Coordinated Channel Selection in Cognitive Macro-Femto Networks

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***Abstract*—In this paper, we study uplink channel selection in a system where a macro base station (MBS) and a number of cognitive femto base stations (FBSs) share the same spectrum to serve their intended users with quality of service (QoS) requirements. In this system, the MBS may experience significant aggregate interference when multiple FBSs select the same channel to serve their FUs. An FBS also experiences strong interference from nearby femtocells if the same channel is utilized by adjacent FBSs. We investigate how to coordinate the channel selection at FBSs to reduce the interference experienced at the MBS and FBSs. We propose a cluster-based coordination mechanism where the operator groups the set of FBSs into clusters, and FBSs in the same cluster can utilize a set of channels simultaneously without violating the QoS requirements. To find the desired clusters, we employ a graph-theoretic approach and propose an efficient FBS clustering scheme. Simulation results show that the proposed coordination mechanism achieves a better performance compared to the channel selection scheme without coordination.**

I. Introduction

Femtocell base stations (FBSs) are short range, low power and low cost base stations, which can serve a small number of cellular users at the operator's licensed spectrum [1]. FBSs are deployed within the existing macrocell infrastructure to improve the quality of service (QoS) for indoor users. By communicating via FBSs, users can achieve a higher data rate and a lower energy consumption [2]. Due to the scarcity of wireless spectrum, operators usually adopt co-channel deployment, where FBSs share the same licensed spectrum with the macrocell base station (MBS) [3]. However, the co-channel deployment introduces interference between the macrocell and femtocells, which degrades the signal quality at the receivers.

Recently, incorporating cognitive radio technique into macro-femto networks has been considered as a promising approach to manage interference [4]–[8]. In a cognitive femtocell, an FBS is equipped with cognitive radio and has the ability to sense the spectrum to obtain the interference information. The FBS can access a channel opportunistically when the interference power sensed on that channel is below a threshold [4]. Coordinated channel assignment in under-lay cognitive networks is studied in [5]. The power control problem for multiuser cognitive networks is considered in [6]. In [7], the trade-off between sensing threshold and spectral reuse efficiency is studied, and the performance of a contention-resolution based access mechanism and a uncoordinated access mechanism is analyzed. A priority-based resource allocation algorithm as well as a channel selection scheme is proposed in [8]. Although interference management with cognitive FBSs has been studied in the existing works, there are still some challenging issues that need to be resolved. For example, in a system with many femtocells, it is possible that many adjacent FBSs have the same sensing result over a channel and access it simultaneously, which results in significant interference among the femtocells. Simultaneous channel access in different femtocells may also introduce significant aggregate interference to the macrocell. These issues have become the bottleneck of the system performance in dense cognitive macro-femto networks, and are not fully addressed in the existing works, which motivates the research in this paper.

In this paper, we study uplink channel selection in cognitive macro-femto networks. We consider a system where a large number of cognitive FBSs are deployed within one macrocell and share the same spectrum with the MBS to serve their users with QoS requirements. We are interested in investigating how to coordinate the channel selection at FBSs so that all users in the system can achieve their desired QoS. The major contributions of this work are as follows:

- We propose an operator-assisted coordination framework, which does not require message exchange among the femtocells and is easy to implement in practice.
- We analyze the channel reuse condition among a set of FBSs, and develop an efficient FBS clustering scheme by using a graph-theoretic approach.
- Based on the coordination framework and the FBS clustering scheme, we design a cluster-based coordination mechanism to assist the channel selection at FBSs. Simulation results show that this mechanism achieves a better performance than the mechanism where FBSs select their channels only based on the sensing results.

The rest of this paper is organized as follows. In Section II, we describe the system model, and introduce the framework of the coordination mechanism. In Section III, we propose an FBS clustering algorithm and design a cluster-based coordination mechanism. Performance of the proposed coordination mechanism is evaluated in Section IV, and conclusions are drawn in Section V.

II. System Model and Problem Formulation

A. System Model

We consider the uplink of a two-tier macro-femto wireless system as shown in Fig. 1. The system consists of an MBS

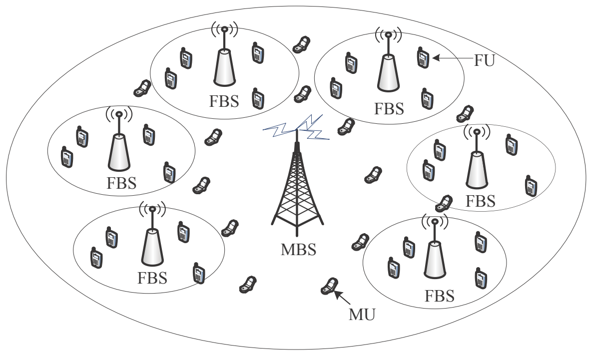

Fig. 1. A two-tier macro-femto system model.

and J cognitive FBSs which are deployed in a macrocell. We denote the set of FBSs as $\mathcal{J} = \{1, \ldots, J\}$, and use index 0 to represent the MBS. The MBS serves a set of MUs, denoted as $\mathcal{U}_0$. Each FBS $j \in \mathcal{J}$ serves a dedicated set of FUs, denoted as $\mathcal{U}_j$. The FBSs connect to the operator's network via wired backhaul links. We assume the capacity of each backhaul link is large enough to handle the data transmission for all the users. The MBS and FBSs share the same licensed spectrum, which is divided into N channels with bandwidth B for each channel. We denote $\mathcal{N} = \{1, \ldots, N\}$ as the set of channels.

The FBSs are equipped with cognitive radios, which have the capability to sense the environment and select the channels with interference power less than a threshold ϵ_f to serve their FUs. We consider each user $u_j \in \bigcup_{j \in \mathcal{J} \bigcup \{0\}} \mathcal{U}_j$ requests a service (e.g., video streaming) that requires a minimum average data rate $R_{u_j}^{\min}$ to guarantee its QoS. Users select the transmission power to achieve their desired QoS and to minimize their energy consumption. We consider the MUs have priority to access a channel while the FUs that are using the same channel should limit their transmission power such that the aggregate interference at the MBS is below a threshold ϵ_0. We assume the total amount of resources in the system is sufficient to satisfy the QoS requirements for all the users.

Similar to [9], we consider time is slotted and there is a network configuration process at the beginning of each transmission period (which consists of a number of time slots). The configuration process involves resource allocation and power control at the base stations and user devices. Specifically, at the beginning of this process, the MBS allocates resource blocks (i.e., frequency-time slots) to its associated MUs and these MUs determine their transmission power accordingly. Next, each MU associated with the MBS broadcasts a message with their determined transmission power on its allocated channel to inform its nearby FBSs of its existence. The FBSs sense the MUs' signal strength and select the channels based on their sensing results. Then, the FBSs allocate the resource blocks to their associated FUs. Finally, FUs choose the minimum transmission power to achieve their desired QoS.

B. Coordination Framework

In the considered system model, if the FBSs select their channels independently without coordination, an FBS may experience strong interference from neighboring femtocells, and the MBS may experience significant aggregate uplink interference when the number of FBSs which use the same channel is large. In order to limit the aggregate interference from femtocells to the macrocell, global coordination among all femtocells is needed, which may incur large communication overhead if femtocells exchange messages with each other. To reduce the communication overhead, we propose an operator-assisted coordination framework as follows. During the network configuration process, the operator collects necessary information of the system and determines some coordination variables for each FBS. We denote $\mathcal{C}_j$ as the set of coordination variables for FBS $j \in \mathcal{J}$. These variables are distributed to the FBSs via control channel. Then, each FBS selects channels independently based on the coordination variables it obtained from the operator and its sensing result. Note that this coordination framework does not require message exchange among the femtocells, and thus is more desirable in practical systems. We define $\mathcal{A}_j$ as the sensing result at FBS j, which is the set of channels with interference power (experienced at the FBS) less than a certain threshold ϵ_f. We further denote $\mathcal{D}_j$ as the corresponding set of selected channels at the end of the channel selection process. Our objective is to design a coordination mechanism to assist the channel selection at the FBSs. That is, we design the set of coordination variables $\mathcal{C} \triangleq \{\mathcal{C}_j, j \in \mathcal{J}\}$ and channel selection strategy in order to find the desired set of decisions $\mathcal{D} \triangleq \{\mathcal{D}_j, j \in \mathcal{J}\}$, which satisfies: (i) for each channel $c \in \mathcal{N}$, the aggregate interference experienced by the MBS is less than the threshold ϵ_0; (ii) for each FBS $j \in \mathcal{J}$, the QoS of FUs associated with it should be satisfied with $\mathcal{D}_j$.

III. Cluster-Based Coordination Mechanism

As previously discussed, the coordination mechanism deals with interference experienced at both the MBS and the FBSs. An efficient approach to control the interference is to let FBSs form clusters, where in each cluster the FBSs are not close to each other and can achieve the QoS of their FUs without generating significant interference to the MBS when using the same channel. To achieve this, we analyze the channel reuse condition among the FBSs and develop an FBS clustering scheme. Based on this scheme, we design a cluster-based coordination mechanism.

A. Channel Reuse Condition at the FBSs

We consider a cluster of FBSs, denoted as $\mathcal{J}' \subseteq \mathcal{J}$, that use the same channels to serve their intended FUs. We first analyze a simple scenario where each FBS $j \in \mathcal{J}'$ serves a single user u_j over the same channel c. In this scenario, the achievable data rate at FBS j from user u_j is

$$R_{u_j}^c = B \log_2 \left(1 + \frac{g_{u_j j} P_{u_j}^c}{\sigma^2 + g_{u_0 j} P_{u_0}^c + \sum_{v \in \mathcal{J}', v \neq j} g_{u_v j} P_{u_v}^c} \right), \tag{1}$$

where $g_{u_j j}$ is the distance-dependent average channel gain from user u_j to base station $j \in \mathcal{J}$, $P_{u_j}^c$ is u_j's transmission power, σ^2 is the noise power and $g_{u_0 j} P_{u_0}^c$ is the interference power that FBS j received from the MU that uses the same channel c, which is known during the network configuration process. As mentioned in Section II, user u_j tends to choose the smallest transmission power $P_{u_j}^c$ in order to save energy. To guarantee the QoS of all users that use the same channel c, it is required that

$$\frac{g_{u_j j} P_{u_j}^c}{\sigma^2 + \sum_{v \in \mathcal{J}' \bigcup \{0\}, v \neq j} g_{u_v j} P_{u_v}^c} \geq 2^{\frac{R_{u_j}^{\min}}{B}} - 1, \quad \forall\, j \in \mathcal{J}'. \quad (2)$$

To ensure that the aggregate interference generated from the FUs to the MBS is below the threshold ϵ_0, we should have

$$P_{u_j}^c > 0, \qquad \forall\, j \in \mathcal{J}', \quad (3)$$

and

$$\sum_{j \in \mathcal{J}'} g_{u_j 0} P_{u_j}^c \leq \epsilon_0. \quad (4)$$

Inequalities (2)-(4) constitute the conditions for channel reuse when each FBS in $\mathcal{J}'$ serves one particular user using one channel. However, in the considered system, an FBS may select multiple channels, and FUs can share the same channel using time division multiple access (TDMA), where several FUs may be scheduled on the same channel at different time slots. In this case, since the channel gains from various FUs to the FBSs are different, it is difficult to characterize the exact interference generated from FUs in one femtocell to other FBSs without the corresponding scheduling decision at that FBS, which makes it difficult to find the exact channel reuse condition. In this work, instead of determining the exact channel reuse condition for each channel, we find an approximate channel reuse condition, which can be applied to any channel, as follows. We treat the group of FUs associated with FBS $j \in \mathcal{J}'$ as a *super FU*, denoted as s_j. We define the minimum data rate required by this super FU as

$$R_{s_j}^{\min} \triangleq \max\left\{ \max_{u_j \in \mathcal{U}_j} \left\{ R_{u_j}^{\min} \right\},\ \frac{1}{n_j} \sum_{u_j \in \mathcal{U}_j} R_{u_j}^{\min} \right\}, \quad (5)$$

where n_j is the maximum number of channels that can be used by FBS j at one time slot (after coordination). The rationale for this data rate selection is as follows. Since a user can access at most one channel for transmission at a time slot, if $\max_{u_j \in \mathcal{U}_j} \{R_{u_j}^{\min}\} > \frac{1}{n_j} \sum_{u_j \in \mathcal{U}_j} R_{u_j}^{\min}$, it can be verified that it is not necessary for FBS j to schedule multiple users on the same channel where the FU with the maximum rate requirement is being served. In this case, the FBS needs to obtain a rate no less than $\max_{u_j \in \mathcal{U}_j} \{R_{u_j}^{\min}\}$ to satisfy the QoS of this FU. On the other hand, when $\max_{u_j \in \mathcal{U}_j} \{R_{u_j}^{\min}\} < \frac{1}{n_j} \sum_{u_j \in \mathcal{U}_j} R_{u_j}^{\min}$, in order to satisfy the total rate requirement, the FBS needs to schedule more than one FU on a channel, and the minimum average rate required over each channel is $\frac{1}{n_j} \sum_{u_j \in \mathcal{U}_j} R_{u_j}^{\min}$.

Since the size of the femtocell is relatively small and FUs are close to their FBS, we determine the channel gain from the super FU s_j to any other FBS v, denoted as $g_{s_j v}$, based on the distance from FBS j to FBS v. We also let the channel gain from s_j to its own FBS be $g_{s_j j} = \frac{1}{|\mathcal{U}_j|} \sum_{u_j \in \mathcal{U}_j} g_{u_j j}$. We further denote P_{s_j} as the transmission power of the super FU s_j. Then, we have the following definition.

Definition 1: The approximate channel reuse condition for FBSs in cluster $\mathcal{J}'$ to serve their FUs simultaneously without violating the QoS requirements is that there exists a set of power $\{P_{s_j}, j \in \mathcal{J}\}$ that satisfies (2)-(4) when replacing $g_{u_j j}$, $g_{u_v j}$, $R_{u_j}^{\min}$ and $g_{u_0 j} P_{u_0}^c$ with $g_{s_j j}$, $g_{s_v j}$, $R_{s_j}^{\min}$ and ϵ_f.

In Definition 1, we replace $g_{u_0 j} P_{u_0}^c$ in (2) by the sensing threshold ϵ_f. This makes the condition more conservative, since any available channel c for FBS j satisfies $g_{u_0 j} P_{u_0}^c \leq \epsilon_f$.

B. FBS Clustering Scheme

Based on the analysis of channel reuse condition, we propose the following FBS clustering scheme to coordinate the interference. We group the set of FBSs $\mathcal{J}$ into K clusters $\mathcal{J}_1, \ldots, \mathcal{J}_K$, and assign each cluster with a number of channels. That is, we divide the set of channels $\mathcal{N}$ into disjoint subsets $\mathcal{N}_1, \ldots, \mathcal{N}_K$, and assign the channels in $\mathcal{N}_k$ to $\mathcal{J}_k$, $\forall\, k \in \mathcal{K} \triangleq \{1, \ldots, K\}$. The FBSs in a cluster can select the same channels assigned to that cluster, and each cluster of FBSs ($\mathcal{J}_k$) satisfy the approximate channel reuse condition in Definition 1. We use an indicator function $I(\mathcal{J}_k, |\mathcal{N}_k|)$ to denote the approximate channel reuse condition for cluster $\mathcal{J}_k$, where $I(\mathcal{J}_k, |\mathcal{N}_k|) = 1$ indicates the condition is satisfied, and is equal to 0 otherwise. The condition depends on both the cluster of FBSs ($\mathcal{J}_k$) and the number of channels assigned to it ($|\mathcal{N}_k|$), since the rate requirement of a super FU $R_{s_j}^{\min}$ is related to n_j, which is bounded by the number of FUs associated with FBS j (since an FU can only access one channel at a time) and the number of channels assigned to the cluster.

To find the desired clusters and their corresponding sets of channels is to solve the following *feasibility* problem.

$$\underset{K,\, \mathcal{J}_k,\, \mathcal{N}_k,\, k \in \mathcal{K}}{\text{minimize}} \quad 0 \quad (6a)$$

$$\text{subject to} \quad \bigcup_{k \in \mathcal{K}} \mathcal{J}_k = \mathcal{J}, \quad (6b)$$

$$\bigcup_{k \in \mathcal{K}} \mathcal{N}_k = \mathcal{N}, \quad (6c)$$

$$\mathcal{N}_k \bigcap \mathcal{N}_v = \emptyset, \qquad \forall\, k, v \in \mathcal{K}, k \neq v, \quad (6d)$$

$$I(\mathcal{J}_k, |\mathcal{N}_k|) = 1, \qquad \forall\, k \in \mathcal{K}. \quad (6e)$$

Problem (6) determines whether the constraints are consistent and if so, find a solution that satisfies them. The optimal value is either 0 (if the feasible set is non-empty) or ∞ (if the feasible set is empty). Constraint (6b) indicates that each FBS should be included in at least one cluster. Constraints (6c)-(6d) imply that each channel is assigned to only one cluster of FBSs. Problem (6) may have multiple solutions. However, it is difficult solve the problem directly, since the set of candidate solutions that satisfy the first three constraints is very large and for each candidate we need to verify the approximate channel reuse condition (i.e., constraint (6e)). In this paper, we transform problem (6) into a related problem by modifying the set of constraints, and propose an efficient algorithm to solve the related problem. Then, we find a solution to problem (6) based on the solution to the related problem.

We consider the following constraints

$$\mathcal{J}_k \bigcap \mathcal{J}_v = \emptyset, \qquad \forall\ k, v \in \mathcal{K}, k \neq v, \tag{7a}$$

$$|\mathcal{N}_k| = \left\lfloor \frac{|\mathcal{N}|}{K} \right\rfloor, \qquad \forall\ k \in \mathcal{K}, \tag{7b}$$

where $\lfloor \cdot \rfloor$ is the floor function. Constraint (7a) indicates that one FBS can only be present in one cluster. Constraint (7b) corresponds to the scenario where the number of channels allocated to all clusters are the same. By adding constraint (7a) and replacing constraint (6c) with (7b), we obtain the following related feasibility problem.

$$\underset{K,\, \mathcal{J}_k,\, \mathcal{N}_k,\, k\in\mathcal{K}}{\text{minimize}} \qquad 0 \tag{8a}$$

$$\text{subject to}\ \ \text{constraints (6b), (6d), (6e), (7a), (7b).} \tag{8b}$$

Next, we employ a graph-theoretic approach to solve problem (8). We consider the set of FBSs forms an undirected graph $G = (\mathcal{J}, \mathcal{E})$, where each FBS $j \in \mathcal{J}$ is a node in the graph and $\mathcal{E}$ represents the set of edges in the graph. We define $e_{j,l}$ as a binary variable to indicate whether there is an edge between nodes j and l. For any pair of nodes $\{j, l\}$, if $I(\{j, l\}, \lfloor |\mathcal{N}|/K \rfloor) = 1$, then there is an edge between the two nodes, which is represented as $e_{j,l} = 1$. Otherwise, we set $e_{j,l} = 0$. The set of edges in the graph is $\mathcal{E} = \{\{j, l\} \mid e_{j,l} = 1, j, l \in \mathcal{J}\}$. We further define a clique as a subset of nodes $\mathcal{J}_k^c \in \mathcal{J}$, where there is an edge between any two nodes in the subset, i.e., $e_{j,l} = 1, \forall\ j, l \in \mathcal{J}_k^c$. Then, solving problem (8) is equivalent to finding K non-overlapping cliques $\{\mathcal{J}_k^c, k \in \mathcal{K}\}$ that covers all nodes in $\mathcal{J}$, where the set of nodes in each clique satisfies constraint (6e). Note that the clique partition problem is NP-complete [10] and is in general difficult to solve. Since we consider the channel resources are sufficient to guarantee the QoS of all users (in Section II), in the following, we assume the solution to problem (8) exists, and propose an algorithm to find it efficiently.

The main idea of our algorithm is as follows. We search K from 1 to $|\mathcal{N}|$. For each fixed K, we construct a graph according to the aforementioned graph model, and find the neighbors that are linked to each node $j \in \mathcal{J}$, denoted as $\mathcal{V}_j$. Then, we partition the graph into a minimal number of cliques, denoted as K_c, such that each node is in one clique that satisfies the approximate channel reuse condition. To find the K_c cliques, we design an iterative algorithm by modifying the clique partition algorithm proposed in [11]. We first create the initial cliques $\mathcal{S}_j, \forall\ j \in \mathcal{J}$, where each clique $\mathcal{S}_j$ contains one node $j \in \mathcal{J}$. In the first iteration, we find two nodes i_1 and i_2 which have the largest number of common neighbors, denoted as $|\mathcal{V}_{com}| \triangleq |\mathcal{V}_{i_1} \bigcap \mathcal{V}_{i_2}|$, and we merge the cliques $\mathcal{S}_{i_1}$ and $\mathcal{S}_{i_2}$ into a new clique $\mathcal{S}_{i_1 i_2}$. We then delete nodes i_1 and i_2 in the graph and add a super node $i_1 i_2$. We create an edge between each node in $\mathcal{V}_{com}$ and the super node if they satisfy the approximate channel reuse condition. In each of the remaining iterations, we merge two nodes (or super nodes) and their corresponding cliques in the new graph in the same way as we did in the first iteration. This merge process continues until there is no edge between any two nodes (or super nodes), which gives all the desired cliques. We then determine K_c as the total number of cliques. The search of K stops when $K_c \leq K$. The procedures of the algorithm are shown in Algorithm 1.

Algorithm 1 Algorithm to solve problem (8)

1: **for** $m := 1$ to $|\mathcal{N}|$
2: ***Construct a graph*** G**:**
3: Set $e_{jl} := I(\{j, l\}, \lfloor |\mathcal{N}|/m \rfloor), \forall\ j, l \in \mathcal{J}$
4: Set $\mathcal{E} := \{e_{j,l} \mid e_{j,l} = 1,\ j, l \in \mathcal{J}, j \neq l\}$
5: Set $\mathcal{V}_j := \{l \mid e_{j,l} = 1, l \in \mathcal{J}\}, \forall\ j \in \mathcal{J}$
6: ***Clique partition*****:**
7: Set $\mathcal{S}_j := \{j\}, \forall\ j \in \mathcal{J}$
8: Set $\mathcal{J}' := \mathcal{J}$ and $\mathcal{E}' := \mathcal{E}$
9: **Repeat**
10: Set $n_{\max} := -1$
11: **for each** $e_{j,l} \in \mathcal{E}'$ **do**
12: Set $\mathcal{V}_{com} := \mathcal{V}_j \bigcap \mathcal{V}_l$
13: **for each** $q \in \mathcal{V}_{com}$ **do**
14: **if** $I(\mathcal{S}_l \bigcup \mathcal{S}_j \bigcup \{q\}, \lfloor |\mathcal{N}|/m \rfloor) = 0$ **then**
15: Set $\mathcal{V}_{com} := \mathcal{V}_{com} \backslash \{q\}$
16: **endif**
17: **endfor**
18: **if** $|\mathcal{V}_{com}| > n_{\max}$ **then**
19: Set $n_{\max} =: |\mathcal{V}_{com}|$, $\mathcal{V}_{\max} := \mathcal{V}_{com}$, $i_1 := j$, $i_2 := l$
20: **endif**
21: **endfor**
22: Set $\mathcal{E}' := \mathcal{E}' \backslash \{e_{vi_1}, e_{ki_2} \mid v \in \mathcal{V}_{i_1}, k \in \mathcal{V}_{i_2}\}$
23: Merge nodes i_1 and i_2, and denote the new node as $i_1 i_2$.
24: Set $\mathcal{S}_{i_1 i_2} := \mathcal{S}_{i_1} \bigcup \mathcal{S}_{i_2}$
25: Set $\mathcal{J}' := (\mathcal{J}' \backslash \{i_1, i_2\}) \bigcup \{i_1 i_2\}$.
26: **for each** $q \in \mathcal{V}_{\max}$ **do**
27: $\mathcal{E}' := \mathcal{E}' \bigcup \{e_{q, i_1 i_2}\}$
28: **endfor**
29: **Until** $\mathcal{E}' = \emptyset$
30: Find the number of super nodes in $\mathcal{J}'$, denoted as K_c
31: **if** $K_c \leq m$ **then**
32: Set $K := K_c$
33: Set $\mathcal{J}_k := \mathcal{S}_j, \forall\ k \in \mathcal{K}$, where j is the kth element in $\mathcal{J}'$
34: **endif**
35: **endfor**

In Algorithm 1, Lines 3-5 create the initial graph G. Lines 7-30 correspond to the proposed clique partition algorithm. Note that Algorithm 1 provides the number of clusters K. We find the subset of channels for each cluster of FBSs as

$$\mathcal{N}_k = \{(k-1)K+1, (k-1)K+2, \ldots, (k-1)K+K\}. \tag{9}$$

Thus, we have found the desired solution $\{K, \mathcal{J}_k, \mathcal{N}_k, k \in \mathcal{K}\}$ to problem (8).

If $|\mathcal{N}|/K$ is an integer, then the solution to problem (8) is also a solution to problem (6) since all the constraints in problem (6) can be satisfied. When $|\mathcal{N}|/K$ is not an integer, we have a number of $|\mathcal{N}| - K\lfloor |\mathcal{N}|/K \rfloor$ channels left after solving problem (8). In this case, we assign the remaining channels to FBSs one by one. For each of these channels, we assign it to the cluster $\mathcal{J}_k$ which has the largest average data rate required over a channel, and obtain a new subset of channels. Then, we move on to assign the next channel until all the remaining channels are assigned. Note that adding a channel to a cluster does not violate the channel reuse condition of that cluster, since FBSs have more resources to allocate to their FUs and the FUs may choose a lower transmission power which results in less interference among the femtocells. In addition to allocate the remaining channels to each cluster, we also relax constraint (7a) (which is the additional constraint introduced in problem (8)) by checking whether each cluster can admit more FBSs without violating the channel reuse condition. The procedures are summarized in Algorithm 2, which finds the desired solution $\{K, \mathcal{J}_k^*, \mathcal{N}_k^*, k \in \mathcal{K}\}$ to problem (6).

Algorithm 2 Algorithm to find a solution of problem (6)

1: Determine K, $\mathcal{N}_k$ and $\mathcal{J}_k$, $\forall\ k \in \mathcal{K}$ according to Algorithm 1
2: Set $\mathcal{N}_k^* := \mathcal{N}_k$, $\mathcal{J}_k^* := \mathcal{J}_k$, $\forall\ k \in \mathcal{K}$
3: **if** $K(\lfloor |\mathcal{N}|/K \rfloor) < |\mathcal{N}|$ **then**
4:   **for** $l := K(\lfloor |\mathcal{N}|/K \rfloor) + 1$ **to** $|\mathcal{N}|$ **do**
5:     Subset $\mathcal{J}_k := \arg\max_{\mathcal{J}_k} \sum_{u_j \in \mathcal{U}_j, j \in \mathcal{J}_k} R_{u_j}^{\min} / |\mathcal{N}_k^*|$
6:     Set $\mathcal{N}_k^* := \mathcal{N}_k^* \bigcup \{l\}$
7:   **endfor**
8: **endif**
9: **for** $k := 1$ **to** K **do**
10:   **for each** $j \in \mathcal{J} \backslash \mathcal{J}_k^*$ **do**
11:     **if** $I\left(\mathcal{J}_k^* \bigcup \{j\},\ |\mathcal{N}_k^*|\right) = 1$ **then**
12:       Set $\mathcal{J}_k^* := \mathcal{J}_k^* \bigcup \{j\}$.
13:     **endif**
14:   **endfor**
15: **endfor**

In Algorithm 2, Lines 1-8 allocate the remaining channels to different clusters. Lines 9-15 check whether a cluster can include more FBSs. After performing Algorithm 2, one FBS may be included in multiple clusters, and can select any channel which is assigned to those clusters.

C. Cluster-based Coordination Mechanism

Based on the coordination framework and the FBS clustering scheme, we design a coordination mechanism as follows. We first consider the channel selection strategy for each FBS. According to the FBS clustering scheme, each FBS can select any channel which is assigned to its cluster(s) without violating the QoS requirements. We denote $\mathcal{Q}_j = \{k \mid j \in \mathcal{J}_k\}$ as the index of cluster(s) that FBS j belongs to, and the corresponding set of candidate channels is $\bigcap_{k \in \mathcal{Q}_j} \mathcal{N}_k$. However, some of these channels may be occupied by nearby MUs which generate significant interference to the FBS. Based on FBS j's sensing result $\mathcal{A}_j$, the set of available channels for FBS j is $\Gamma_j = \bigcap_{k \in \mathcal{Q}_j} \mathcal{N}_k \bigcap \mathcal{A}_j$. Note that each FU can only access one channel at a time. Therefore, when $|\Gamma_j| > |\mathcal{U}_j|$, FBS j selects $|\mathcal{U}_j|$ of the available channels to serve its FUs. To assist the channel selection, the operator can send FBS j the estimated interference from other femtocells on channels assigned to clusters $k \in \mathcal{Q}_j$, which is $\Phi_j^k \triangleq \sum_{v \in \mathcal{J}_k, v \neq j} g_{s_v j} P_{s_v}^*$, where $P_{s_v}^*$ is the minimum transmission power of super user s_v that satisfies the channel reuse condition, which can be obtained by solving problem (6). We further denote Γ_j' as the set of $|\mathcal{U}_j|$ channels in Γ_j on which FBS j experience less interference. Then, the channel selection strategy for FBS j is

$$\mathcal{D}_j = \begin{cases} \Gamma_j, & \text{if } |\Gamma_j| \leq |\mathcal{U}_j|, \\ \Gamma_j', & \text{otherwise.} \end{cases} \tag{10}$$

According to the channel selection strategy, FBS j needs the information of which cluster(s) it belongs to and the corresponding set of assigned channels, as well as the estimated interference for each cluster in order to make the decision. Therefore, we design the coordination variables at FBS j as

$$\mathcal{C}_j = \left\{\mathcal{Q}_j; \mathcal{N}_k, \Phi_j^k, \forall\ k \in \mathcal{Q}_j\right\}. \tag{11}$$

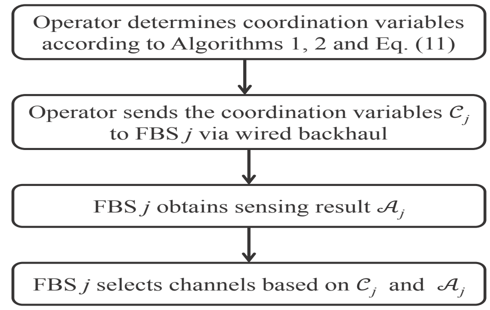

Fig. 2. Procedures of the cluster-based coordination mechanism.

Thus, the proposed cluster-based coordination mechanism can be implemented as shown in Fig. 2. The coordination process is performed periodically, i.e., every 1000 time slots. Note that this coordination mechanism does not require information exchange among the femtocells, and thus will not incur extra communication overhead for the existing systems.

IV. Performance Evaluation

In this section, we evaluate the performance of the proposed coordination mechanism. The simulation model consists of an MBS and J FBSs randomly deployed within a circular region with radius 100 m. The radius of each femtocell is 10 m. Four FUs are randomly distributed within each femtocell. The MBS serves $|\mathcal{U}_0|$ MUs in the region and we restrict the MUs to be located near the FBSs. There are N channels available for the system, each with a bandwidth of 180 kHz. The path loss exponent between a user and the MBS (or an FBS) is 4 (or 3). The noise power is -120 dBm. The minimum average data rate required by each user is randomly selected from $\{200, 300, 400, 500\}$ kbps. The interference threshold at the MBS is -80 dBm. The sensing threshold at each FBS is -80 dBm. Unless stated otherwise, we set $J = 15$, $N = 12$ and $|\mathcal{U}_0| = 10$. We compare the performance of the proposed coordination mechanism with a mechanism where FBSs select channels only based on their sensing results without coordination, which is similar to the mechanism in [7].

We first evaluate the performance of the aforementioned mechanisms with respect to different number of channels N. Fig. 3 shows the average throughput of an FBS in the system increases as the number of channels increases for both mechanisms. The proposed mechanism achieves a higher throughput than the mechanism without coordination and the performance gap becomes smaller when N is large. This is

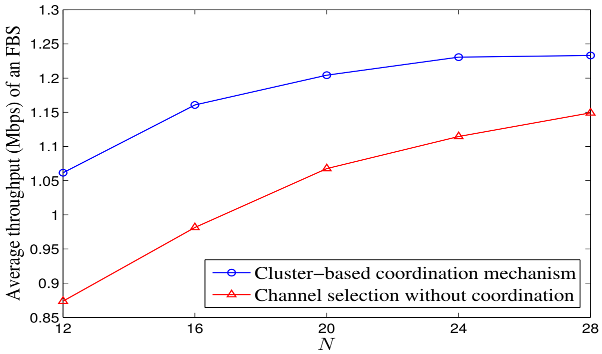

Fig. 3. Average throughput of an FBS versus different number of channels.

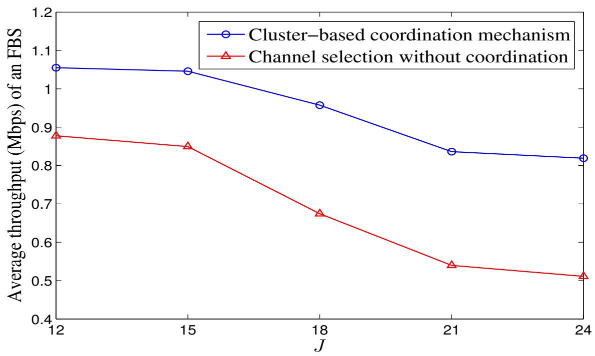

Fig. 4. Average throughput of an FBS versus different number of FBSs.

because when the number of channels is small, there is a high probability that multiple adjacent femtocells select the same channel without coordination, and they experience significant interference from each other which causes transmission failure. As N increases, the probability of selecting the same channel among the femtocells becomes smallers, and the performance of these mechanisms becomes closer.

Next, we vary the number of FBSs (J) and evaluate the performance of the two mechanisms. It is shown in Fig. 4 that the average throughput of an FBS in the system decreases as J decreases. The reason is as follows. For the proposed mechanism, as the number of FBSs increases, the number of clusters may also increase, while the number of channels assigned to each cluster becomes smaller. Therefore, each FBS has fewer channels to serve its FUs, which degrades the average throughput at the FBS. For the mechanism without coordination, increasing the number of FBSs does not affect the sensing result at an FBS (from MUs). However, it is possible that more FBSs select the same channels, which results in a decrease of the throughput at each of these FBSs.

Finally, we evaluate the performance of both mechanisms with respect to different number of MUs ($\mathcal{U}_0$). Fig. 5 shows that the average throughput of an FBS decreases as the number of MUs increases. This is because when the number of MUs near an FBS increases, the available channels for this FBS becomes fewer since they are occupied by the MUs, which degrades the FBS's throughput. Nevertheless, the proposed mechanism achieves a better performance compared to the mechanism without coordination.

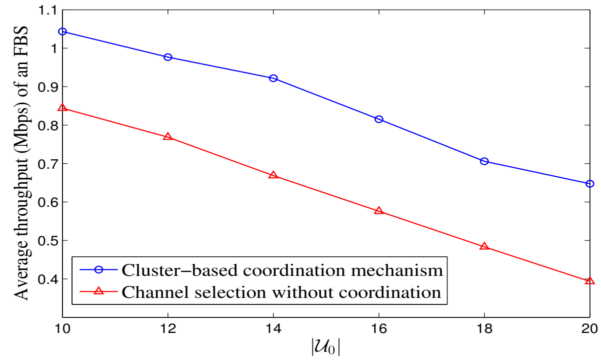

Fig. 5. Average throughput of an FBS versus different number of MUs.

V. Conclusion

In this paper, we designed a cluster-based coordination mechanism to assist the channel selection at cognitive FBSs for a macro-femto system. This mechanism follows an operator-assisted coordination framework and adopt an FBS clustering scheme which employs a graph-theoretic approach. The mechanism does not require message exchange among femtocells and is suitable for practical systems. We showed that the proposed coordination mechanism achieves a better performance than the mechanism without coordination. We noticed that when many MUs are close to an FBS, the number of available channels at the FBS is small. This issue may be addressed by applying hybrid access control at FBSs, which is an interesting topic in our future work.

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