

Dynamic Spectrum Sharing in Cognitive Radio Femtocell Networks (Invited Paper)

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Abstract. Femtocell is envisioned as a highly promising solution to tackle the communications in the indoor environments, which has been a very challenging problem for mobile network operators. Currently, the spectrum allocated to femtocells is from the same licensed spectrum of macrocells, and the same mobile network operator. In this case, the capacity of femtocell networks may be largely limited due to the finite number of licensed spectrum bands and also the interference with other femtocells and macrocells. In this paper, we propose a radically new communications paradigm by incorporating cognitive radio in femtocell networks (COGFEM). In COGFEM, the cognitive radio enabled femtocells are able to access licensed spectrum bands not only from macrocells but also from other licensed systems (e.g. TV systems). Thus, the co-channel interference in femtocells can be greatly reduced and the network capacity can be significantly improved. We formulate a joint channel allocation and power control problem in COGFEM, and present two intelligent algorithms for efficient spectrum sharing in COGFEM. Results indicate that COGFEM is able to achieve much higher capacity than the femtocell networks which does not employ agile spectrum access.

Keywords: femtocell, cognitive radio, spectrum sharing, power control.

1 Introduction

The demand for higher data rates and lower power consumptions in mobile wireless networks is continuously increasing, while the capacity provided by the existing macrocell networks is limited. Studies on wireless usage have shown that more than 50% voice calls and 70% data traffic originate indoors [1]. This phenomenon motivates the reserach and development of femtocell networks, which just require that each customer installs a short-range low-cost low-power home base station. These femtocell base stations (FBSs) can communicate with macrocell networks by a broadband connection such as digital subscriber line (DSL), cable modem, or a separate wireless backhaul channel [2]. Femtocells can provide high data rates and Quality of Service (QoS) with low transmission power for consumers. For example, [2] demonstrates that the transmission power can be

saved about 34dB and 77dB in different fading environments. As a result, network operators may experience less traffic on their expensive macrocell networks, and can focus their resources on the truly mobile users [2][3].

The problem of spectrum sharing emerges when deploying femtocell networks. Traditional spectrum allocation in neighboring cellular networks is based on a coloring method that no neighboring cells can use the same spectrum at the same time, e.g., [4]. Since the number of femtocells could be much higher than the number of macrocells in a certain area, this kind of spectrum allocation requires more spectrum bands and will lead to inefficient and unfair spectrum utilization. This motivates our research in this paper to improve the spectrum utilization and cell capacity.

It has been shown that spectrum is not efficiently used by licensed (primary) users/systems according to the fixed spectrum allocation regulation. Recent years, cognitive radio (CR) technology has been developed to allow unlicensed users to exploit the spectrum opportunity from primary systems [5]. Thus the spectrum utilization would be improved significantly. In this paper, we incorporate the CR technology into femtocell networks, where the CR-enabled femtocell users and FBSs can identify and utilize the spectrum opportunities from the licensed systems such as macrocell networks and TV broadcast systems as shown in Fig.1. In the following of this paper, we call this kind of cognitive radio femtocell networks COGFEM. Besides the spectrum agility ability, COGFEM has the following features: (a), the number of users in each femtocell is small, e.g., 2, 4. (b), the size of the cell coverage is about the house or apartment range, e.g., 100 m^2 . (c), the availability of licensed channels is similar in neighboring cells, this is the major difference than cognitive radio macrocell networks, where the channel availability may vary a lot between neighbor cells.

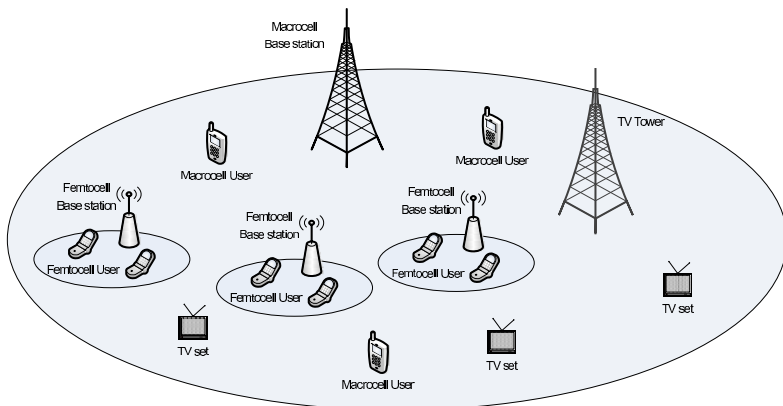


Fig. 1. An illustration of the coexistence between cognitive radio femtocells and primary systems such as macrocells and TV systems

Nevertheless, to improve spectrum utilization and cell capacity in COGFEM, spectrum sharing schemes should be present. Basically, there are two spectrum sharing modes in CR networks. One is called underlay mode, wherein the femtocell users and FBSs can use the spectrum as long as the interference to the licensed system is under a predefined threshold. The other one is called overlay mode, wherein the femtocell users and FBSs can use the spectrum only if the spectrum is not occupied by the nearby primary systems. In this paper, we focus on the overlay mode.

In literature, there are few attempts on femtocell networks. In [6], the authors applied a finite-difference time-domain (FDTD) method to predict the coverage of WiMAX femtocells. In [7], the authors used a centralized method of dynamic frequency planning (DFP) to minimize the overall femtocell network interference to allocate the spectrum to femtocells. In [8], the authors studied the resource management problem in Orthogonal Frequency-Division Multiple Access (OFMDA) femtocells and proposed a location-based allocation scheme between macro and femto cells to adapt the varying user population.

There are also attempts on the spectrum sharing in CR cellular networks. In [9], the authors studied the uplink admission and power control problem while sharing the same spectrum in one CR cellular network. In [10], the authors studied the uplink channel allocation and power control problem in one CR cellular network with multiple available channels. In [11], the authors proposed a joint spectrum and power allocation framework for inter-cell spectrum sharing in cognitive radio networks. In [12], the authors studied the downlink channel assignment and power control for several cognitive radio cellular networks with the objective to maximize the number of admitted users amongst all the cells.

In this paper address the spectrum sharing problem in COGFEM to maximize the capacity of femtocell networks. In particular, our contributions include:

- we first incorporate CR into femtocells, and analyze the interference amongst femtocell networks in overlay spectrum sharing mode.
- we propose two joint spectrum sharing and power control schemes for the downlink transmission in COGFEM networks, and present numerical results to evaluate the performance.

The rest of the paper is organized as follows. In section 2, we introduce the system model and assumptions, and formulate the downlink spectrum sharing problem in COGFEM. Then, we relax this problem and find out a solution by Lagrangian method, and propose two joint channel allocation and power control schemes in section 3. In section 4, we evaluate the performance of our proposed schemes for normal femtocells and COGFEM, respectively. Finally, we draw conclusions in section 5.

2 System Model and Problem Formulation

In this section, we will introduce the system model and assumptions of COGFEM, and formulate the downlink spectrum sharing problem.

2.1 System Model and Assumptions

Suppose that there are a set of \mathcal{N}^B femtocells in a macrocell coverage. For any FBS $i \in \mathcal{N}^B$, there are a set of \mathcal{N}_i^U femtocell users. Normally the number of femtocell users is between 2 and 4 as indicated in [2]. In this paper, we also use i as the ID of the femtocell where FBS i is located. Each femtocell i has a coverage of radius d_i . There are a set of \mathcal{N}^C licensed channels can be used for femtocells. \mathcal{N}^C may change timely depends on the activities of nearby primary systems. These channels are not only from macro cells but also from other licensed systems. In this paper, we consider OFDMA scheme, wherein the channels are narrowband subchannels containing several subcarriers typically 100KHz similar in IEEE 802.22 draft standard [13].

Each FBS is responsible to allocate spectrum to its users, and decides channel switching when any primary user returns. Synchronization between different FBSs is not obligatory, but it is an optional if any FBS wants to synchronize with its neighbors. The synchronization can be implemented by listening to neighboring FBS information to obtain the frame length and structure.

In our COGFEM architecture, each femtocell user and FBS are equipped with one cognitive radio with the ability of spectrum sensing and switching on different spectrum. The available spectrum list can be stored into a local database at FBS or a database in the Internet for future use. FBSs can do spectrum sensing cooperatively by obtaining the results from other femtocells. There are two kinds of control channels. One is called *inter-femtocell* control channel, whereby each FBS can communicate with each other to exchange spectrum sensing result, etc. The other one is called *intra-femtocell* control channel, whereby each user in a femtocell can communicate with its FBS to obtain the working channel and transmission power. These control channels could be dedicated control channels or rendezvous channels which are selected from the available spectrum according to some metrics such as channel availability.

2.2 Downlink Spectrum Sharing in Overlay Mode

In this paper, we consider the downlink spectrum sharing problem in overlay mode, where femtocells use the licensed channels when they are not occupied by primary systems. Thus, there is no co-channel interference between primary systems and femtocells. The only interference should be managed is amongst femtocells. Suppose each femtocell user in a femtocell i requires one subchannel with an equal bandwidth B . We consider the worst case when all neighboring femtocells are in downlink transmission. In the following, we will analyze the downlink capacity and then formulate the spectrum sharing problem.

Downlink capacity. Any femtocell user will receive interference from neighboring femtocells using the same channel. Consider an Additive White Gaussian Noise (AWGN) channel, the Signal to Interference-plus-Noise Ratio (SINR) of the received signal from FBS i at femtocell user j can be denoted as

$$\xi^d(i, j, c) = \frac{H(i, j, c)P(i, c)x(i, j, c)}{N_0 + I_S(i, j, c)} \tag{1}$$

where N_0 denotes the background noise power. $I_S(i, j, c)$ represents the interference measured at user j on channel c from femtocells other than i . $H(i, j, c)$ is the channel gain from FBS i to its user j on channel c including path loss and channel fading. $P(i, c)$ is the transmission power for FBS i on channel c . $x(i, j, c)$ is a binary indicator. If $x(i, j, c) = 1$, user j in femtocell i works on channel c , zero otherwise.

The downlink capacity of any femtocell user j in femtocell i can be calculated according to Shannon’s capacity theory as follows.

$$C^d(i, j) = \sum_{c \in \mathcal{N}^C} x(i, j, c)B \log_2(1 + \xi^d(i, j, c)) \tag{2}$$

where B denotes the channel bandwidth. Then, we can calculate the downlink capacity of femtocell i which is the sum of all the capacity of its users.

$$C_i = \sum_{j \in \mathcal{N}_i^U} C^d(i, j), \quad \forall i \in \mathcal{N}^B \tag{3}$$

Spectrum sharing problem. The spectrum sharing problem in COGFEM downlink transmission is to maximize the downlink capacity of all FBSs while guarantee the channel and power constraints.

$$\max \sum_{i \in \mathcal{N}^B} C_i \tag{4}$$

s.t.

$$x(i, j, c) \in \{0, 1\}, \quad \forall i \in \mathcal{N}^B, j \in \mathcal{N}_i^U, c \in \mathcal{N}^C \tag{5}$$

$$\sum_{c \in \mathcal{N}^C} x(i, j, c) = 1, \quad \forall i \in \mathcal{N}^B, j \in \mathcal{N}_i^U \tag{6}$$

$$\sum_{j \in \mathcal{N}_i^U} \sum_{c \in \mathcal{N}^C} x(i, j, c) = n_i, \quad \forall i \in \mathcal{N}^B \tag{7}$$

$$\xi^d(i, j, c) \geq \psi^d, \quad \text{if } x(i, j, c) = 1, \quad \forall i \in \mathcal{N}^B, j \in \mathcal{N}_i^U, c \in \mathcal{N}^C \tag{8}$$

$$P(i, c) = 0, \quad \text{if } x(i, j, c) = 0, \quad \forall i \in \mathcal{N}^B, j \in \mathcal{N}_i^U, c \in \mathcal{N}^C \tag{9}$$

$$P(i, c) \geq 0, \quad \forall i \in \mathcal{N}^B, c \in \mathcal{N}^C \tag{10}$$

$$\sum_{c \in \mathcal{N}^C} P(i, c) \leq P_{max}, \quad \forall i \in \mathcal{N}^B \tag{11}$$

where ψ^d denotes the minimum required SINR for femtocell users. Constraint (6) means every user in a COGFEM can only use one channel. Constraint (7) means the total number of channels can be used in one femtocell is equal to the number of users in that femtocell. Constraint (8) represents that if channel c is allocated to user j in femtocell i for downlink transmission, the SINR received on user j should be higher than a predefined threshold. Constraint (9) means any FBS i will not allocate any power on channel c if channel c is not allocated to i . Constraint (10) represents the transmission power of any FBS i should be no less than 0, while constraint (11) indicates the total transmission power of any FBS i on all channels can not exceed the maximum power budget P_{max} .

3 Proposed Dynamic Spectrum Sharing Schemes

The formulated spectrum sharing problem in the previous section is a mixed integer optimization problem, which is generally NP-hard. The solution of that problem includes transmission power allocation variable $P(i, c)$, and channel allocation variable $x(i, j, c)$ for both inter-cell and intra-cell spectrum sharing. In this section, we try to simplify the formulation to a robust scenario, where we consider the worst case when all users of a femtocell is at the cell boundary, and have similar channel gain information. Thus, FBS will not distinguish different users in its service range. In this situation, the downlink SINR of channel c at femtocell i can be represented as

$$\xi^d(i, c) = \frac{H(d_i, c)P(i, c)}{N_0 + I_S(i, c)} \tag{12}$$

where $H(d_i, c)$ denotes the gain on channel c in femtocell i through distance d_i . $I_S(i, c)$ represents an approximate interference on channel c to all users in femtocell i . In practice, $I_S(i, c)$ can be estimated by femtocell users and FBS. Substituting (1) to (2) and (3), we can obtain

$$C_i = n_i B \sum_{c \in \mathcal{N}^C} x_B(i, c) \log_2(1 + \xi^d(i, c)) \tag{13}$$

where $x_B(i, c)$ is a binary variable, whereby $x_B(i, c) = 1$ represents that channel c is allocated to femtocell i , zero otherwise. To reduce the complexity of mixed integer optimization problem, we relax the binary variable $x_B(i, c)$ into a continuous variable in a range of $[0, 1]$. Thus, the inter-cell spectrum sharing problem can be formulated as follows.

$$\max_{x_B(i, c) \in [0, 1], P(i, c) \geq 0} \sum_{i \in \mathcal{N}^B} C_i \tag{14}$$

s.t.

$$\sum_{c \in \mathcal{N}^C} x_B(i, c) = n_i, \quad \forall i \in \mathcal{N}^B \tag{15}$$

$$\xi^d(i, c) \geq x_B(i, c)\psi^d, \quad \forall i \in \mathcal{N}^B \quad (16)$$

$$\sum_{c \in \mathcal{N}^C} P(i, c) \leq P_{max}, \quad \forall i \in \mathcal{N}^B \quad (17)$$

By using Lagrangian $L(P(i, c), x_B(i, c), \lambda_i, \lambda_{i,c}, \mu_i)$, where λ_i , $\lambda_{i,c}$, and μ_i are Lagrange multipliers, we have

$$\begin{aligned} & L(P(i, c), x_B(i, c), \lambda_i, \lambda_{i,c}, \mu_i) \\ = & \sum_{i \in \mathcal{N}^B} C_i + \sum_{i \in \mathcal{N}^B} \lambda_i \left(\sum_{c \in \mathcal{N}^C} x_B(i, c) - n_i \right) + \\ & \sum_{i \in \mathcal{N}^B} \sum_{c \in \mathcal{N}^C} \lambda_{i,c} (\xi^d(i, c) - x_B(i, c)\psi^d) + \sum_{i \in \mathcal{N}^B} \mu_i \left(P_{max} - \sum_{c \in \mathcal{N}^C} P(i, c) \right) \end{aligned} \quad (18)$$

Suppose $P^*(i, c)$ and $x_B^*(i, c)$ are the optimal power and channel allocation, respectively, according to Karush-Kuhn-Tucker (KKT) condition [14], we have the following equations.

$$\left. \frac{\partial L(P(i, c), x_B(i, c), \lambda_i, \mu_i, \mu'_i)}{\partial P(i, c)} \right|_{P(i, c)=P^*(i, c)} = 0; \quad (19)$$

$$\sum_{c \in \mathcal{N}^C} x_B(i, c) - n_i = 0, \quad \forall i \in \mathcal{N}^B; \quad (20)$$

$$\lambda_{i,c} (\xi^d(i, c) - x_B(i, c)\psi^d) \Big|_{P(i, c)=P^*(i, c)} = 0, \quad \forall i \in \mathcal{N}^B, c \in \mathcal{N}^C; \quad (21)$$

$$\mu_i \left(P_{max} - \sum_{c \in \mathcal{N}^C} P(i, c) \right) \Big|_{P(i, c)=P^*(i, c)} = 0, \quad \forall i \in \mathcal{N}^B; \quad (22)$$

and

$$\mu_i \geq 0, \quad \lambda_{i,c} \geq 0, \quad \forall i \in \mathcal{N}^B, c \in \mathcal{N}^C. \quad (23)$$

According to (19), we can obtain

$$\frac{n_i B x_B(i, c)}{\left(\frac{N_0 + I_S(i, c)}{H(d_i, c)} + P^*(i, c) \right) \ln 2} + \mu_i \frac{H(d_i, c)}{N_0 + I_S(i, c)} - \mu'_i = 0 \quad (24)$$

where $I_S(i, c)$ can be estimated by each FBS in practice. Thus

$$\begin{aligned}
P^*(i, c) &= \left(\frac{n_i B x_B(i, c)}{\lambda'_i \ln 2} - \frac{N_0 + I_S(i, c)}{H(d_i, c)} \right)^+ \\
&= \begin{cases} \frac{n_i}{\lambda'_i} - \frac{N_0 + I_S(i, c)}{H(d_i, c)}, & 0 < \lambda'_i < \frac{n_i B H(d_i, c)}{(N_0 + I_S(i, c)) \ln 2}, x_B(i, c) = 1 \\ 0, & \text{otherwise} \end{cases} \quad (25)
\end{aligned}$$

where

$$\lambda'_i = \frac{\ln 2}{B} \left(\mu_i - \lambda_{i, c} \left(\frac{H(d_i, c)}{N_0 + I_S(i, c)} \right) \right) \quad (26)$$

According to (16), we can obtain

$$P^*(i, c) \geq \frac{\psi^d(N_0 + I_S(i, c))}{H(d_i, c)} \quad (27)$$

Substituting (25) to (22) when $x_B(i, c) = 1$, we have

$$\lambda'_i = \frac{n_i^2}{P_{max} + \sum_{c \in \mathcal{N}^{C'}} \frac{N_0 + I_S(i, c)}{H(d_i, c)}} \quad (28)$$

where $\mathcal{N}^{C'}$ is the selected channel set for FBS i . Substituting (28) to (25) when $x_B(i, c) = 1$, we have

$$P^*(i, c) = \frac{1}{n_i} P_{max} + \frac{1}{n_i} \sum_{c \in \mathcal{N}^{C'}} \frac{N_0 + I_S(i, c)}{H(d_i, c)} - \frac{N_0 + I_S(i, c)}{H(d_i, c)} \quad (29)$$

In the following, we propose two schemes to implement the solution of the formulated problem. Specially, we are interested in distributed algorithms where each FBS can decide the preferred channel by itself and allocate power for its users.

3.1 A Scheme Based on Local Measurements of FBS

The first scheme is based only on the local measurements of FBS. Any FBS i measures each available channel from primary systems and characterizes these channels with interference levels. Channels with lower interference level are preferred. Thus, it will choose the lowest n_i channels. Then, the FBS will allocate these selected n_i channels to its users randomly. After channel allocation, according to (29) the power of FBS i on each channel is roughly by

$$P(i, c) = \frac{1}{n_i} P_{max} + \frac{1}{H(d_i, c)} \left(\frac{1}{n_i} \sum_{c \in \mathcal{N}^C} I_S(i, c) - I_S(i, c) \right) \quad (30)$$

The details of the channel allocation and power control for each FBS are shown in Algorithm 1. The complexity of this scheme for any FBS i depends on the channel selection and power allocation. It is then bounded by $O(|\mathcal{N}^C|^{|\mathcal{N}_i^U|} + |\mathcal{N}_i^U|)$, where $|\cdot|$ denotes the cardinal of the set within. If we employ sorting algorithms such

Algorithm 1. Channel allocation and power control algorithm based on local measurements of FBS

Input: $i, \mathcal{N}_C, \mathcal{N}_i^U$.

Output: $\{x(i, j, c)\}, \{P(i, c)\}$.

```

1: Initialization:  $\mathcal{N}_i^{U'} \leftarrow \mathcal{N}_i^U, N^{C'} \leftarrow \mathcal{N}_C$ 
2: while  $\mathcal{N}_i^{U'} \neq \emptyset$  do
3:   if  $N^{C'} = \emptyset$  then
4:     //not enough channels for femtocell  $i$ .
5:     Break;
6:   else
7:      $c^* = \arg \max_{c \in \mathcal{N}^{C'}} I_S(i, c)$ 
8:     Randomly choose a user  $j^*$  for channel  $c^*$ 
9:      $\mathcal{N}^{C'} \leftarrow \mathcal{N}^{C'} - c^*$ 
10:     $N_i^{U'} \leftarrow N_i^{U'} - j^*$ 
11:   end if
12: end while
13: for  $j \in \mathcal{N}_i^U$  do
14:   Calculate  $P(i, c_j)$  by (30).
15:   Calculate  $\xi^d(i, j, c)$  by (1).
16:   if  $\xi^d(i, j, c) < \psi^d$  then
17:      $P(i, c_j) \leftarrow 0$ 
18:     //power allocation for user  $j$  is failed.
19:   else
20:      $x(i, j, c) \leftarrow 1$ 
21:   end if
22: end for

```

as quicksort in channel selection, the complexity can be reduced to $O(|\mathcal{N}^C|^2 + |\mathcal{N}_i^U|)$ for the worst case. Whenever a FBS detects a return of primary users on the licensed channel, it will inform its users to switch to another channel with the least interference on the available channel list, decide a transmission power according to (30), and update the transmission power on other active channels.

3.2 A Scheme Based on Measurements of FBS and Its Users

In the second scheme, each FBS will make the decision of channel selection and power allocation according to the measurements not only on FBS but also on its users. In practice, each femtocell user is required to negotiate a control channel with its FBS, and reports its measurements to the FBS through this channel. Based on these information, FBS then characterizes the channels with the accurate interference levels for each user, and chooses n_i channels with lowest interference levels.

The channel allocation is based on the following metric.

$$g(i, j, c) = \frac{H(d_i, c)}{N_0 + I_S(i, j, c)}, \quad \forall i \in \mathcal{N}^B, j \in \mathcal{N}_i^U, c \in \mathcal{N}^C. \quad (31)$$

Channel c^* is allocated to user j^* , if $g(i, j^*, c^*)$ has the maximum value in the available channels and users. Then the allocated channel and user will be removed from the sets of channels and users. Repeat the channel and user selection until there is no user or channel left. After channel allocation, the power for each user j in femtocell i can be calculated according to (29) as follows

$$P_j(i, c_j) = \frac{1}{n_i} P_{max} + \frac{1}{n_i} \sum_{k \in \mathcal{N}_i^U} \frac{N_0 + I_S(i, k, c_k)}{H_k(d_i, c_k)} - \frac{N_0 + I_S(i, j, c_j)}{H_j(d_i, c_j)} \quad (32)$$

where $H_j(d_i, c_j)$ is the channel gain of user j on channel c_j . $I_S(i, j, c_j)$ is the interference on channel c_j reported by user j .

Algorithm 2. Channel allocation and power control algorithm based on measurements of FBS and its users

Input: $i, \mathcal{N}_C, \mathcal{N}_i^U$.

Output: $\{x(i, j, c)\}, \{P(i, c)\}$.

```

1: Initialization:  $\mathcal{N}_i^{U'} \leftarrow \mathcal{N}_i^U, \mathcal{N}^{C'} \leftarrow \mathcal{N}^C$ .
2: while  $\mathcal{N}_i^{U'} \neq \emptyset$  do
3:   if  $\mathcal{N}^{C'} = \emptyset$  then
4:     //not enough channels for femtocell  $i$ .
5:     Break;
6:   else
7:      $\{j^*, c_{j^*}\} \leftarrow \arg \max_{j \in \mathcal{N}_i^{U'}, c \in \mathcal{N}^{C'}} g(i, j, c)$ 
8:      $\mathcal{N}^{C'} \leftarrow \mathcal{N}^{C'} - c_{j^*}$ 
9:      $\mathcal{N}_i^{U'} \leftarrow \mathcal{N}_i^{U'} - j^*$ 
10:   end if
11: end while
12: for  $j \in \mathcal{N}_i^U$  do
13:   Calculate  $P_j(i, c_j)$  by (32).
14:   Calculate  $\xi^d(i, j, c)$  by (1).
15:   if  $\xi^d(i, j, c) < \psi^d$  then
16:      $P_j(i, c_j) \leftarrow 0$ 
17:     //power allocation for user  $j$  in cell  $i$  is failed.
18:   else
19:      $x(i, j, c) \leftarrow 1$ 
20:   end if
21: end for

```

The details of the channel allocation and power control for each FBS are shown in Algorithm 2. The complexity of this scheme depends on the channel selection and power allocation. For any FBS i , it is bounded by $O((|\mathcal{N}^C| \times |\mathcal{N}_i^U|)^2)$ by employing quicksort in channel and user selection. Similar as the first scheme, in this scheme, whenever a FBS detects a return of primary users on the licensed channel, it will perform the following procedures sequentially, i.e., inform its user to switch to another channel with the least interference on the available channel

list, decide a transmission power according to (32), and update the transmission power on other active channels.

4 Numerical Results

In this section, we will evaluate our proposed spectrum sharing schemes by numerical results.

We have implemented a COGFEM simulator in MATLAB, where we create an urban apartment topology as shown in Fig. 2. There are n_r rows of apartment buildings. Each row has n_b buildings, while each building has n_f floors. The length, width, height of an apartment are l , w , and h , respectively. We call the gap between neighboring buildings in a row *side gap*, and denote it as g_s , while we call the gap between neighboring rows *row gap*, and denote it as g_r . In our simulations, we choose these parameters as shown in Table 1. Each apartment has a FBS, and has n_u users in a range of 2 to 4 suggested in [3]. These users sit randomly in each apartment. For simplicity, each FBS is located at the middle of the apartment. The maximum transmission power for FBS is 10dBmW [15]. The number of subchannels for normal femtocells, n_c , is 10, while the number of channels for COGFEM, n'_c , changes randomly from a range of 10 to 20 during the simulation. For the estimation of channel gain in our simulation, we consider a slow fading channel, and the path loss is $\frac{1}{d^\alpha}$, where d is the distance between a transmitter and its receiver. We run each case 10 times with different random seeds for the number of users in each femtocell and the number of available channels, and then calculate the average capacity per femtocell.

Figure 3 shows the variation of average capacity per femtocell while changing the available channels. Here, we fix the topology as 3 rows, 5 buildings per row, and 5 floors per building. It shows that the average capacity per femtocell increases while the number of available channels increases. That is because more channel candidates can reduce the interference from neighboring femtocells by allocating different channels to neighboring femtocells. Algorithm 2 achieved a bit higher capacity than algorithm 1, since it uses more accurate interference and channel gain information from the report of femtocell users.

Table 1. Simulation Parameters

Symbol	value	Symbol	value
l	10m	n_r	[1, 10]
w	10m	n_b	[1, 10]
h	3m	n_f	[1, 10]
g_s	1m	g_r	5m
n_c	10	n'_c	[10, 20]
P_{max}	10dBmW	n_u	[2, 4]
ψ^d	10dBm	N_0	-110dBmW
B	100KHz		

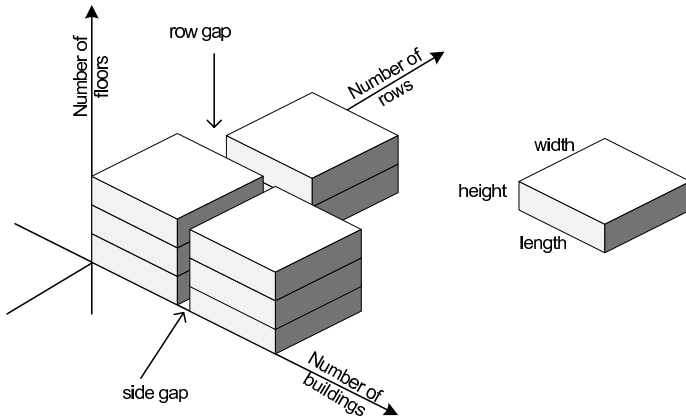


Fig. 2. An illustration of the simulation scenario

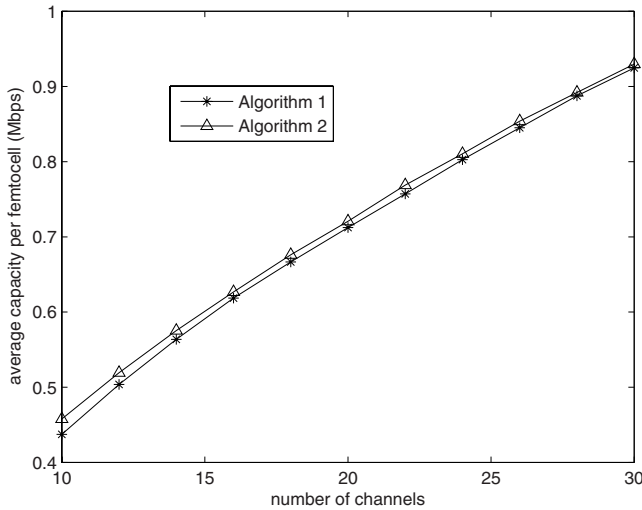


Fig. 3. Average capacity per femtocell in terms of number of channels. (3 rows, 5 buildings per row, 5 floors per building).

Figure 4, 5, and 6 show the variation of average capacity per femtocell while changing the number of floors, buildings, and rows, respectively. Specially, the average capacity per femtocell decreases while increasing the number of floors, buildings, and rows, respectively. When the number of floors, buildings, and rows increases, the number of FBSs increases. This results in more interference amongst femtocells given a limited number of available channels. In the case of normal femtocells, where the number of available channels is fixed to 10,

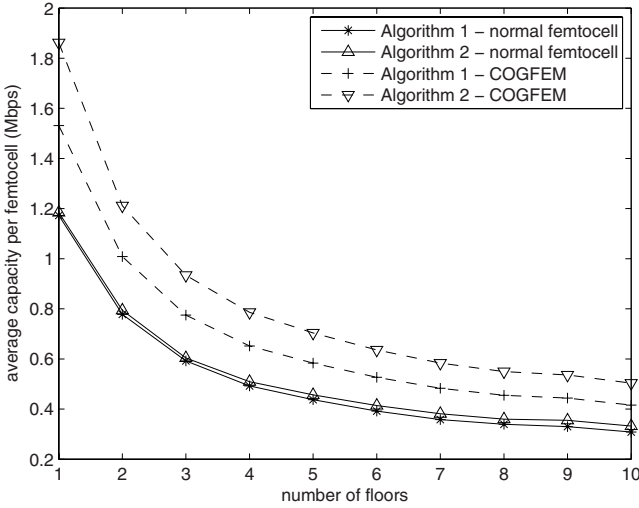


Fig. 4. Average capacity per femtocell in terms of number of floors in each building. (3 rows, and 5 buildings per row)

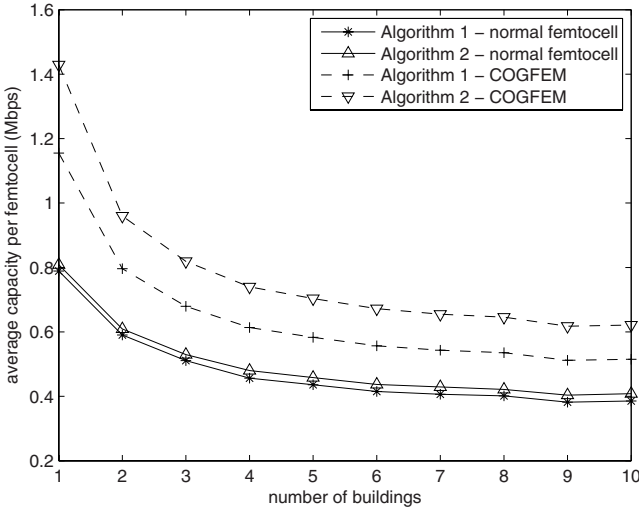


Fig. 5. Average capacity per femtocell in terms of number of buildings in each row. (3 rows, and 5 floors per building)

Algorithm 2 achieves slightly higher capacity than Algorithm 1. In the case of COGFEM, where the number of available channels is randomly changed from 10 to 20, Algorithm 2 achieves much higher capacity than Algorithm 1. From

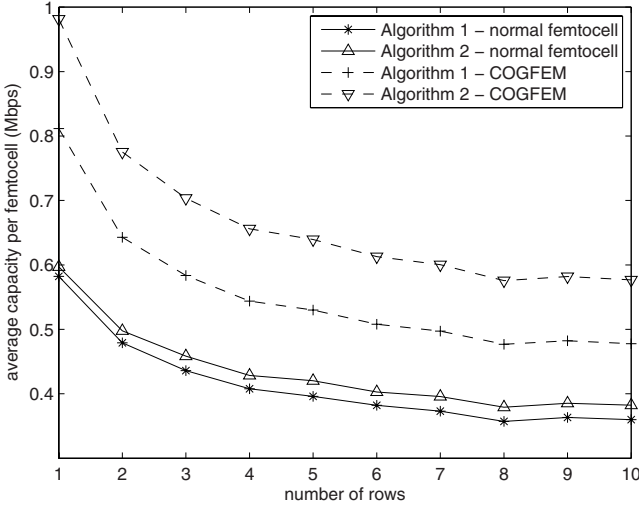


Fig. 6. Average capacity per femtocell in terms of number of rows of buildings. (5 floors per building, and 5 buildings per row)

all the results, COGFEM achieved much higher capacity than normal femtocells without CR capability by using either Algorithm 1 or 2. This is essentially due to more channel opportunities in COGFEM than normal femtocells.

5 Conclusion

In this paper, we have investigated the spectrum sharing problem in downlink transmission while applying CR technology into femtocell networks. We formulated this problem as a mixed integer problem and then relaxed it using Lagrangian method. According to the solution of the relaxed problem, we proposed two distributed schemes with low complexity to jointly select downlink channels and allocate the transmission power for each channel. Numerical results showed that COGFEM with more spectrum opportunity can achieve much higher capacity than normal femtocells by both schemes. The scheme which requires femtocell users report the channel state and interference information to their FBSs can achieve higher capacity than the scheme which only makes channel and power decision based on the local measurements on FBS.

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