\alpha_n = \lvert g_n \rvert^2 / \sigma^2 \tilde{I}_n$, $W_s <= W_s + \omega_n$, $P^* <= P^* - (d_{i+1} - d_i) W_s$, then $i <= i+1$, where the symbol" $<=$ " represents the assignment operation.
3. if $P^* > 0$ and $i \le N$, $P_M = P^*$,
repeat step 2.
else
Output $k^* = i - 1$, $W_s = W_s - \omega_i$ and $s_{k^*} = \omega_{k^*} / W_s P_M$
end if
4. Compute the power allocated to subcarrier i as follows: $s_i = [s_{k^*} / \omega_{k^*} + (d_{k^*} - d_i)] \omega_i$, $1 \le i \le k^*$, $s_i = 0$, $k^* \le i \le N$.
5. Set 0,
if $\Lambda = \varnothing$
output $\{s_i\}_{i=1}^{N}$
else $s_i = P_i^{\max}$
6. Update date: $E = E \setminus \Lambda$, $P_T = P_T - \sum_{i \in \Lambda} s_i$, return 2.

The total computational complexity of the ILRA algorithm is $\sum_1^L O(\lvert N_l \log_2 \lvert N_l \rvert \rvert) \le O(N \log_2 N)$. For the GWFPP, it needs θ loops to compute the results. The complexity of GWFPP is $O(N \log_2 N + \theta N) \le O(N \log_2 N + N^2)$. The total complexity of the proposed algorithm is lower than $O(N \log_2 N + N^2)$. Compared with the exhaustive search method, which has a complexity of $O(N^3)$, the proposed algorithm has a much lower complexity.

4. Simulation Results

Simulations of the cognitive macro/femtocell system as shown in **Fig. 1** are performed. Set the MBS and femtocell using co-spectrum scheme. The probability of MU's occupation q_n^p, false alarm q_n^f, misdetection q_n^m are uniformly distributed over [0,1],[0.05,0.10],[0.01,0.05]. The channels suffer from Rayleigh fading and have a path loss exponent 4.The channel gain is modeled as independent and identically distributed random variables with unit mean. The channel model is generated by the simulation parameters are provided in **Table 4**. The efficiency of the proposed algorithm is compared with the suboptimal scheme in [19] and the joint iterative JIA algorithm in [20].

Table 4. Simulation parameters

Parameter	Value
Maximum MBS transmit power	46dBm
FBS transmit power(Max/Min)	20dBm/0dBm
Number of users	3MUE/sector 2FUE/FBS
Antenna gain(MBS/FBS)	14dBi/5dBi
Channel shadowing	Rayleigh shadowing
Carrier frequency	2000MHz
Noise spectral density	-174dBm/Hz
Bandwidth of subcarrier	15KHz
Bandwidth	10MHz

In our proposed algorithm, the power allocated to subcarrier i is $s_i = [s_{k^*}/\omega_{k^*} + (d_{k^*} - d_i)]\omega_i$. Set $i \in \{1,2,...,8\}$, $P_T = 30$, we first make a simple numerical simulation about the suboptimal scheme. **Fig. 2** shows the suboptimal scheme solution.

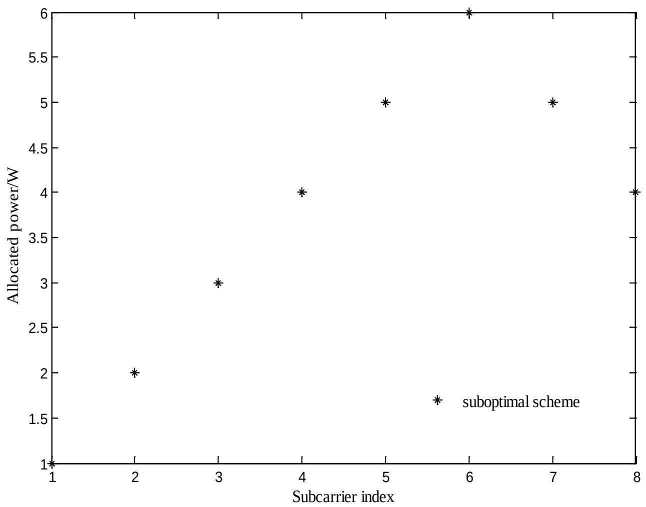

Fig. 2. Power allocation for the suboptimal scheme

Ignoring the power budget, we can obtain the optimal power allocation solution as shown in **Fig. 3**. In **Fig. 3**, the results obtained with the optimal scheme are maximums. **Fig. 2** shows that the power allocated to subcarrier 7 and 8 is lower than the results obtained with the optimal scheme in **Fig. 3**. From the results, it can be noted that the results of optimal scheme and the proposed suboptimal scheme are approximately similar, bur there is still a gap between the two schemes in individual subcarriers power allocation.

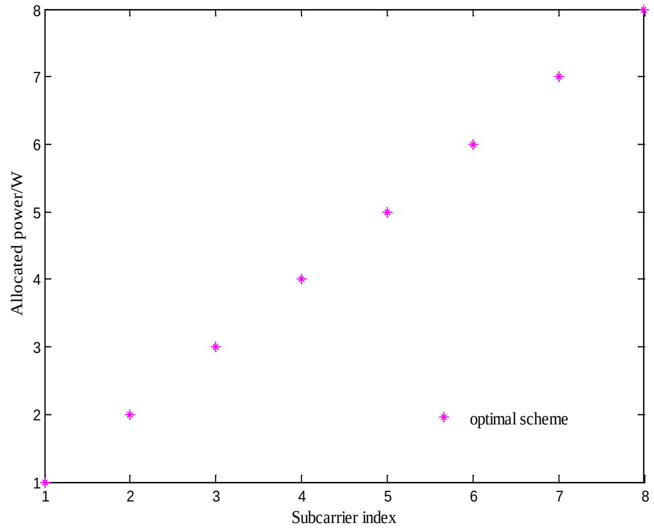

Fig. 3. Power allocation for the optimal scheme

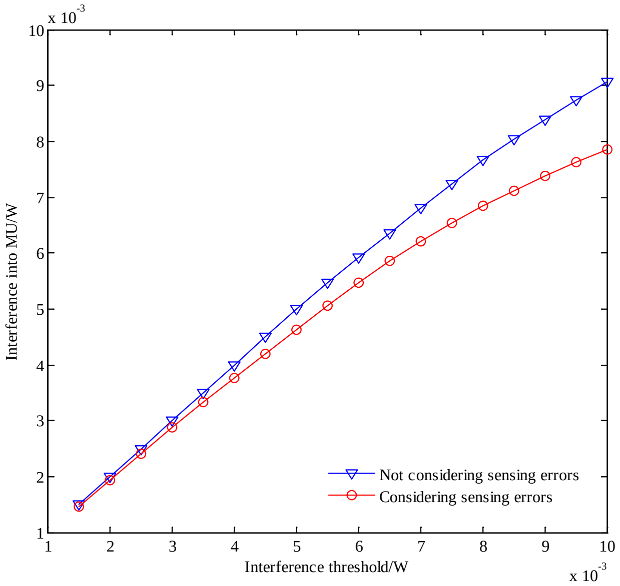

Fig. 4. Interference into MU versus interference threshold

Fig. 4 shows the relationship between the interference introduced to MU and the different interference threshold values, the cognitive networks total power is set as 1W. It can be noted that the interference introduced to MU is always below the interference threshold with the increase of the interference threshold which satisfies the interference constraints in R1-R3. This measure ensures that the MU's communication is normal when cognitive FU access the vacant subcarrier. With the threshold value increases, the interference introduced to MU using the proposed algorithm with considering spectrum sensing errors is less than that of algorithm without considering spectrum sensing errors. When spectrum sensing errors occurs in the system, FU will access the sensing error's subcarrier if ignore the error. It will cause the MU and FU signals coexist on the sensing error's subcarrier, the receiver will not demodulate the original signal and this situation will seriously affect the FU and MU's normal communication.

Fig. 5 shows that the system throughput with different interference constraints, and the cognitive networks total power is set as 1W. It can be seen from the figure that the capacity using the proposed algorithm is 1.5Mbps higher than that without considering spectrum sensing errors. The throughput which using the proposed algorithm with considering spectrum sensing errors is largest. Because the algorithm has less interference than the algorithm without considering spectrum sensing errors, the subcarrier can get more power. On the whole, the throughput using the proposed algorithm is largest, the throughput using the suboptimal scheme in Ref. [19] is second, and the CWF algorithm has the least throughput. In addition, the proposed algorithm curve grows slowly because the proposed algorithm has less interference than other algorithms, and the power allocated to each subcarrier approaches the maximum.

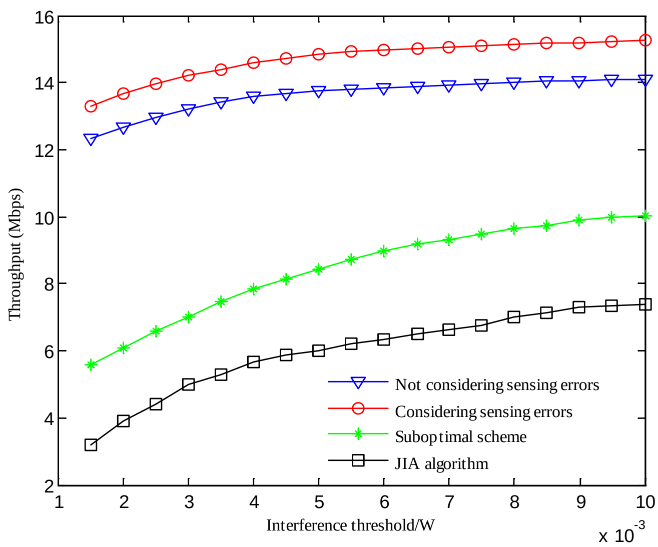

Fig. 5. System throughput versus interference threshold

In some specific scenarios, the MU has strict requirement for the cognitive user access to the licensed band. **Fig. 6** shows the system throughput with low interference threshold. At the low interference threshold, the MU's tolerance to interference is reduced. In this case, the interference threshold constraint will dominate the constraint conditions of the optimization problem. It can be seen from the figure that the throughput of considering the spectrum sensing errors is still higher than that of other algorithms, which shows that the proposed algorithm has better throughput performance under the condition of low interference tolerance. Because of the increase of the threshold value is slower, the throughput of the proposed algorithm becomes more stable.

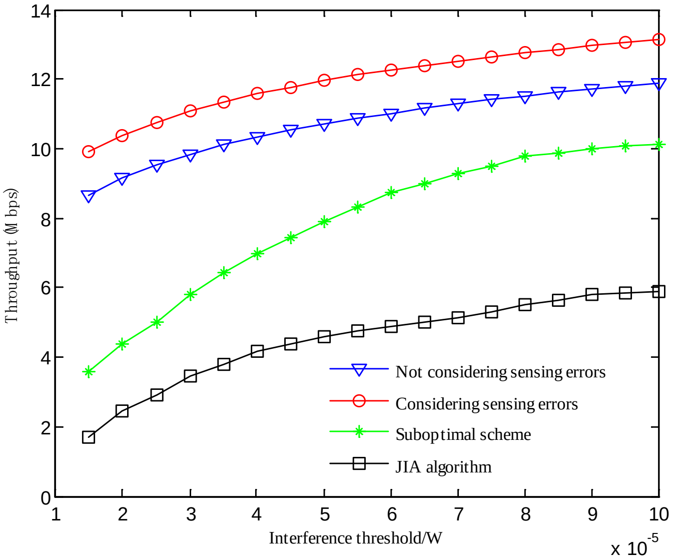

Fig. 6. System throughput versus interference (low) threshold

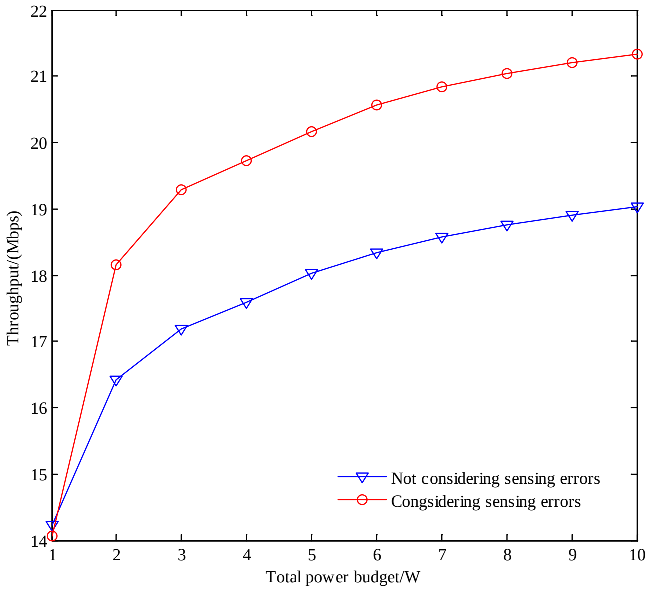

Fig. 7. The system throughput versus total power budget

Fig. 7 is the throughput of the cognitive system with different total power thresholds and the interference threshold is set as 0.01W. It can be noticed that the throughput using the proposed algorithm increases by about 2Mbps. As the total power threshold increases, the system throughput increases gradually. The system throughput increases slowly as the power threshold increases. This is because the interference introduced to MU approaches the interference threshold, so even if increases the total power, the throughput will not improve too much. The algorithm allocates subcarriers according to user subcarrier requirement, allocates power on subcarriers using GWFPP and considers spectrum sensing errors, which effectively improves system throughput.

5. Conclusion

In this paper, we have proposed a resource allocation algorithm for cognitive femtocells, considering the source of interference and imperfect spectrum sensing. By analyzing the source of interference completely, the interference model with imperfect spectrum sensing was established. The optimization problem was built to maximize the downlink throughput with considering total power constraint and interference constraint. Then simplified the problem based on the analysis of KKT conditions, and designed the resource allocation algorithm with the imperfect spectrum sensing. Finally, the GWFPP algorithm is used to allocate the power. Simulation results and performance analyses show that the proposed algorithm causes less interference to MU than the algorithm with perfect spectrum sensing, and achieves better throughput performance. For future work, we will focus on practical applications of 5G in cognitive heterogeneous networks.

6. Appendix

The proof of Eq.(23)
According to the KKT conditions, we have

$$p_n^* \geq 0, \forall n \tag{29}$$

$$\beta_n \geq 0, \forall n \tag{30}$$

$$\beta_n p_n^* = 0, \forall n \tag{31}$$

$$\frac{\partial L}{\partial p_n^*} = -\frac{\omega_n \Delta f}{\sigma^2 / |g_n|^2 + p_n^*} + \alpha + \gamma_l \tilde{I}_n - \beta_n = 0, \forall n \tag{32}$$

Eliminate β_n from (30), (31) and rewrite the KKT conditions as follows:

$$p_n^* \geq 0, \forall n \tag{33}$$

$$\alpha + \gamma_l \tilde{I}_n \geq \frac{\omega_n \Delta f}{\sigma^2 / |g_n|^2 + p_n^*}, \forall n \tag{34}$$

$$(\alpha + \gamma_l \tilde{I}_n - \frac{\omega_n \Delta f}{\sigma^2 / |g_n|^2 + p_n^*}) p_n^* = 0, \forall n \tag{35}$$

If $\alpha + \gamma_l \tilde{I}_n < \omega_n \Delta f \, |g_n|^2 / \sigma^2$, the condition in (34) holds if $p_n^* > 0$, which implies

$$p_n^* = \frac{\omega_n \Delta f}{\alpha + \gamma_l \tilde{I}_n} - \frac{\sigma^2}{|g_n|^2} \tag{36}$$

Moreover, if $\alpha + \gamma_l \tilde{I}_n \geq \omega_n \Delta f \, |g_n|^2 / \sigma^2$, we assume $p_n^* > 0$, which implies

$\alpha + \gamma_l \tilde{I}_n \geq \omega_n \Delta f \, |g_n|^2 / \sigma^2 \geq \omega_n \Delta f / (\sigma^2 / |g_n|^2 + p_n^*)$ and violates (35).Thus, the only

possible solution in this case is $p_n^* = 0$.

Therefore, the optimal power allocation solution can be written as follows:

$$P_n^* = \begin{cases} \dfrac{\omega_n \Delta f}{\alpha + \gamma_l \tilde{I}_n} - \dfrac{\sigma^2}{|g_n|^2}, & \text{if } \alpha + \gamma_l \tilde{I}_n < \dfrac{\omega_n \Delta f |g_n|^2}{\sigma^2} \\ 0, & \text{if } \alpha + \gamma_l \tilde{I}_n \geq \dfrac{\omega_n \Delta f |g_n|^2}{\sigma^2} \end{cases} \tag{37}$$

which is equal to

$$p_n^* = \left[\frac{\omega_n \Delta f}{\alpha + \gamma_l \tilde{I}_n} - \frac{\sigma^2}{|g_n|^2} \right]^+ \tag{38}$$

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