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Dynamic downlink resource allocation and access strategy for femtocell networks

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Abstract

Femtocells are small, low-power cellular base stations 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 2-tier femtocell network with 1 macro base station and multiple Femto access points (FAPs). The objective is to maximize the overall network capacity, while guaranteeing the quality of service requirement of all user equipments. We develop an access scheme for macro user equipments and a spectrum allocation mechanism for the FAPs. Spectrum allocation is used as an incentive mechanism to encourage FAPs to serve more macro user equipments. 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.

1 | INTRODUCTION

For us to meet the challenge of fast growing mobile data, many new technologies are under development, such as spectrum expansion,[1,2] spectrum efficiency enhancement,[3–6] and network densification.[7,8] Historic data show that spatial reuse is the most effective in improving wireless network capacity, which can be achieved by deploying small cells or femtocells. Femtocells, also named as Femto access points (FAP), are small, low-power cellular base stations (BS). Femtocells are designed for use at homes and offices and are usually connected to the core network with broadband wireline connections.[7,9–11] In addition to providing a shortcut to the core network, the wireline connection also enables coordination among FAPs and macrocell base stations (MBS) to improve the performance of the 2-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 user equipments (UE) is greatly reduced, thus enabling better signal transmissions and better spatial reuse of spectrum.

Interference modeling and management play a critical role in traditional wireless networks.[12] The success of femtocell networks largely relies on the management of interference. The deployment of femtocells provides better coverage to nearby Femtocell UE (FUE), but it may also produce a "dead zone" to nearby macro user equipments (MUE). Femto access points 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 (ie, 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

- closed access, where only subscribers can access the FAPs, and
- 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 nonsubscriber 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

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- cochannel scenarios, where MBS's and FAPs share the spectrum band, and
- 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 2-tier femtocell networks. We assume 1 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 2 parts, 1 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 consider both cases of nonoverlapping and overlapping femtocells and develop 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 present the problem formulation in Section 2. We propose access control and spectrum resource allocation algorithms and derive the capacity upper bound for nonoverlapping FAPs in Section 3 and for overlapping FAPs in Section 4. Simulation studies are presented in Section 5, and related works are discussed in Section 6. Section 7 concludes the paper.

2 | SYSTEM MODEL AND PROBLEM STATEMENT

2.1 | System model

The system model is illustrated in Figure 1. We consider a femtocell network with 1 MBS (indexed with 0) collocated with $\mathcal{N} = \{1, 2, \cdots, N\}$ FAPs, as illustrated in Figure 1. Let $\mathcal{L}_0 = \{1, 2, \cdots, L_0\}$ denotes the set of active MUEs in the network. Each FAP $k \in \mathcal{N}$ serves a set of active FUEs, denoted as $\mathcal{L}_k = \{1, 2, \cdots, L_k\}$, for $k = 1, 2, \cdots, N$.

The spectrum B for this femtocell network is divided into 2 parts: (1) B_0 allocated to the MBS, and (2) the remaining portion $(B - B_0)$ allocated to the FAPs. An FAP k will use spectrum $(B - B_0)$ to serve its subscribers $\mathcal{L}_k$ 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 1 FAP with an extended coverage. 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.[13,14]

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 $j \in \mathcal{L}_k$ (ie, originally subscribed to BS k).

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

That is, $\rho_{i,j}(k)$ is the access strategy of a UE $j/in\mathcal{L}_k$, ie, to be or not to be connected to base station i. We have $\rho_{i,}j(k) = 1$ if UE j access base station i (for all $j \in \mathcal{L}_k$), and vice versa. Let $B_{i,j}(k)$ be the corresponding bandwidth allocation. 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[15]

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

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[15]

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

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.

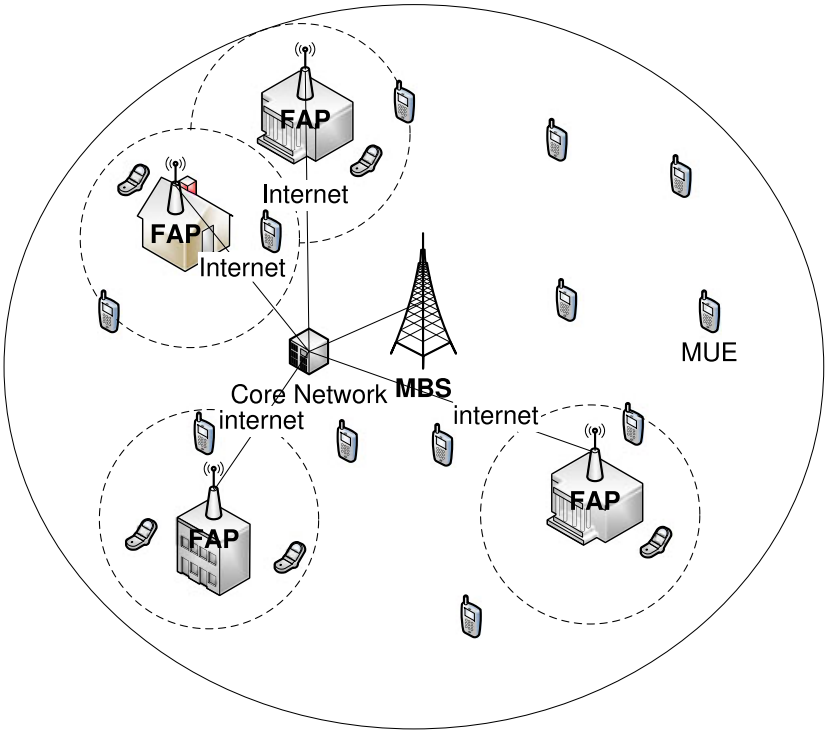

FIGURE 1 A femtocell network with 1 macro base station (MBS) and 4 Femto Access Points (FAP). MUE indicates macro user equipments

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

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

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

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

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

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

2.2 | 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 nonsubscribed 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. Let C denotes the required minimum downlink capacity for each user. The dynamic access and resource allocation problem can be formulated as in Equations 7 to 14.

In the formulated problem, constraint (Equation 13) indicates that an FUE can only access the FAP to which it subscribes, while constraint (Equation 8) indicates that a

UE can only access the MBS or 1 FAP at a time. Constraint (Equation 9) represents that the MBS have spectrum resource B_0 for all the MUEs, while constraint (Equation 10) represents that the FAPs have spectrum resource $(B - B_0)$. Constraint (Equation 11) is the QoS requirement that the downlink capacity of each UE should be no less than C.

We aim to maximize the capacity of the entire network. The solution of this problem involves optimizing the access strategy of the MUEs (ie, determining the binary values of $\rho_{i,j}(k)$'s) and the allocation of the spectrum resource (ie, determine the nonnegative real values of $B_{i,j}(k)$'s). Problem (Equation 7) is an MINLP problem, which is nondeterministic polynomial-time–hard in general. In the following sections, we proposed algorithms to solve this problem with near-optimal solutions as well as a proven performance bound, for the case of nonoverlapping FAPs in Section 3 and the case of overlapping FAPs in Section 4.

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

subject to

$$\sum_{i} \rho_{i,j}(k) = 1, i, k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k$$
$$\sum_{k} \sum_{j} B_{i,j}(k)\rho_{i,j}(k) = B_0, \tag{8}$$

$$i \in \{0\}, k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k$$
$$\sum_{k} \sum_{j} B_{i,j}(k)\rho_{i,j}(k) = B - B_0, \tag{9}$$

$$i \in \mathcal{N}, k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k \tag{10}$$

$$0 \leqslant C_j(k) \leqslant C, k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k. \tag{11}$$

$$\rho_{i,j}(k) \in \{0, 1\}, \quad i, k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k \tag{12}$$

$$\rho_{k,j}(k) = 1, k \in \mathcal{N}, j \in \mathcal{L}_k \tag{13}$$

$$B_{i,j}(k) \geqslant 0, i, k \in \{0\} \cup \mathcal{N}, j \in \mathcal{L}_k. \tag{14}$$

3 | THE CASE OF NONOVERLAPPING FAPS

We consider the case of nonoverlapping FAPs in this section. We first reformulate problem (Equation 7) to obtain a simplified version. On the basis of observations obtained from the reformulation, we then develop 2 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.

3.1 | Solution algorithms

To solve the problem, we first simplify it by reformulating the objective function (Equation 7). Equations 12, 13, and 8 has shown that the objective function (Equation 7) can be reformulated as in Equation16 on top of page 16.

$$\sum_{i=0}^{N} C_i = C_0 + \sum_{i=1}^{N} C_i = \sum_{k=0}^{N} \sum_{j \in \mathcal{L}_k} \rho_{0,j}(k) B_{0,j}(k) \log_2(1 + \epsilon_{0,j}(k)) + \sum_{i=1}^{N} \sum_{k=0}^{N} \sum_{j \in \mathcal{L}_k} \rho_{i,j}(k) B_{i,j}(k) \log_2(1 + \epsilon_{i,j}(k))$$
$$= \sum_{j \in \mathcal{L}_0} \rho_{0,j}(0) B_{0,j}(0) \log_2(1 + \epsilon_{0,j}(0)) + \sum_{i=1}^{N} \left\{ \sum_{j \in \mathcal{L}_0} \rho_{i,j}(0) B_{i,j}(0) \log_2(1 + \epsilon_{i,j}(0)) + \sum_{j \in \mathcal{L}_i} \rho_{i,j}(i) B_{i,j}(i) \log_2(1 + \epsilon_{i,j}(i)) \right\} \tag{15}$$
$$= \sum_{j \in \mathcal{L}_0} \sum_{i=0}^{N} \rho_{i,j}(0) B_{i,j}(0) \log_2(1 + \epsilon_{i,j}(0)) + \sum_{i=1}^{N} \sum_{j \in \mathcal{L}_i} \rho_{i,j}(i) B_{i,j}(i) \log_2(1 + \epsilon_{i,j}(i)). \tag{16}$$

According to the reformulation in Equation 16, the total capacity of the network can be divided into 2 parts:

- The capacity achieved by the MUEs served by the MBS, which shares a total spectrum of B_0 (see Equation 9).
- 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 Equation10).

The solution algorithm is motivated by the following 2 observations. First, according to Equation 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. It follows that

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

The inequality in Equation 17 is because there is only 1 $\rho_{i,j}(0)$ that is 1 and all others are 0 (see constraint (Equation 8). Hence, each MUE should access an MBS or FAP that offers the best SINR for the downlink link.

Second, consider the case when $\max_{\{0\leqslant i\leqslant N\}}\{\log_2(1+\epsilon_{i,j}(0))\} = \log_2(1+\epsilon_{0,j}(0))$, ie, 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 spectrum efficiency $G_{i,j}(k)$, if UE $j \in \mathcal{L}_k$ connects to BS i, as

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

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

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

and define n^* as

$$n^* = \arg\max_{1\leqslant i\leqslant N}\left\{G_{i,j}(0)\right\}. \tag{20}$$

Then we have Theorem 1 for the condition to switch an MUE that is originally associated with the MBS to an FBS for spatial reuse of the spectrum.

Theorem 1. *Let FAP n^* be the FAP that offers the best SINR among all FAPs for an MUE j that is initially associated with the MBS. The network-wide capacity can be increased by switching MUE j to access FAP n^*, if the following inequality holds true,*

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

Proof. Consider that an MUE j that is originally associated with the MBS, since the MBS has the best SINR among all the BS's. Recall that the MUE is assigned with bandwidth B_j. Now, if we switch MUE j to access FAP n^*, and assign the bandwidth B_j to all the FAPs, then the overall network capacity will be changed as follows.

CASE 1: For the MBS, its capacity is decreased by $B_jG_{0,j}(0)$, as the MUE is served by a FAP other than the MBS and the corresponding spectrum bandwidth is assigned to the FAPs.

CASE 2: For the FAPs other than FAP n^*, the capacity can be increased by $B_j\sum_{i\in\mathcal{N}\setminus n^*}\psi_i$ as the spectrum resource B_j is assigned to the FAPs.

CASE 3: For FAP n^*, the net capacity gain would be

$$-\psi_{n^*}B_j\left(\frac{G_{0,j}(0)}{G_{n^*,j}(0)} - 1\right) + B_jG_{0,j}(0).$$

The reason is as follows. Since the MUE initially connects to the MBS, the SINR of the MBS must be better than that of any FAP, ie, $\frac{G_{0,j}(0)}{G_{n^*,j}(0)} > 1$. FAP n^* should assign a spectrum bandwidth $B_j\frac{G_{0,j}(0)}{G_{n^*,j}(0)}$ for the MUE to achieve the same capacity. Consequently, the spectrum assigned to the FUEs served by FAP n^* will be decreased by $B_j\left(\frac{G_{0,j}(0)}{G_{n^*,j}(0)} - 1\right)$. This deceased spectrum assignment will bring about a capacity decrease of at most $\psi_{n^*}B_j\left(\frac{G_{0,j}(0)}{G_{n^*,j}(0)} - 1\right)$, according to the definition in Equation 19. In addition, as the MUE is now served by FAP n^* and achieves the same capacity, it brings about an capacity increase of $B_jG_{0,j}(0)$.

In summary, if the MUE is switched to access FAP n^*, the net increase of the network-wide capacity can be lower bounded by

$$\Delta C = -B_jG_{0,j}(0) + B_j\sum_{i\in\mathcal{N}\setminus n^*}\psi_i - \psi_{n^*}B_j\left(\frac{G_{0,j}(0)}{G_{n^*,j}(0)} - 1\right) + B_jG_{0,j}(0).$$

If $\Delta C > 0$, then the MUE can achieve a larger network-wide capacity by switching to FAP n^*. The theorem is proved. □

On the basis of the above 2 observations (ie, see (Equations 17 and 21), we develop a 2-step access scheme for the MUEs, which is presented in Algorithm 1. In the first step, each MUE chooses the BS (ie, the MBS or a FAP) with the best channel condition to access, as given in Lines 3 to 4 in Algorithm 1. In the second step, for the MUEs that falls within the coverage of an FAP but are connected to the MBS in Step 1 (as determined in Lines 3-4), we next examine if switching such MUEs to the corresponding FAP can achieve further gains in the overall network capacity, as in Line 9. We switch such MUEs to the corresponding FAP if this is the case, as in Lines 10 to 11. It can be verified that the complexity of Algorithm 1 is $\mathcal{O}(L_0N)$.

Algorithm 1 MUE access algorithm

1: Initialize $\rho_{i,j}(0) = 0$, for all i, j
2: **for** $j = 0 \to L_0$ **do**
3: $\quad i = \underset{0\leq i\leq N}{\operatorname{argmax}}\{G_{i,j}(0)\}$
4: $\quad \rho_{i,j}(0) = 1$
5: **end for**
6: **for** $j = 0 \to L_0$ **do**
7: $\quad$ **if** $\rho_{0,j}(0) == 1$ **then**
8: $\quad\quad n^* = \underset{1\leq i\leq N}{\operatorname{argmax}}\left\{G_{i,j}(0)\right\}$
9: $\quad\quad$ **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**
10: $\quad\quad\quad \rho_{n^*,j}(0) = 1$
11: $\quad\quad\quad \rho_{0,j}(0) = 0$
12: $\quad\quad$ **end if**
13: $\quad$ **end if**
14: **end for**

Once the cell associations for the MUEs are determined by Algorithm 1,* 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 (Equation 11). The algorithm is presented in Algorithm 2, where $G_{i,j}(k)$ and ψ_i are defined in Equations 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.

Algorithm 2 Spectrum allocation algorithm

for $j = 0 \to L_0$ **do**
  if $\rho_{0,j}(0) == 1$ **then**
    $B_{0,j}(0) = C/G_{0,j}(0)$
  end if
end for
for $i = 1 \to N$ **do**
  for $j = 0 \to L_i$ **do**
    $B_{i,j}(i) = C/G_{i,j}(i)$
  end for
  for $j = 0 \to L_0$ **do**
    if $\rho_{i,j}(0) == 1$ **then**
      $B_{i,j}(0) = C/G_{i,j}(0)$
    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

The spectrum B is allocated as follows. If $\psi_0 \geqslant \sum_{i=1}^{N} \psi_i$, allocate the extra spectrum to the MBS, and the MBS then allocates the extra spectrum 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 will allocate the extra spectrum to the UEs with the best channel condition among those connecting to it. It can be verified that the complexity of Algorithm 2 is also $\mathcal{O}(L_0 N)$.

*The FAP associations for the FUEs are already determined; see Equation 13.

3.2 | Performance upper bound

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

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

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

Theorem 2. *The network-wide capacity achieved by the proposed algorithms is upper bounded as follows.*

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

4 | THE CASE WITH OVERLAPPING FAPS

In practical scenarios, the deployment of FAPs may not be well planned, as FAPs are deployed by users. In this case, the coverage of some FAPs may overlap. With overlapping coverages, not all FAPs are able to reuse spectrum simultaneously because of the interference among the overlapping FAPs. This makes the access scheme and the spectrum allocation much more complicated. In the introduction, we address the case of overlapping FAPs by forming them into FAP

clusters and then allocating frequency spectrum to the clusters. We first present the access scheme and the spectrum allocation scheme and then derive the capacity bound for the case of overlapping FAPs.

4.1 | Access scheme with overlapping FAPs

In Equation 17, we have shown that the frequency efficiency of each MUE can be improved if it accesses an MBS or FAP that offers the best SINR. Besides, as shown in Equation 21, sometimes the entire system will achieve better overall performance if some MUE chooses to access an FAP even if the MBS offers a higher SINR. However, as evaluating the overall performance of scenario with overlapping FAPs is much more complicated than the non-overlapping FAPs case, we simplify the access scheme of MUEs to allow then access the MBS or FAP with a stronger SINR in this section.

4.2 | Spectrum allocation with overlapping FAPs

Although the interference deteriorates spectrum spatial reuse among overlapping FAPs, spatial reuse is still feasible between FAPs that do not have overlapping coverage. Hence, if we divide the FAPs into clusters such that there is no interference between clusters, then the same spectrum can be reused between clusters. A cluster is a set of FAPs with mutual interference. There is no interference between FAPs from different clusters. We provide a mathematical definition for clusters as follows.

Definition 1. *If 2 FAPs, A and B, interfere each other, then they are* communicating *, denote at* $A \leftrightarrow B$*. And the communicating relationship is transitive. That is, if* $A \leftrightarrow B$*, and* $B \leftrightarrow C$*, then* $A \leftrightarrow C$*. All FAPs are divided into subsets* $\mathcal{S}_1, \mathcal{S}_2, \cdots, \mathcal{S}_k$ *, called clusters, such that any 2 FAPs within the same cluster communicate, but FAPs from different clusters do not, where* $\mathcal{S}_1 \cup \mathcal{S}_2 \cup, \cdots, \cup \mathcal{S}_k = \{1, 2, \cdots, N\}$ *, and* $\mathcal{S}_1 \cap \mathcal{S}_2 \cap, \cdots, \cap \mathcal{S}_k = \emptyset$ *.*

Note that for a FAP that does not interfere with other FAPs, it forms a single FAP cluster. Therefore, the set of FAPs are divided into clusters. There is no interference between FAPs from different clusters, and spectrum can be simultaneously spatial reused by clusters. However, a FAP is not necessarily interfering with all other FAPs in the same cluster.

For example, there are 4 FAPs in Figure 2. FAP_1 interferes with FAP_2, and FAP_3 interferes with both FAP_2 and FAP_4. In this example, FAP_1 and FAP_2 cannot reuse the same spectrum simultaneously, and FAP_2, FAP_3, and FAP_4 cannot reuse the same spectrum, simultaneously. However, if we divide them into 2 groups, ie, $\{FAP_1$ and $FAP_3\}$ and $\{FAP_2$ and $FAP_4\}$, then the 2 FAPs in the same group can use the same spectrum, simultaneously. Hence, it is necessary for us to find a feasible and effective algorithm to divide every cluster with more than 1 FAP into groups such that all FAPs in the same group can use the same spectrum simultaneously.

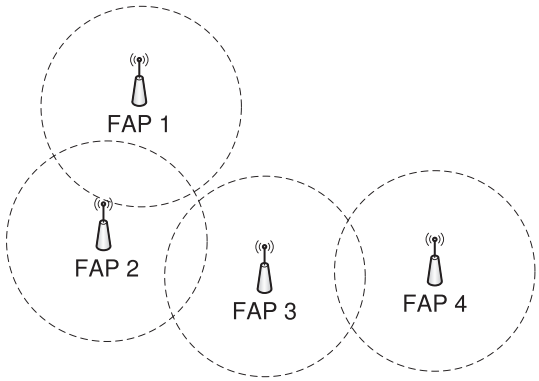

FIGURE 2 An example of a cluster with 4 overlapping Femto access points (FAPs)

We define index variable $V_{i,j}$ as

$$V_{i,j} = \begin{cases} 1, & \text{coverages of FAP}_i \text{ and FAP}_j \text{ overlap} \\ 0, & \text{otherwise,} \end{cases} \quad \forall\, i, k \in \mathcal{N}. \tag{24}$$

According to the definition of $V_{i,j}$, the constraint of spectrum allocation in a cluster can be described as $\sum_{j \in S_k} b_j(t) V_{i,j} \leqslant 1$, for $i \in S_k$, and $S_k \subset N$, where $b_j(t)$ indicates a certain spectrum is assigned to FAP_j at time t. Then the spectrum allocation problem can be formulated as follows.

$$\text{maximize } C_0 + \sum_{n=0}^{k-1} C_{\mathcal{S}_n} \tag{25}$$

$$\text{s. t.: Constraints 8, 9, 11, 12, 13, and 14} \quad \sum_{j \in \mathcal{S}_n} b_j(t) V_{i,j} \leqslant 1, \text{for} \quad i \in \mathcal{S}_n. \tag{26}$$

The formulated problem is also an MINLP problem. The procedure for solving this problem consists of the following 3 steps, which are discussed in detail in this section.

1. Partition the FAPs into clusters.
2. Further partition each cluster into groups, where FAPs in the same group can reuse the same spectrum in the same time.
3. Allocate spectrum resource for each FAP in the clusters.

4.3 | Solution algorithms

We first show how to divide the FAPs into clusters. Consider the topology of FAPs as an undirected graph $G = (V, E)$, where $V = \{1, 2, \cdots, N\}$ represents the FAPs and E is the set of all edges between the vertices. An edge between 2 vertices indicates that the 2 corresponding FAPs have overlapping coverage. According to the cluster definition in definition 1, an FAP can reach to all other FAPs within the same cluster. So we can identify all nodes in a cluster, if we search for all reachable vertices from 1 vertex. Here, we adopt the idea of *breadth-first search*[16] to identify FAPs in the same cluster and

then divide all FAPs into clusters. The algorithm is presented in Algorithm 3.

Algorithm 3 Cluster formation

```
cluster(G)
for each vertex u∈ G.V do
    u.color = WHITE
end for
Q = Ø
i = 0, k = 0
while G.V[k] ≠ Nil do
    s = G.V[k]
    if s.color = = WHITE then
        SEARCH (G, s, i)
    end if
    k++
end while
SEARCH (G, s, i)
ENQUEUE (Q, s)
while Q ≠ Ø do
    u = DEQUEUE (Q)
    for each v=G.Adj[u] do
        if v.color == WHITE
        v.color = GRAY
        ENQUEUE(Q,v)
    end for
    u.color = BLACK
    cluster [i].add (u)
end while
i++
```

In the algorithm, the graph $G = (V, E)$ uses an adjacency list to represent the edges. For each vertex $u \in V$, an *Adj list* is created to record the *Adj vertices*. That is, $Adj[u]$ includes all vertices that share an edge with vertex u. The algorithm also uses a first-in-first-out queue Q. The function ENQUEUE(Q, s) pushes s into the queue Q, and the function DEQUEUE(Q) pushes a node out. The algorithm first labels all nodes WHITE and initializes the first-in-first-out queue Q. Then it selects the first node as the seed node for searching. After the search, all nodes in the same cluster of the seed node are identified and labeled black. Then the algorithm selects the next node that is still white to be the seed and searches again. This process is repeated until all nodes are divided into clusters and labeled black. The function SEARCH (G, s, i) is a modified breath-first search algorithm, readers may refer to chapter 22 of *Introduction to Algorithms, 3rd Edition*[16] for details.

After grouping nodes into clusters, we then need to divide nodes in each cluster into groups. The algorithm should ensure that each FAP does not overlap (not connected in the topology) with any other nodes among the same group. The group formation algorithm is presented in Algorithm 4.

Algorithm 4 Group formation

```
grouping (G)
k=0
while G.V[k] ≠ 0 do
    s = G.V[k]
    s.color = WHITE
end while
i=0
while G.V ≠ Ø do
    k=0
    while G.V[k] ≠ Nil do
        s=G.V[k]
        if s.color == WHITE then
            for each v = G.Adj[s] do
                V.color = BLACK
            end for
            Group[i].add(s)
            delete(s)
        end if
    end while
    k = 0
    while G.V[k] ≠ Nil do
        s=G.V[k]
        s.color = WHITE
    end while
end while
```

In the algorithm, we use $G = (V, E)$ to represent the topology of FAPs in a cluster. In the initialization phase, we label all vertices WHITE. The algorithm selects the first WHITE vertex s, then labels all its adjacent vertices BLACK. By repeating this procedure, the algorithm selects a group of vertices that are not connected with each other, and the remaining vertices are BLACK, which means they are connected to at least 1 of the vertices included in the group. After a group of vertices are selected, we deleted them from the graph, and label the remaining vertices WHITE again. The process is repeated until all vertices are selected. When the algorithm is finished, all vertices are divided into groups, in which each vertex is not connected with any other vertices in the same group.

We next develop an algorithm to allocate the frequency spectrum to the FAPs. Similar to the nonoverlapping scenario, the objective of the algorithm is to maximize the network-wide capacity and to guarantee the QoS requirement of each UE. For the scenario with overlapping FAPs, the spectrum allocation is much more complicated than the case of nonoverlapping FAPs, as the spectrum allocation scheme is not independent among FAPs in a cluster.

First, we address the problem of spectrum allocation within 1 cluster. Assume that in cluster $\mathcal{S}_n$, there are m FAPs, which are divided into k groups as $Group_0, Group_1, \cdots, Group_{k-1}$. Assume that spectrum B' is allocated to the cluster and the QoS requirement of UEs is fulfilled. Then if an extra amount

of spectrum ΔB can be allocated to cluster S_n, the increase in throughput ΔC can be represented as

$$\begin{aligned}\Delta C &= \sum_{i\in S_n} \Delta C_i \\ &= \sum_{j=0}^{k-1} \sum_{i\in Group_j} \Delta C_i \\ &= \sum_{j=0}^{k-1} \sum_{i\in Group_j} \Delta B_j \psi_i \\ &\leqslant \Delta B \max\left\{ \sum_{i\in Group_j} \psi_i \right\},\end{aligned} \tag{27}$$

where ΔB_j is the extra spectrum allocated to $Group_j$, and $\sum_{j=0}^{k-1} \Delta B_j = \Delta B$. Recall that ψ_i is defined in Equation 19. So in each cluster, the extra spectrum resource should be allocated to the group with the maximum $\sum_{i\in Group_j} \psi_i$, to achieve a higher network-wide capacity gain.

For the network-wide throughput, if there is an extra spectrum ΔB, then the throughput increase can be represented as

$$\begin{aligned}\Delta C &= \Delta C_0 + \sum_{n=0}^{k-1} \Delta C_{Sn} \\ &\leqslant (\Delta B_0)\psi_0 + \\ &\quad \sum_{n=0}^{k-1} (\Delta B - \Delta B_0) \max\left\{ \sum_{i\in Group_j, Group_j\subset S_n} \psi_i \right\} \\ &\leqslant \Delta B \max\left\{ \psi_0, \sum_{n=0}^{k-1} \max\left\{ \sum_{i\in Group_j, Group_j\subset S_n} \psi_i \right\} \right\}.\end{aligned} \tag{28}$$

It can be seen that if the following condition holds true,

$$\psi_0 > \sum_{n=0}^{k-1} \max\left\{ \sum_{i\in Group_j, Group_j\subset S_n} \psi_i \right\}. \tag{29}$$

we can achieve a higher network-wide capacity if we allocate the extra spectrum resource to the MBS. Otherwise, we can achieve a higher network-wide capacity if we allocate the extra spectrum resource to the FAPs.

The spectrum allocation algorithm is presented in Algorithm 5. Assume that we have already applied algorithms 3 and 4, ie, we have already divided the FAPs into clusters and groups. The basic idea of the algorithm is that we first need to ensure the QoS requirement of each UE. Then we ensure that different clusters reuse the same spectrum resource; in each cluster, FAPs in the same group should share the same spectrum and the FAPs from different groups must avoid occupying the same spectrum to avoid interference. Lastly, we also need to follow Equations 27 and 28 when allocating spectrum.

Algorithm 5 Spectrum allocation for overlapping FAPs

```
φ_max = 0
for every cluster S_n do
    φ(S_n) = 0
    for every group m ∈ cluster S_n do
        φ(S_n, m) = 0
        for Every FAP i in group m do
            if φ_i > φ(S_n, m) then
                φ(S_n, m) = φ_i
            end if
            for j = 1 → L_0 do
                if ρ_{i,j}(0) == 1 then
                    B_{i,j}(0) = C/G_{i,j}(0)
                end if
            end for
            for j = 1 → L_i do
                B_{i,j}(i) = C/G_{i,j}(i)
            end for
        end for
        φ(S_n) = φ(S_n) + φ(S_n, m)
        for every FAP i in group m do
            if φ_i < φ(S_n, m) then
                B(ψ_i) = B(ψ_i) + ψ(S_n, m) − ψ_i
            end if
        end for
    end for
    if φ(S_n) > φ_max then
        φ_max = φ(S_n)
    end if
end for
for j = 1 → L_0 do
    if ρ_{0,j}(0) == 1 then
        B_{0,j}(0) = C/G_{0,j}(0)
    end if
end for
if ψ_0 > Σ_{n=0}^{k−1} max(Σ_{i∈Group_j, Group_j⊂S_n} ψ_i) then
    B(ψ_0) = B(ψ_0) + B − φ_0 − φ_max
    for every cluster S_n do
        if φ(S_n) < φ_max then
            m = argmax_j {ψ_i | i ∈ Group_j, Group_j ⊂ S_n}
            for every FAP i in group m do
                B(ψ_i) = B(ψ_i) + φ_max − φ(S_n)
            end for
        end if
    end for
else
    for every cluster S_n do
        m = argmax_j {ψ_i | i ∈ Group_j, Group_j ⊂ S_n}
        for every FAP i in group m do
            B(ψ_i) = B(ψ_i) + B − φ_0 − φ(S_n)
        end for
    end for
end if
```

In Algorithm 5, from lines 7 to 9, we calculate the minimum spectrum resource needed to ensure the QoS requirement of all FAPs in each group. From lines 10 to 17, we allocate spectrum for UEs that access to FAPs to meet their QoS requirement. Line 19 calculate the minimum spectrum resource needed to ensure the QoS requirement for each cluster. From lines 20 to line 24, we allocate some extra spectrum to the UEs with the greatest ψ_i in each group to make FAPs in the same group share the same spectrum resource. Lines 26 to 28 calculate the minimum spectrum resource needed to ensure the QoS requirement for all clusters. Lines 30 to allocate the minimum spectrum resource for MUEs that access the MBS to ensure the QoS requirement. In line 35, we check the inequality (Equation 29). If inequality (Equation 29) holds, we allocate the extra spectrum to the MUE with best SINR (greatest ψ_0) among MUEs that access the MBS in line 36. From lines 37 to 44, we allocate some spectrum resource to some UEs access to FAPs with the best SINR to the make all clusters share the same spectrum resource. Otherwise, we allocate the extra spectrum resource to some UEs access to FAPs with best SINR and make them share the same spectrum resource (between lines 46 and 51).

4.4 | Performance upper bound

Based on the discuss in Equations 27 and 28, the upper bound of the network-wide capacity under overlapping FAPs can be derived as follows.

$$\begin{aligned} C &= C_0 + \sum_{n=0}^{k-1} C_{Sn} \\ &\leqslant B_0\psi_0 + \sum_{n=0}^{k-1}(B - B_0)\max\left\{\sum_{i\in Group_j, Group_j\subset S_n}\psi_i\right\} \\ &\leqslant B\max\left\{\psi_0, \sum_{n=0}^{k-1}\max\left\{\sum_{i\in Group_j, Group_j\subset S_n}\psi_i\right\}\right\}. \end{aligned} \tag{30}$$

5 | PERFORMANCE EVALUATION

5.1 | Scenario with nonoverlapping FAPs

We evaluate the performance of the proposed scheme with MATLAB simulations. Specifically, we compared the proposed algorithms with the open access scheme and resource allocation mechanism (termed OA scheme) presented in 1 study,[17] 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 1 FUE, and there are a large number of MUEs. The channel models are defined in Equations 2 and 3, respectively.

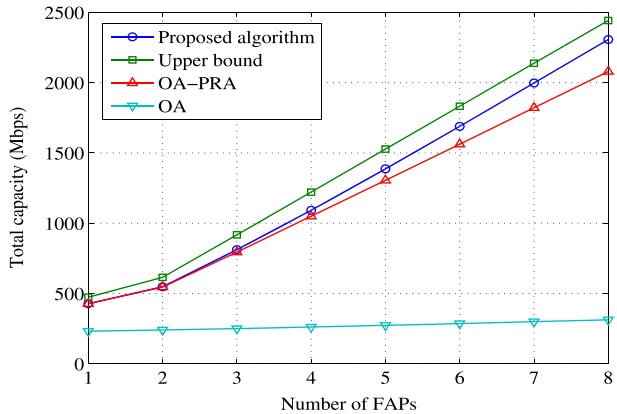

FIGURE 3 Number of FAPs versus total capacity with nonoverlapping FAPs. OA indicates open access scheme and resource allocation mechanism; OA-PRA indicates the OA scheme enhanced with our proposed resource allocation algorithm

In Figure 3, we evaluate the impact of the number of FAPs on the total capacity of the system. In the simulation, there are 100 MUEs, and the QoS requirement 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 1 FAPs. After all, the proposed access scheme has taken into account spatial reuse among FAPs. For the 1 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 1 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 2 is quite tight for the range of FAP numbers examined in this study.

In Figure 4, we evaluate the impact of the QoS requirement 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 2. 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

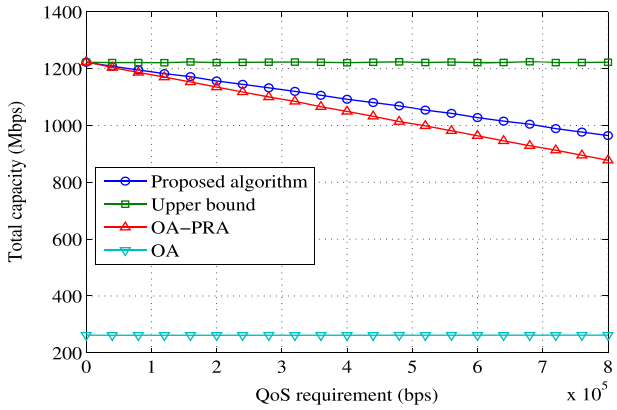

FIGURE 4 Quality of service (QoS) requirement versus total capacity with non-overlapping Femto open access points. OA indicates access scheme and resource allocation mechanism; OA-PRA, OA scheme enhanced with proposed resource allocation algorithm

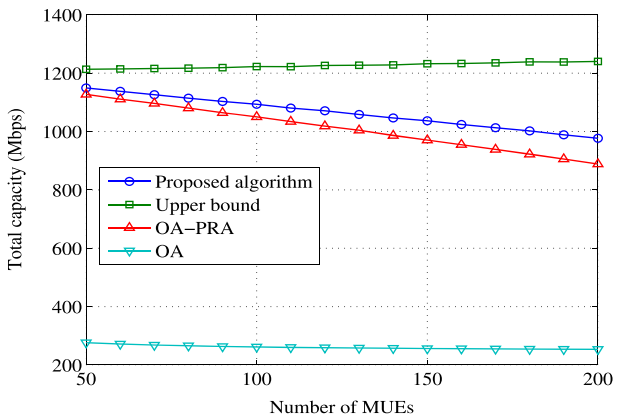

FIGURE 5 Number of macro user equipments (MUEs) versus total capacity with non-overlapping Femto access points. OA indicates access scheme and resource allocation mechanism; OA-PRA, OA scheme enhanced with proposed resource allocation algorithm

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 QoS requirement is increased.

In Figure 5, 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 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 gets worse with more MUEs are enabled. The reason is similar to that in Figure 4. 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.

5.2 | Scenario with overlapping FAPs

We also evaluate the performance of proposed scheme for the scenario with overlapping FAPs. We compare the performance with the proposed algorithm for the nonoverlap case. We also compare the proposed algorithm with the OA scheme.[17] As the OA-PRA scheme may not be applied to the overlapping FAP case, it is not included in the comparison study. In the simulations, there are 6 FAPs, and the femtocell topology is FAP_1 does not overlap with any other FAPs; FAP_2 overlaps with FAP_3; FAP_3 overlaps with FAP_4; and FAP_5 overlaps with FAP_6. Other simulation settings are the same as in the nonoverlap case, if not specifically pointed out.

In Figure 6, we examine the impact of the number of UEs on the total capacity of the system. In this simulation, the QoS requirement C is set to 400 Kbps. It can be seen that the performance of proposed algorithm with overlapping FAPs is worse than that of the nonoverlapping case. But the proposed algorithm still outperforms the OA scheme with considerable margins. In Figure 7, we examine the impact of different QoS requirements on the system performance. Again the

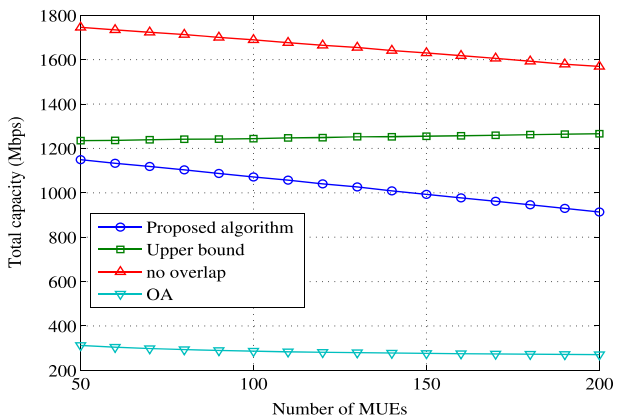

FIGURE 6 Number of macro user equipments (MUEs) versus total capacity with overlapping Femto access points. OA indicates access scheme and resource allocation mechanism

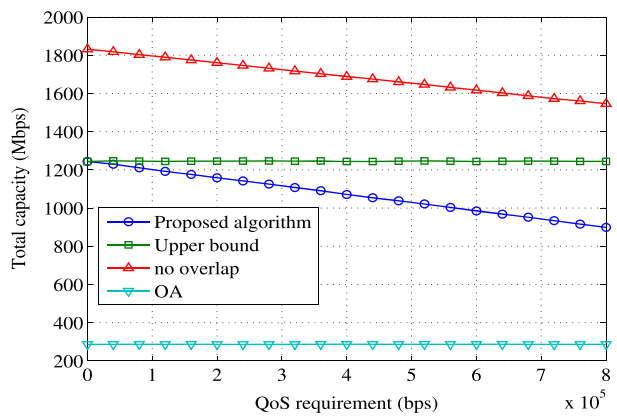

FIGURE 7 Quality of service (QoS) requirement versus total capacity with overlapping Femto access points. OA indicates access scheme and resource allocation mechanism

superior performance of the proposed algorithm over the existing scheme is observed.

In Figures 3 to 7, it can be seen that OA is not sensitive to all x-axis parameters. This is because OA does not allow frequency reuse and dynamic resource allocation. It only benefit from the diversity of SINR with more FAP (ie, with more FAPs, it has a better chance to be associated with a nearby FAP with a good SINR). When OA is enhanced with our proposed resource allocation scheme, it benefits from dynamic resource allocation and frequency reuse, thus having a better performance than OA only. However, it still does not consider a global optimization. So the difference is not so significant.

6 | 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.[7] Because of the advantages for both network operators and customers, the benefits of femtocells cannot be overemphasized in the long term. However, the 2-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.[18] Hence, interference management in femtocell network has received tremendous attention from either academic or industrial areas.[8,13,14,19,20]

As the interference in femtocell network is largely determined by the deployment scenarios,[21] Mahmoud and Guvenc in their comparative study[22] summarized femtocell deployment from 2 perspectives: (1) closed access or open access, (2) co-channel or dedicated channels. A game-theoretic approach for resource allocation in OFDMA femtocells with closed access was proposed in 1 study.[23] However, a nonsubscribed user that is close to an FAP may be far away from the MBS. Its transmitted power should be increased to meet its QoS requirement and introducing stronger interferences to users of the FAP. In previous study,[24] a self-optimized coverage coordination scheme was proposed to provide better indoor femtocell coverage and avoid leaking the femtocell coverage into an outdoor macrocell. And another game-theoretic approach in 1 study[25] was proposed to mitigate the interference between Macrocell and femtocell. For the open access scheme, in previous study,[26] the authors introduced a game-theoretic framework for the FAPs to decide their own access policy in order to maximize the system performance. In previous studies,[27,28] neighborhood femtocell handover schemes were developed improve the system performance in dense femtocellular network.

Apart from closed access and open access schemes, a hybrid access mechanism was introduced in previous study[29] 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. For us to mitigate the interference in co-channel scenarios, a frequency ALOHA was adopted to avoid excessive cross-tier interference in previous study.[30] A femtocell identification approach was proposed in 1 study[31] to avoid co-channel interference between neighbor femtocells. Then performance of 2-tier femtocell networks with co-channel femtocell deployment was analyzed with outage constraints in 1 study.[32]

For dedicated channel schemes, in previous study,[33] a framework of spectrum-sharing rewarding was proposed for hybrid access mechanism to maximize the benefit of femtocell owners. In previous study,[34] a joint subchannel scheme as well as a disjoint subchannel scheme were proposed for resource allocation in the 2-tier femtocell network. And the performance of 2-tier femtocell networks with partially open channels was evaluated in 1 study.[35] In short, in co-channel deployment scenarios, it is usually difficult to guarantee the QoS requirements for users. In dedicated channel scenarios, spectrum is divided into orthogonal portions and allocated to different tiers, to eliminate cross-tier interference at the price of a lower spectrum efficiency.[22]

In addition, some power adaptive schemes were developed to mitigate the interference.[36–40] In previous studies,[14,41,42] the authors proposed a cognitive radio approach to mitigate the cross-tier interference. In 1 study,[43] full-duplex transmissions are incorporated in the FAPs for enhanced capacity. In recently, interference alignment (IA) and interference avoidance are vastly researched to improve the performance of femtocell network. In previous study,[44] the impact of IA in femtocell networks was evaluated, and a game theory approach for IA was proposed in 1 study.[45] In previous work,[46] an interference avoidance strategy is developed in a 2-tier CDMA network to mitigate the uplink interference. In 1 study,[47] a resource allocation scheme with QoS constraints was proposed for the interference avoidance application.

7 | CONCLUSIONS

In this paper, we studied the access strategy of MUEs and spectrum resource allocation for the FAPs in a 2-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 was to maximize the overall performance of the network while guaranteeing the QoS requirement for the users. Both the case of nonoverlapping and overlapping FAPs were considered. 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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