Access Strategy and Dynamic Downlink Resource Allocation for Femtocell Networks

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***Abstract*—Femtocells are small, low power cellular base stations (BS) with high potential for coverage extension and offloading voice and wireless data. In this paper, we study the problem of joint access control and spectrum resource allocation in a two-tier femtocell network with one macro base station (MBS) and multiple Femto Access Points (FAP). The objective is to maximize the overall network capacity, while guaranteeing the quality of service (QoS) requirement of all User Equipments (UE). We develop an access scheme for Macro User Equipments (MUE) and a spectrum allocation mechanism for the FAPs. Spectrum allocation is employed as an incentive mechanism to encourage FAPs to serve more MUEs. We also derive an upper bound of the network-wide capacity through a reformulation of the problem. The proposed algorithms are validated and the upper bound is shown to be quite accurate in the simulation study.**

I. INTRODUCTION

Femtocells, also named as Femto Access Points (FAP), are small, low power cellular base stations (BS). Femtocells are designed for use at homes and small enterprises, and are usually connected to the core network with broadband wireline connections [1]. In addition to providing a shortcut to the core network, the wireline connection also enables coordinations among FAPs and macrocell base stations (MBS) to improve the performance of the two-tier network. Femtocells are considered as a low-cost and effective solution to extend wireless coverage and offload voice and wireless data. This is really important, as research indicates that 70% of data traffic take place indoor where the coverage of conventional cellular networks is usually poor. With femtocells, the distance between BS and a User Equipments (UE) is greatly reduced, thus enabling better signal transmissions and better spatial reuse of spectrum.

The success of femtocell networks largely relies on the management of interference. The deployment of femtocells provides better coverage to nearby Femtocell User Equipments (FUE), but it may also produce a “dead zone” to nearby Macro User Equipments (MUE). FAPs are usually deployed in places where there is poor MBS coverage; the MUE and MBS must use high transmit power to sustain their connection, thus leading to strong interference to FUEs. Unlike well-planned and optimized deployment of cellular networks (i.e., the MBS’s), FAPs are usually installed by end-users in a chaotic manner. The coverage of FAPs may overlap with each other and cause interference among FAPs themselves.

From the perspective of access policy, femtocells can be classified into (i) closed access, where only subscribers can access the FAPs, and (ii) open access, where an FAP serves both subscribers and nearby MUEs. Although open access is more appealing for interference management, its success depends on the willingness of the FAPs to serve non-subscribed MUEs; some incentive mechanisms would be critical to encourage FAP owners to adopt this strategy. From the perspective of spectrum resource allocation, femtocells can be classified into (i) co-channel scenarios, where MBS’s and FAPs share the spectrum band, and (ii) dedicated channel scenarios, where orthogonal channels are assigned. The tension between interference and spectrum efficiency should be carefully balanced.

In this paper, we investigate the problem of access control and spectrum resource allocation in two-tier femtocell networks. We assume one MBS and multiple FAPs in the area and consider the open access scheme. The FUEs are always connected to the corresponding FAPs, while the MUEs can choose between the MBS and a nearby FAP for connection. The spectrum is divided into two parts, one for the MBS and the other part for the FAPs. To provide incentives to FAPs for serving MUEs, we allow dynamic partition of the spectrum according to the network dynamics; more bandwidth will be allocated to the FAPs if they serve more MUEs.

We developed a scheme for joint access control and spectrum resource allocation. The goal is to maximize the network-wide capacity and improve the performance of UEs with poor MBS coverage, by assigning the MUEs to the MBS or FAPs and by dynamically partition the spectrum for the MBS and the FAPs. We also aim to guarantee the quality of service (QoS) of the users in the form of a minimum capacity requirement. The formulated problem is a mixed integer nonlinear programming (MINLP) problem. We then develop an algorithm that assigns MUEs to the BS’s and an algorithm for allocating spectrum resource to the BS’s once the BS association for the MUEs are determined. An upper bound on the network capacity achieved by the proposed algorithms is also derived. The performance of the proposed algorithms are evaluated with simulations, and are shown to outperform an existing scheme with considerable gains. The upper bound is also found to be quite tight for most of the cases examined in the simulation study.

The remainder of the paper is organized as follows. We discuss related work in Section II and the problem formulation in Section III. In Section IV, we propose access control and spectrum resource allocation algorithms and derive the capacity upper bound. Simulation studies are presented in Section V. Section VI concludes the paper.

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II. RELATED WORK

Compared with Wi-Fi access points, femtocells provide a solution of supporting better voice and data coverage by switching from the cellular network to another service provider when the signal quality is poor indoor, instead of just providing high speed data transmissions. Femtocells are now primarily viewed as a cost-effective means of offloading data and voice from the macrocell network [1]. Because of the advantages for both network operators and customers, the benefits of femtocells cannot be overemphasized in the long term. However, the two-tier architecture of macrocells and femtocells inevitably brings about the cross-tier interference problem. Further, as femtocells are usually deployed by end-users and the deployment of femtocells are not well planned, femtocells may be overlapped with each other, causing co-tier interference among such femtocells [2]. Hence, interference management in femtocell network has received tremendous attention from either academic or industrial areas [3], [4].

As the interference in femtocell network is largely determined by the deployment scenarios, Mahmoud and Guvenc in [5] summarized femtocell deployment from two perspectives: (i) closed access or open access, (ii) co-channel or dedicated channels. A game-theoretic approach for resource allocation in OFDMA femtocells with closed access was proposed in [6]. However, an non-subscribed user that is close to an FAP may be far away from the MBS. Its transmit power should be increased to meet its QoS requirement, thus introducing stronger interferences to users of the FAP. In [7], the authors introduced a game-theoretic framework for the FAPs to decide their own access policy in order to maximize the system performance. In [8], an algorithm was proposed for the open access scenario to improve network throughput, while a hybrid access mechanism was introduced in [9] to guarantee the resources for users and reduce interference.

In co-channel scenarios, the spectrum is available for all users but it may lead to high cross-tier interference. To mitigate the interference in co-channel scenarios, a Frequency ALOHA (F-ALOHA) was adopted to avoid excessive cross-tier interference in [10]. In [4], [11], the authors proposed a Cognitive Radio (CR) approach to mitigate the cross-tier interference. In [12], the impact of Interference Alignment (IA) in femtocell networks was evaluated. In Co-channel deployment scenarios, it is usually difficult to guarantee the Quality of Service (QoS) requirements for users. In dedicated channel scenarios, spectrum is divided into orthogonal portions and allocated to different tiers, in order to eliminate cross-tier interference at the price of a lower spectrum efficiency [5].

III. SYSTEM MODEL AND PROBLEM STATEMENT

A. System Model

We consider a femtocell network with one MBS (indexed with 0) collocated with $\mathcal{N} = \{1, 2, \cdots, N\}$ FAPs. Let $\mathcal{L}_0 = \{1, 2, \cdots, L_0\}$ denote the set of active MUEs in the network. Each FAP $i \in \mathcal{N}$ serves a set of active FUEs, denoted as $\mathcal{L}_i = \{1, \ldots, L_i\}$, for $i = 1, 2, \cdots, N$.

The spectrum B for this femtocell network is divided into two parts: (i) B_0 allocated to the MBS, and (ii) the remaining portion $(B - B_0)$ allocated to the FAPs. An FAP i will use spectrum $(B-B_0)$ to serve its subscribers $\mathcal{L}_i$ and some of the MUEs; the remaining MUEs will be served by the MBS using spectrum B_0. Since the spectrum allocated to the MBS and the FAPs are orthogonal, there is no cross-tier interference.

Due to the autonomous, chaotic deployment of the FAPs, the set of FAPs can be classified into disjointed clusters. The FAPs in a cluster has overlapped coverage and may interfere with each other, but there is no interference among different clusters. If a cluster consists of an isolated FAP, the FAP can use all the $(B - B_0)$ spectrum without interfering other FAPs or the MBS. A cluster with multiple FAPs is treated as a "virtual" FAP. From the perspective of MUEs and the MBS, the cluster behaves like one FAP. Within the cluster, we assume the interfering FAPs are allocated with orthogonal spectrum resources in the $(B-B_0)$ band to avoid interference. For example, interference graphs can be used to model the exclusive relationship among the interfering FAPs [4].

In this paper, we consider an open access scheme, in which all the MUEs are allowed to access a nearby FAP, while the FUEs always connect to the corresponding FAPs. Recall that $\mathcal{L}_k$ is the set of UEs subscribed to BS k, for $k = 0, 1, \cdots, N$ ($\mathcal{L}_0$ is the set of MUEs). For open access of the MUEs, we define a variable $\rho_{i,j}(k)$ to indicate the access strategy of a UE $j \in \mathcal{L}_k$ originally subscribed to BS k.

$$\rho_{i,j}(k) = \begin{cases} 1, & \text{UE } j \in \mathcal{L}_k \text{ accesses BS } i \\ 0, & \text{otherwise,} \end{cases} \quad \forall\, i, k \in \{0\} \cup \mathcal{N}. \quad (1)$$

Since we assume that all FUEs in $\mathcal{L}_k$ access to the correspondent FAP k, it follows that $\rho_{k,j}(k) = 1$, for all $k \neq 0$.

As FAPs are usually deployed by customers for home or office use, we adopt the standard indoor propagation model for the FAP link between UE j, $j \in \mathcal{L}_k$, and BS i as [13]

$$\lambda_{i,j}(k) = 37 + 30\log_{10} d_{i,j}(k) + 18.3 n^{\left(\frac{n+2}{n+1} - 0.46\right)}, \quad \forall\, i, k \neq 0, \quad (2)$$

where $d_{i,j}(k)$ is the separation from BS i to UE j, for all $j \in \mathcal{L}_k$; n is the number of floors along the path. For the MBS, we adopt the standard outdoor model for the path loss from the MBS to MUE $j \in \mathcal{L}_0$ as [13]

$$\lambda_{0,j}(0) = 40\log_{10} d_{0,j}(0) + 30\log_{10} f + 49, \quad (3)$$

where f (in MHz) is the central carrier frequency. As the bandwidth of the spectrum is much small comparing to the carrier frequency, we can fix f to a constant f_0 for simplification.

Consider an addictive white Gaussian noise (AWGN) channel, the Signal to Interference plus Noise (SINR) of user j, $j \in \mathcal{L}_k$, from BS i is denoted as

$$\varepsilon_{i,j}(k) = p_{i,j}(k) h_{i,j}(k), j \in \mathcal{L}_k, i, k \in \{0, 1, \cdots, N\}, \quad (4)$$

where $h_{i,j}(k) = 10^{(-\lambda_{i,j}(k)/10)}/(N_0 + I_j(k))$; $p_{i,j}(k)$ is the transmit power of BS i to UE j, $j \in \mathcal{L}_k$; N_0 denotes the power of background white Gaussian noise; $I_j(k)$ is the received interference of UE j, $j \in \mathcal{L}_k$, from nearby FAPs. Therefore, the downlink capacity for UE j, $j \in \mathcal{L}_k$ can be approximated by the Shannon capacity as

$$C_j(k) = \sum_{i=0}^{N} \rho_{i,j}(k) B_{i,j}(k) \log_2(1 + \varepsilon_{i,j}(k)), j \in \mathcal{L}_k, \forall\, k, \tag{5}$$

where $B_{i,j}(k)$ denotes the spectrum band allocated to UE j, $j \in \mathcal{L}_k$ by BS i. Then, the downlink capacity of BS i can be computed as

$$C_i = \sum_{k=0}^{N} \sum_{j \in \mathcal{L}_k} \rho_{i,j}(k) B_{i,j}(k) \log_2(1 + \varepsilon_{i,j}(k)), \forall\, i. \tag{6}$$

B. Problem Formulation

In femtocell networks, the deployment of FAPs makes the transmitter and receiver closer to each other, hence offering better QoS and reducing power consumption and interference. However, FAPs may introduce strong interference to, or be interfered by nearby MUEs, if the same spectrum is used. Consequently, some open access schemes have been introduced as a means for mitigating such cross-tier interference. However, it is usually hard to persuade FAP owners to offer open access to non-subscribed users, as FAPs are installed and owned by end-users, rather than service providers.

In this paper, we propose an incentive scheme that compensates FAPs with spectrum resource for offering open access to nearby MUEs. Specifically, we dynamically partition the spectrum resource according to the association of the MUEs. If more MUEs are switched to nearby FAPs for better service, the MBS share of the spectrum B_0 will be reduced and more spectrum will be allocated to the FAPs. Since the FAP clusters are not interfering with each other, the share $(B - B_0)$ can be used by all the FAP clusters simultaneously, achieving the gain of spatial reuse. It is worth noting that the share $(B-B_0)$ for FAPs is determined by the FAP cluster that serves the most MUEs. For other FAPs serving fewer MUEs, the extra spectrum can be allocated to their FUEs for better service, as an additional incentive for the FAPs to serve MUEs.

The objective is then to maximize the overall capacity of the femtocell network. To achieve this goal, an efficient access scheme for the MUEs and a corresponding spectrum allocate mechanism are needed to dynamically determine the spectrum partition and the spectrum resource allocated to each UE. The constraints are the total spectrum resource of the system and the QoS requirements of the UEs. The dynamic access and resource allocation problem can be formulated as follows.

$$\text{maximize} \quad \sum_{i=0}^{N} C_i \tag{7}$$

subject to:

$$\rho_{i,j}(k) \in \{0,1\}, \;\; i,k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k \tag{8}$$

$$\rho_{k,j}(k) = 1, k \in \mathcal{N}, j \in \mathcal{L}_k \tag{9}$$

$$\sum_{i} \rho_{i,j}(k) = 1, i,k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k \tag{10}$$

$$B_{i,j}(k) \geq 0, i,k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k \tag{11}$$

$$\sum_{k} \sum_{j} B_{i,j}(k) \rho_{i,j}(k) = B_0, \quad i \in \{0\}, k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k \tag{12}$$

$$\sum_{k} \sum_{j} B_{i,j}(k) \rho_{i,j}(k) = B - B_0, \quad i \in \mathcal{N}, k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k \tag{13}$$

$$0 \leq C_j(k) \leq \mathcal{C}, k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k. \tag{14}$$

In the formulated problem, constraint (9) indicates that an FUE can only access the FAP to which it subscribes, while constraint (10) indicates that a UE can only access the MBS or one FAP at a time. Constraint (12) represents the fact that the MBS have spectrum resource B_0 for all the MUEs, while constraint (13) represents the fact that the FAPs have spectrum resource $(B-B_0)$. Constraint (14) is the QoS requirement that the downlink capacity of each UE should be no less than $\mathcal{C}$.

We aim to maximize the capacity of the entire network. The solution of this problem involves optimizing the access strategy of the MUEs (i.e., determining the binary values of $\rho_{i,j}(k)$'s) and the allocation of the spectrum resource (i.e., determine the non-negative real values of $B_{i,j}(k)$'s). Problem (7) is an MINLP problem, which is NP-hard in general. In the following section, we proposed an algorithm to solve this problem with near-optimal solutions as well as a proven performance bound.

IV. ALGORITHMS AND PERFORMANCE BOUND

In this section, we first reformulate problem (7) to obtain a simplified version. Based on observations obtained from the reformulation, we then develop two algorithms that assign the MUEs to either the MBS or an FAP based on the achievable capacity gains, and then to allocate the spectrum resource to the FAPs, We also develop an upper bound for the network-wide capacity achieved by the proposed algorithms.

A. Solution Algorithms

To solve the problem, we first simplify it by reformulating the objective function (7). Based on (8), (9) and (10), the objective function (7) can be reformulated as in (16). According to the reformulation in (16), the total capacity of the network can be divided into two parts:

- the capacity achieved by the MUEs served by the MBS, which shares a total spectrum of B_0 (see (12)).
- the capacity achieved by the MUEs served by FAPs and the capacity achieved by the FUEs, where each FAP cluster has spectrum resource of $(B - B_0)$ (see (13)).

According to (16), the first component to reformulate is the capacity achieved by MUEs. Let $B_{i,j}(0) \equiv B_j$, where B_j is a constant, for all base stations i and MUE $j \in \mathcal{L}_0$. That is, for MUE j it should be allocated with the same amount of spectrum resource no matter which base station it connects to.

$$\sum_{i=0}^{N} C_i = C_0 + \sum_{i=1}^{N} C_i = \sum_{k=0}^{N} \sum_{j\in\mathcal{L}_k} \rho_{0,j}(k) B_{0,j}(k) \log_2(1+\varepsilon_{0,j}(k)) + \sum_{i=1}^{N}\sum_{k=0}^{N}\sum_{j\in\mathcal{L}_k} \rho_{i,j}(k) B_{i,j}(k) \log_2(1+\varepsilon_{i,j}(k))$$

$$= \sum_{j\in\mathcal{L}_0} \rho_{0,j}(0) B_{0,j}(0) \log_2(1+\varepsilon_{0,j}(0)) + \sum_{i=1}^{N} \left\{ \sum_{j\in\mathcal{L}_0} \rho_{i,j}(0) B_{i,j}(0) \log_2(1+\varepsilon_{i,j}(0)) + \sum_{j\in\mathcal{L}_i} \rho_{i,j}(i) B_{i,j}(i) \log_2(1+\varepsilon_{i,j}(i)) \right\} \quad (15)$$

$$= \sum_{j\in\mathcal{L}_0} \sum_{i=0}^{N} \rho_{i,j}(0) B_{i,j}(0) \log_2(1+\varepsilon_{i,j}(0)) + \sum_{i=1}^{N}\sum_{j\in\mathcal{L}_i} \rho_{i,j}(i) B_{i,j}(i) \log_2(1+\varepsilon_{i,j}(i)). \quad (16)$$

It follows that

$$\sum_{j\in\mathcal{L}_0}\sum_{i=0}^{N} \rho_{i,j}(0) B_{i,j}(0) \log_2(1+\varepsilon_{i,j}(0))$$
$$= \sum_{j\in\mathcal{L}_0}\sum_{i=0}^{N} \rho_{i,j}(0) B_j \log_2(1+\varepsilon_{i,j}(0))$$
$$\le \sum_{j\in\mathcal{L}_0} B_j \cdot \max_{\{0\le i\le N\}}\{\log_2(1+\varepsilon_{i,j}(0))\}. \quad (17)$$

The inequality is because there is only one $\rho_{i,j}(0)$ is one and all others are zero. Hence, each MUE should access an MBS or FAP that offers the best SINR for the downlink link.

Consider the case when $\max_{\{0\le i\le N\}}\{\log_2(1+\varepsilon_{i,j}(0))\} = \log_2(1+\varepsilon_{0,j}(0))$, i.e., the MBS can offer the best SINR for MUE j. Even in this case, accessing a nearby FAP may still bring a larger capacity gain for the entire network, since the spectrum resource allocated to the FAPs can be spatially reused. Define

$$G_{i,j}(k) = \log_2(1+\varepsilon_{i,j}(k)), \quad (18)$$

and let ψ_i denote the maximum $G_{i,j}(k)$ among the UEs served by BS i, i.e.,

$$\psi_i = \max_{j\in\mathcal{L}_k, 0\le k\le N}\{G_{i,j}(k)\}, \forall\, i, \quad (19)$$

and define n^* as

$$n^* = \arg\max_{1\le i\le N}\{G_{i,j}(0)\}. \quad (20)$$

In this case, if the following condition is satisfied, i.e.,

$$G_{0,j}(0) < \sum_{i\in\mathcal{N}\setminus n^*} \psi_i - \psi_{n^*}\left(\frac{G_{0,j}(0)}{G_{n^*,j}(0)} - 1\right) + G_{0,j}(0),$$

we have that

$$\sum_{i\in\mathcal{N}\setminus n^*} \psi_i \frac{1}{G_{0,j}(0)} - \psi_{n^*}\left(\frac{1}{G_{n^*,j}(0)} - \frac{1}{G_{0,j}(0)}\right) > 0. \quad (21)$$

Then an MUE can achieve larger network-wide capacity by accessing FAP n^*.

According to (17) and (21), we develop an access scheme for the MUEs, which is given in Algorithm 1. With this access scheme, each MUE chooses the BS (i.e., the MBS or an FAP) with the best channel condition to access, as given in Lines 2–3 in Algorithm 1. For the MUEs that falls within the coverage of each FAP but are connected to the MBS (as determined in Lines 2–3), we next examine if switching such MUEs to the corresponding FAP can achieve further gains in the overall network capacity, as in Line 8, and switch such MUEs to the corresponding FAP if this is the case, as in Lines 9–10. It can be verified that the complexity of Algorithm 1 is $\mathcal{O}(L_0 N)$.

Algorithm 1 Access Scheme

```
 1: for $j = 0 \to L_0$ do
 2:     $i = \arg\max_{0\le i\le N}\{G_{i,j}(0)\}$
 3:     $\rho_{i,j}(0) = 1$
 4: end for
 5: for $j = 0 \to L_0$ do
 6:     if $\rho_{0,j}(0) == 1$ then
 7:         $n^* = \arg\max_{1\le i\le N}\{G_{i,j}(0)\}$
 8:         if $\sum_{i\in N\setminus n^*} \frac{\psi_i}{G_{0,j}(0)} - \frac{\psi_{n^*}}{G_{n^*,j}(0)} + \frac{\psi_{n^*}}{G_{0,j}(0)} > 0$ then
 9:             $\rho_{n^*,j}(0) = 1$
10:             $\rho_{0,j}(0) = 0$
11:         end if
12:     end if
13: end for
```

Once the cell associations for the MUEs are determined by Algorithm 1 (note that for the FUEs, the FAP associations are already determined; see (9)), we next develop a greedy algorithm for spectrum resource allocation for the users. The goal of this algorithm is to greedily maximize the overall capacity of the system under the QoS constraint (14). The algorithm is shown in Algorithm 2, where $G_{i,j}(k)$ and ψ_i are defined in (18) and (19), respectively; ϕ_i is the spectrum needed by FAP i to satisfy the QoS requirements of all the UEs it serves; $B(\psi_i)$ is the spectrum resource of the UE corresponding to ψ_i. The algorithm first determines the bandwidth needed for satisfying the QoS requirement for each UE, and then allocates the spectrum to each BS according to the number of UEs it serves, which is given by Algorithm 1.

The spectrum B is allocated as follows. If $\psi_0 \ge \sum_{i=1}^{N}\psi_i$, allocate the extra spectrum to the MBS and the MBS then allocates it to the MUE connecting to it and having the best channel condition. In this case, as the spectrum resource allocated to the FAPs is determined by the FAP that needs the most spectrum resource to meet the QoS requirements of the UEs connecting to it, some other FAPs may still have some extra spectrum for allocation and they allocate the extra spectrum to the UEs with the best channel condition among those that connect to it. On the other hand, if $\psi_0 < \sum_{i=1}^{N}\psi_i$, the extra spectrum is allocated to the FAPs, and the FAPs

Algorithm 2 Spectrum Allocation

```
for $j = 0 \to L_0$ do
    if $\rho_{0,j}(0) == 1$ then
        $B_{0,j}(0) = \mathcal{C}/G_{0,j}(0)$
    end if
end for
for $i = 1 \to N$ do
    for $j = 0 \to L_i$ do
        $B_{i,j}(i) = \mathcal{C}/G_{i,j}(i)$
    end for
    for $j = 0 \to L_0$ do
        if $\rho_{i,j}(0) == 1$ then
            $B_{i,j}(0) = \mathcal{C}/G_{i,j}(0)$
        end if
    end for
end for
if $\psi_0 \geq \sum_{i=1}^{N} \psi_i$ then
    $B(\psi_0) = B(\psi_0) + B - \phi_0 - \max_{\{1 \leq i \leq N\}} \phi_i$
    for $i = 1 \to N$ do
        $B(\psi_i) = B(\psi_i) + \max_{\{1 \leq i \leq N\}} \phi_i - \phi_i$
    end for
else
    for $i = 1 \to N$ do
        $B(\psi_i) = B(\psi_i) + B - \phi_0 - \phi_i$
    end for
end if
```

will allocate the extra spectrum to the UEs with best channel condition among those connecting to it. It can be verified that the complexity of Algorithm 2 is also $\mathcal{O}(L_0 N)$.

B. Performance Upper Bound

We next derive a performance upper bound for the overall network capacity. According to (15), we can derive the upper bound as in (22).

In (22), first inequality is due to the definition of ψ_i, i.e., as the maximum $G_{i,j}(k)$. The second inequality is due to the fact that $(B - B_0) \leq B$ (i.e., $B_0 \geq 0$). This result is summarized in the following theorem.

Theorem 1. *The network-wide capacity achieved by the proposed algorithms is upper bounded as follows.*

$$\sum_{i=0}^{N} C_i \quad \leq \quad B \max\left\{ \sum_{i=1}^{N} \psi_i, \psi_0 \right\} \tag{23}$$

V. PERFORMANCE EVALUATION

We evaluate the performance of the proposed scheme with MATLAB simulations. Specifically, we compared the proposed algorithms with the access scheme and resource allocation mechanism (termed OA scheme) presented in [8], as well as the OA scheme enhanced with our proposed resource allocation algorithm (OA-PRA). In OA, the MUEs decide to access the MBS or an FAP that provides the best SINR; if an MUE chooses to access an FAP, the FAP will be allocated with the corresponding spectrum resource. In the following simulations, the network has a total spectrum resource of $B = 20$ MHz. The coverage of the MBS is 500 m and the coverage of the FAPs are 50 m. In addition, we assume each FAP has one FUE and there are a large number of MUEs. The channel models are defined in (2) and (3), respectively.

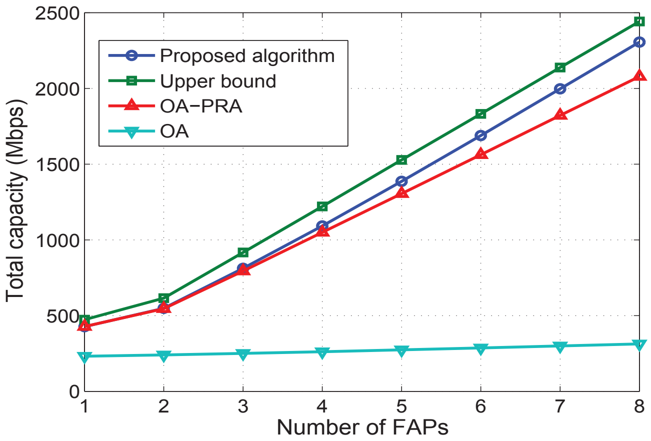

Fig. 1. Number of FAPs versus total capacity.

In Fig. 1, we evaluate the impact of the number of FAPs on the total capacity of the system. In the simulation, there are 100 MUEs, the QoS requirement $\mathcal{C}$ is set to 400 Kbps. As shown in the figure, the total capacity increases as more FAPs are deployed. For OA, the total capacity increases slightly with the number of FAPs N. In the proposed algorithm and OA-PRA, the total capacity increases greatly with N. This is because that more resources are allocated to users with better SINR, and resources can be spatially reused among the FAPs. The proposed algorithm achieves better performance than OA-PRA when there are more than one FAPs. After all, the proposed access scheme has taken into account spatial reuse among FAPs. For the one FAP scenario, OA-PRA and the proposed algorithms achieve an equal total capacity. Actually OA-PRA is equivalent to the proposed algorithm when there is only one FAP in the system. In short, the proposed algorithm achieves considerable network capacity gains than OA, due to the integration of access control and resource allocation. We also find that the upper bound given in Theorem 1 is quite tight for the range of FAP numbers examined in this study.

In Fig. 2, we evaluate the impact of the QoS requirement $\mathcal{C}$ on the total capacity of the system. In this simulation, there are 100 MUEs and 4 FAPs. From the figure, we notice that when QoS requirement is 0, the upper bound, proposed algorithm and OA-PRA achieve the same capacity. Actually, when there is no QoS requirement, in the proposed scheme and OA-PRA, the system allocates all the spectrum resource to the UEs that bring larger capacity gains, hence achieving the upper bound given in Theorem 1. With increased QoS requirement, the performance of the proposed scheme and OA-PRA degrades, but is still much higher than that of OA. This is because that a more stringent QoS requirement forces the system to allocate more spectrum resource to UEs with a lower SINR to ensure that their QoS requirements are met. Hence, there is a balance between fairness and efficiency, as can be seen from this study. The proposed scheme always achieves better performance than that of OA-PRA and OA, and the gain gets larger when the

$$
\begin{aligned}
\sum_{i=0}^{N} C_i &= \sum_{j\in\mathcal{L}_0} \rho_{0,j}(0)B_{0,j}(0)\log_2(1+\varepsilon_{0,j}(0)) + \sum_{i=1}^{N}\left\{\sum_{j\in\mathcal{L}_0}\rho_{i,j}(0)B_{i,j}(0)\log_2(1+\varepsilon_{i,j}(0)) + \sum_{j\in\mathcal{L}_i}\rho_{i,j}(i)B_{i,j}(i)\log_2(1+\varepsilon_{i,j}(i))\right\} \\
&\le \sum_{j\in\mathcal{L}_0}\rho_{0,j}(0)B_{0,j}(0)\psi_0 + \sum_{i=1}^{N}\left\{\sum_{j\in\mathcal{L}_0}\rho_{i,j}(0)B_{i,j}(0)\psi_i + \sum_{j\in\mathcal{L}_i}\rho_{i,j}(i)B_{i,j}(i)\psi_i\right\} \\
&= B_0\psi_0 + (B-B_0)\sum_{i=1}^{N}\psi_i = B\psi_0 + (B-B_0)\left(\sum_{i=1}^{N}\psi_i - \psi_0\right) \le B\psi_0 + B\max\left\{\sum_{i=1}^{N}\psi_i - \psi_0, 0\right\} = B\max\left\{\sum_{i=1}^{N}\psi_i, \psi_0\right\}. \qquad (22)
\end{aligned}
$$

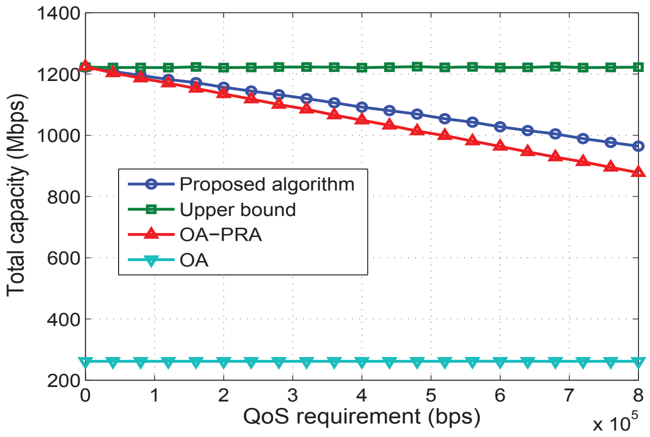

Fig. 2. QoS requirement versus total capacity.

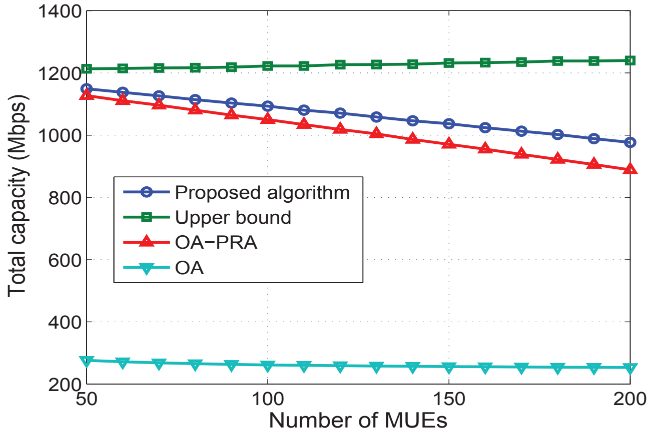

Fig. 3. Number of MUEs versus total capacity.

QoS requirement is increased.

In Fig. 3, we examine the impact of the number of UEs on the total capacity of the system. In this simulation, there are 4 FAPs, and the QoS requirement $\mathcal{C}$ is set to 400 Kbps. It can be seen that the proposed scheme always outperforms both OA and OA-PRA. In addition, the performance of the proposed scheme and OA-PRA get worth with more MUEs are enabled. The reason is similar to that in Fig. 2. With more MUEs, the system needs to allocate more spectrum resource to the UEs with lower SINRs and hence less spectrum resource will be available for the MUEs with good channels.

VI. CONCLUSION

In this paper, we studied the access strategy of MUEs and spectrum resource allocation for the FAPs in a two-tier femtocell network. We considered the dedicated channel and open access deployment scenario, and used spectrum resource as incentives to encourage FAPs to serve more MUEs. The objective is to maximize the overall performance of the network while guaranteeing the QoS requirement for the users. To solve the formulated MINLP problem, we proposed an algorithm to decide the access policy for the MUEs, and an algorithm for allocation of spectrum resources to the FAPs. An upper bound was derived for the total capacity achieved by the proposed algorithms. The bound and proposed algorithms were evaluated with simulations and shown to outperform an existing scheme.

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