Resource Allocation with Interference Avoidance in OFDMA Femtocell Networks

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***Abstract*—Interference control and quality-of-service (QoS) awareness are the major challenges for resource management in orthogonal frequency-division multiple access femtocell networks. This paper investigates a self-organization strategy for physical resource block (PRB) allocation with QoS constraints to avoid the co-channel and co-tiered interference. Femtocell self-organization including self-configuration and self-optimization is proposed to manage the large femtocell networks. We formulate the optimization problem for PRB assignments where multiple QoS classes for different services can be supported, and interference between femtocells can be completely avoided. The proposed formulation pursues the maximization of PRB efficiency. A greedy algorithm is developed to solve the resource allocation formulation. In the simulations, the proposed approach is observed to increase the system throughput by over 13% without femtocell interference. Simulations also demonstrate that the rejection ratios of all QoS classes are low and mostly below 10%. Moreover, the proposed approach improves the PRB efficiency by over 82% in low-loading scenario and 13% in high-loading scenario.**

***Index Terms*—Femtocell, interference avoidance, orthogonal frequency-division multiple access (OFDMA), resource allocation, resource reuse.**

I. Introduction

MOBILE applications demanding high-quality communications have tremendously increased in recent years. The femtocell network has widely been studied [1], [2] as a promising candidate in the next-generation wireless system to improve the radio resource reuse efficiency. The femtocell base stations can be deployed to cover dead zones or to share traffic loads from macrocells. With the large amount of traffic being properly handled by femtocells, the coverage and capacity of macrocells can be enhanced in cellular networks. Moreover, certain studies show that deployment of macrocells can be reduced since 70–80% of traffic can be offloaded from macrocells [3], [4]. Instead of deploying more macrocells, the deployment of femtocells is an economical option due to its low cost and low power consumption. Based on the Third-Generation Partnership Project (3GPP) specifications [5], a femto architecture is composed of multiple sets of femtocell user equipment (FUEs), femtocells, and a femtocell management system (FMS). The FUEs, e.g., mobile devices or laptops, connect to its associated femtocells through air interface. Femtocells can be deployed in houses, enterprise buildings, or public places. Femtocells with geographical proximity are logically grouped and connected to the Internet through the same FMS via broadband wire-line connections.

Because femtocells are designed to be deployed by the end users with minimum intervention from the service providers, the femtocell deployment is not well controlled. Numerous femtocells may be randomly distributed in a surrounding area. With the coverage of neighboring femtocells overlapped, their FUEs may interfere with one another. The femtocell interference occurs when radio resources with the same frequency and time slot are allocated to overlapping FUEs [6], [7]. There are two categories of femtocell interference specified by the network tier or the frequency. The first category is specified as co-tiered and cross-tiered interference in the tiered network [8], [9]. In the co-tiered interference, the source node and the interfered node are in the same network tier. For example, a femtocell is disturbed by unwanted signals sent from other femtocells. When a larger number of neighbors are densely deployed, severe co-tiered interference arises more often and is difficult to manage [6], [10]–[12]. The deployment of femtocells in an urban area typically leads to overlapping coverage areas of multiple neighboring femtocells [6]. For example, the deployments are likely to be in adjacent houses or blocks of apartments [4]. In cross-tiered interference, the source and the victim belong to different network tiers. The problem of cross-tiered interference has been widely studied through techniques of spectrum allocation [7], [9], [13]–[18], power adjustment [18], [19], and open versus closed access operation [20]–[22]. The cross-tiered interference is independent of co-tiered interference, as shown in [4]. Since the mitigation of co-tiered interference requires adaptive techniques [7], we focus on the control of co-tiered interference in this paper.

The other category is specified as co-channel and adjacent-channel interference. In co-channel interference, the same time–frequency resources are occupied by two different transmitters. For the adjacent-channel interference, the different but

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insufficiently separated resources are reused. With co-channel deployments, the femtocells are expected to reuse resources to improve the spectral utilizations and system capacities [23]. However, the same resources may be reused by closely deployed femtocells that cause low communication quality [10]–[12]. With co-channel interference, femtocells lose the original advantages of resource reuse [23], [24]. Since a flexible resource assignment technique alleviates co-channel interference, the orthogonal frequency-division multiple access (OFDMA), intensely considered by 3GPP long-term evolution (LTE), is considered in this paper. In addition, since OFDMA reduces the interference from the adjacent cells operating in the same frequency by assigning different sets of orthogonal frequencies in different cells, the effect of adjacent-channel interference can be ignored [6]. The OFDMA exploits multiuser diversity by assigning resources according to the channel qualities of FUEs. Based on OFDMA, the smallest unit of resource that can be assigned is called a physical resource block (PRB), which is a time–frequency block corresponding to 0.5 ms and 180-kHz frequency band. One resource frame has 20 time slots, where the frame length is 10 ms [5]. To enable the femtocell technology, this work aims to propose a resource allocation strategy to cope with interference and improve PRB efficiency in OFDMA femtocell networks.

The quality of service (QoS) is a crucial factor in radio resource management. Different FUE connections can be classified into different QoS classes with its own QoS requirements. In 3GPP LTE specifications, nine different services specified by one to nine QoS class identifiers (QCIs) are defined. The QoS requirements for different QCIs of services are specified by L2 packet delay budget, L2 packet loss rate, and guarantee bit rate (GBR). Since different QoS services have different performance requirements, the mechanism design to guarantee QoS services is one of the major challenges for femtocell applications. To guarantee QoS without significant losses in PRB efficiency, this paper investigates QoS requirements for connections jointly with the resource allocation mechanism.

In this paper, we investigate a complete radio resource allocation scheme in OFDMA femtocell network, the major contributions include the following: 1) the co-channel and co-tiered interference can entirely be avoided, and no additional operation is necessary in the design of femtocells; 2) the resource allocation is more flexible since the resource allocation units are narrowed down to PRBs instead of subchannels; 3) the resource efficiency is improved, and more FUEs can be accommodated within the same amount of resources; 4) the QoS requirements are guaranteed or the requests are dropped for connections in the proposed scheme; 5) a greedy algorithm is performed through the self-organization process.

The rest of this paper is organized as follows. Section II presents the related works for a radio resource allocation scheme in femtocell networks. In Section III, we outline our problem and enumerate our assumptions. In Section IV, the optimization problem is formulated to assign PRBs, followed by the proposed greedy-based algorithm in Section V. In Section VI, the complexity analysis is presented. Simulation results for evaluating the proposed scheme are presented in Section VII. Finally, Section VIII concludes this paper.

II. Related Work

In LTE networks, the indoor access networks are supported by the deployment of femtocells. Because femtocells are designed to be deployed by user demand, the co-channel and co-tiered interference problems are severe. To mitigate the effects of co-channel and co-tiered interference, Jun *et al.* proposed intercell interference cancellation techniques. Jun and Andrews [25] proposed the intercell interference cancellation techniques, but the approach is often disregarded due to errors in the cancellation process [26]. Moreover, the sectorized antenna and multiple radio paths have also been suggested by Chandrasekhar and Andrews [8]. This approach reduces the possibility of neighboring interference, and beamforming is also one of the effective techniques. In addition, Claussen and Pivit [27] introduced a dynamic selection of predefined antenna patterns to reduce the unwanted power leakage. The preceding hardware-based approaches usually increase hardware cost. In contrast, the power control algorithms and radio resource management serve as cost effective approaches. Yun and Shin [28] and Jung *et al.* [29] reduced the interference by adjusting the transmission power. López-Pérez *et al.* [18] described the power control technique to restrict the transmit power at a femtocell. While the power control techniques at femtocells alleviate the co-channel interference, it may significantly vary the performance of FUEs since reduction of the power of a femtocell also reduces the total throughput of femtocell users [18].

From the point of view of resource management, López-Pérez *et al.* [7] suggested a framework to allocate different resources with different users' requirements. Rahman and Yanikomeroglu presented a dynamic interference avoidance scheme to coordinate a group of neighboring cells [23]. However, this scheme was designed for macrocell base stations. In femtocell networks, the design of cognitive femto network was studied. Attar *et al.* [30] suggested that a cognitive base station can exploit their knowledge of the radio scene for interference management. Huang and Krishnamurthy [31] proposed the implementation of cognitive femtocell base stations for resource allocation by using a game-theoretic framework. With cognitive femtocell base stations, Lien *et al.* [10] recommended the insertion of sensing frames to scan the whole wireless resources periodically. However, when sensing the whole wireless resources, the femtocell cannot receive and transmit the data. Moreover, the cognitive base station is required, and cognitive radio capabilities need to be incorporated into the femtocell base stations. In addition, Tan *et al.* [32] presented a graph coloring based dynamic subband allocation (GC-DSA) as a graph coloring based dynamic subband allocation technique to avoid downlink interference. Uygungelen *et al.* [33] also developed a graph-based dynamic frequency reuse (GB-DFR) as a resource allocation method based on graph coloring. With graph coloring algorithms, the assignment of PRBs to a femtocell is restricted since a vertex can only be assigned a single color.

The dynamic frequency planning (DFP) was also proposed by López-Pérez *et al.* [34] to decrease interference and reuse available subchannels in OFDMA networks. Lee *et al.* [11] proposed an adaptive fractional frequency reuse (FFR) algorithm where the FMS plans the coverage areas of femtocells according to the minimum acceptable signal strength

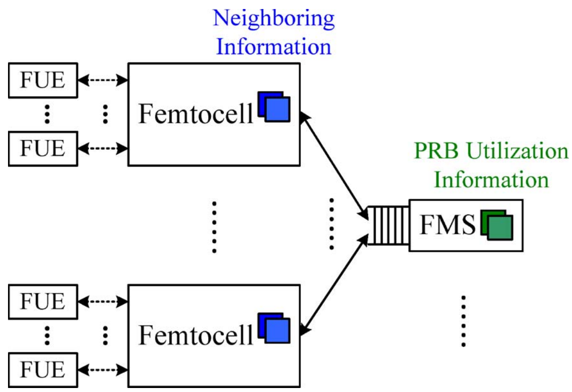

Fig. 1. Network model.

of femtocells. The FMS allocates usable resources for every femtocell in accordance with the number of cliques, which is formed by the union of neighboring femtocells. Sundaresan and Rangarajan [12] proposed that each femtocell adopted a modulo-prime function and an interference topology to randomly access some frequency bands. The proposed distributed random access (DRA) scheme is specifically designed for co-channel and co-tiered deployment. However, different users might be allocated to the same wireless frequency bands with modulo-prime, where different users will acquire the interfering resources.

The methods described in [11], [12], and [34] allocate fixed subchannels to a femtocell, where a subchannel is composed of several PRBs within the same frequency band. Certain PRBs in the allocated subchannels may be used by the femtocell, depending on the traffic conditions. If the PRBs in the subchannels are not fully utilized, the remaining PRBs cannot be reused by other femtocells and are wasted. Through the proposed RAFF algorithm, all PRBs in a frame can be assigned flexibly instead of fixed subchannel assignment. The PRB efficiency can be improved, and PRBs, as crucial and scarce wireless resources, can therefore be assigned to more femtocells.

III. Problem Statement and Assumption

We assume a cellular system with femtocells deployed in the restricted indoor areas, such as home or enterprise environments. The coverage of randomly deployed femtocells may be overlapped. Multiple femtocells are connected to the FMS serving as a controller and a gateway toward the cellular system. The relationships between FMSs and other network components are depicted in Fig. 1, where FUEs, femtocells, and FMSs constitute the entire femtocell networks. The neighboring femtocells operating on the same operator's network may cause potentially high interference to each other. We can visualize the scenario of the femtocell deployment as several groups in a densely deployed area, where the femtocells connected to one FMS are considered as a group. Each group of femtocells is comprised of femtocells deployed in a geographically adjacent space. This grouping scheme renders that femtocells in different groups do not interfere with each other. In the proposed method, the FMS is applied to perform interference avoidance by using global information on femto interference. The framework of using global information enables FMS to perform better than

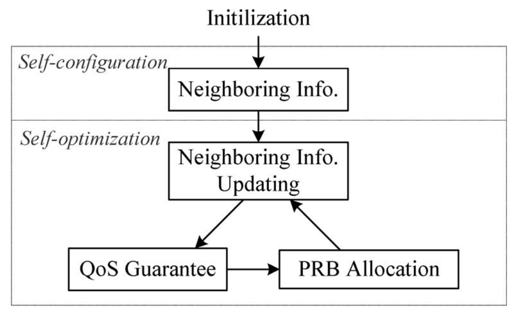

Fig. 2. Self-organization states.

femtocells do with only local information. The interference can be completely avoided through the adoption of the proposed method.

To reduce the interference among neighboring femtocells, a femtocell must be able to organize itself automatically. The deployment of femtocells with self-organization is crucial. In this paper, we consider that the resource allocation scheme automatically operates in a self-organizing network. The self-organization mechanism includes self-configuration and self-optimization, as depicted in Fig. 2. After initialization, the femtocell will configure itself. The femtocell is assumed to transmit a neighbor-informing message with signal power twice as much as the regular information-bearing signal to overcome hidden terminal problem. The femtocell waits for a period of time for feedbacks from neighboring femtocells during self-configuration. The femtocell collects feedback messages and establishes the list of its neighbors. After the self-configuration, the femtocell is in the operation mode and ready to provide services for FUEs. In the self-organization, the signals through FUE-to-femtocell, femtocell-to-FMS, and FMS-to-Internet connections can be used to facilitate self-optimization. During self-optimization, neighboring information needs to be updated every fixed period of time to avoid stale neighboring list. We consider the scenario where each femtocell maintains its neighboring list.

Since the femto usage allows numerous femtocells to be randomly deployed in a certain area, the radio resources, i.e., PRBs, may not be sufficient to accommodate the huge demand from the applications. The conventional methods only consider the reuse of resources without QoS constraints. However, different connections require different amounts of PRBs to support the QoS specifications. In the proposed design, the QoS constraints, as measured by the required number of PRBs, are taken into consideration in allocating PRBs, with the objective to improve PRB efficiency. In our design, each connection belongs to a single QCI in accordance with its application. For example, the services of QCI 1–4 are applicable to conventional voice, conventional video, buffered streaming, or real-time gaming. QCI 5–6 apply to IP multimedia signaling or live streaming, and QCI 7–9 apply to file sharing, email, P2P, or Web. The allocated resources must be sufficient to meet the requirements for the corresponding QCIs in both uplink and downlink transmissions. In other words, the appropriate resources must be allocated to guarantee L2 packet delay budget, GBR limitation, and the required data rate in each QCI. As shown in Table I, the delay budget and GBR requirements are explicitly defined in 3GPP

TABLE I
QCI CHARACTERISTICS FOR THE BEARER QOS PROFILE

QCI	L2 Packet Delay Budget	GBR
1	100 ms	GBR
2	150 ms	GBR
3	300 ms	GBR
4	50 ms	GBR
5	100 ms	Non- GBR
6	100 ms	Non- GBR
7	300 ms	Non- GBR
8	300 ms	Non- GBR
9	300 ms	Non- GBR

specifications [35]. Since GBR is required in QCI 1–4, the allocated number of PRBs should be equal to the requested PRBs. The remaining QCI 5–9 are non-GBR, which allows insufficient PRBs. The femtocells are assumed to operate with OFDMA technology in LTE, and the requirements of PRB numbers, corresponding to data rates, are predefined in 3GPP LTE specifications [36]. Therefore, the required resources are unique in different QCIs.

IV. PROBLEM MODELING

The proposed optimization problem aims to pursue the maximization of PRB efficiency by allocating PRBs to avoid co-tiered and co-channel interference under the constraints of frame utilization and QCI requirements. We call this problem the resource allocation optimization of femtocell-to-femtocell interference (OPT-FF) problem. To model the problem, a femtocell network is first defined as a graph $G = (V, E)$, where V represents the set of vertices, and E represents the set of edges. Let v_1 denote the FMS, $V_2 = \{h_1, h_2, \ldots, h_M\}$ the set of femtocells, and $V_3 = \{u_1, u_2, \ldots, u_P\}$ the set of FUEs, where the numbers of femtocells and FUEs are $|V_2| = M$ and $|V_3| = P$, respectively. Let E_1 be the set of valid communication links between a FMS/FUE and a femtocell, and E_2 be the set of interfered links among neighboring femtocells. We denote $V = v_1 \cup V_2 \cup V_3$ and $V = E_1 \cup E_2$. It can easily be verified that $v_1 \cap V_2 = \varnothing$, $V_2 \cap V_3 = \varnothing$, $V_3 \cap v_1 = \varnothing$, and $E_1 \cap E_2 = \varnothing$. As shown in Fig. 3, a femtocell is connected to one FMS, and an FUE is connected to one femtocell in a femtocell network. Let x_i be the indicator to identify the link between the FMS v_1 and the femtocell h_i. Let y_{ij} be the indicator to identify the link between the femtocell h_i and the FUE u_j, which is expressed as

$$x_i = \begin{cases} 1, & \text{if } (v_1, h_i) \in E_1 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

$$y_{ij} = \begin{cases} 1, & \text{if } (h_i, u_j) \in E_1 \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Let the interference link n_{ij} between the femtocells h_i and h_j be defined by

$$n_{ij} = \begin{cases} 1, & \text{if } (h_i, h_j) \in E_2 \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

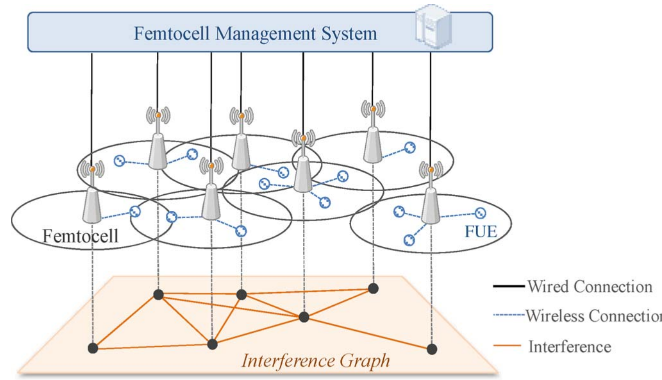

Fig. 3. Example of interference graph embedded in femtocell networks.

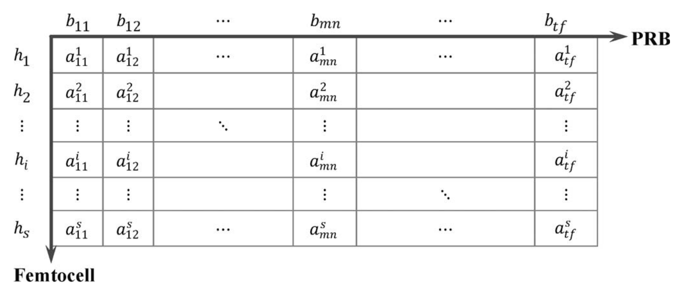

Fig. 4. Resource frame maintained by a FMS.

Then, we denote a resource frame $B = \{b_{11}, b_{12}, \ldots, b_{tf}\}$ as the set of PRBs, where the number of time slots is t, and the number of frequencies is f. The number of PRBs per frame is denoted as $|B| = t.f$. In fact, the number of PRBs that can be reserved by a femtocell is restricted. We define B_i as the number of acceptable PRBs by the femtocell h_i. Let $m = 1 \ldots t$ and $n = 1 \ldots f$. To describe the assignment of the PRB b_{mn}, an indicator parameter a^i_{mn} is defined as

$$a^i_{mn} = \begin{cases} x_i, & \text{if } b_{mn} \text{ is allocated to } h_i \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

The relation between the femtocell h_i and the indicator a^i_{mn} is shown in Fig. 4. In addition, the PRB efficiency α_{mn} is defined as the accumulative utilization of the PRB b_{mn}, which is expressed as

$$\alpha_{mn} = \sum_{\forall i \in V_2} a^i_{mn}. \tag{5}$$

Our objective function is the sum of PRB efficiency in a frame, expressed as $\sum_{\forall m, \forall n} \alpha_{mn}$. In addition, the frame utilization ratio of a frame β restricted to $0 \leq \beta \leq 1$ is defined as

$$\beta = \sum_{\forall m, \forall n} \frac{u_{mn}}{t.f} = \sum_{\forall m, \forall n} \frac{u_{mn}}{|B|} \tag{6}$$

where

$$u_{mn} = \begin{cases} 1, & \text{if } \sum_{i=1}^{M} a^i_{mn} \neq 0 \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

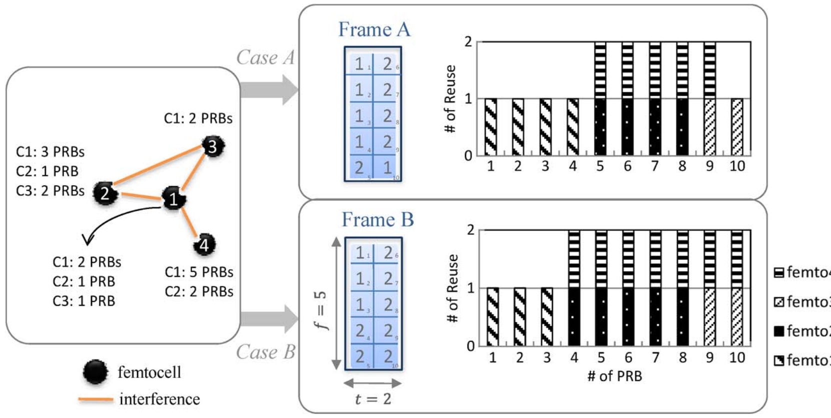

Fig. 5. Example of resource allocation.

A connection c belongs to a type of QCI, including the constraints of GBR, the required PRBs, and the delay. Let $N = \{n_1, n_2, \ldots, n_9\}$ be the set of all connections with QCI $1 \ldots 9$, where n_q represents the set of connections with QCI q. Since QCI $1 \ldots 4$ are GBR, we denote $N_{\text{GBR}} = \{n_1, n_2, n_3, n_4\}$ as the set of connections constrained by GBR. The set of connections constrained by non-GBR is defined as $N_{\text{nG}} = \{n_5, n_6, \ldots, n_9\}$ with QCI $5 \ldots 9$. Notice that $N = N_{\text{GBR}} \cup N_{\text{nG}}$ and $N_{\text{GBR}} \cap N_{\text{nG}} = \varnothing$. The allocated PRB z_c of a connection c needs to satisfy the requested PRB r_c if $c \in N_{\text{GBR}}$. For the connections with QCI $5 \ldots 9$, the allocated PRB z_c is allowed to be less than the required PRBs r_c. The delay of a connection c, which is denoted d_c, should be no longer than the maximum delay limitation D_q of QCI q. An example of PRB allocation is shown in Fig. 5, where each femtocell requests different connections with different number of PRBs. In this example, femto 1 requests three connections, where connection 1 denoted as C1 requires two PRBs, connection 2 denoted as C2 requires one PRB, and connection 3 denoted as C3 requires one PRB. The resource frame maintained in the FMS consists of ten PRBs. In case A, all the required PRBs are supported, except C3 of femto 2 and C2 of femto 4. In case B, all the required PRBs are supported, except C3 of femto 1 and C2 of femto 2. The average PRB efficiency α is 1.7 in case B, which is higher than $\alpha = 1.5$ in case A. The frame utilization in frames A and B is the same with $\beta = 1$.

After defining the variables, we formulate the problem OPT-FF in the following optimization framework:

$$\text{Maximize} \sum_{\forall m, \forall n} \alpha_{mn}. \tag{8}$$

$$\text{Subject to} \sum_{e \in E(S)} x_e + y_e \le |S| - 1 \tag{9}$$

$$\max(x_i + x_j - n_{ij}) \ge 1 \tag{10}$$

$$\sum_{\forall m, \forall n} a^i_{mn} \le B_i \forall i = 1 \ldots M \tag{11}$$

$$\beta \le 1 \tag{12}$$

$$n_{ij}. \sum_{\forall m, \forall n} a^i_{mn}.a^j_{mn} = 0 \tag{13}$$

$$z_c = r_c, \text{ for } c \in N_{\text{GBR}} \tag{14}$$

$$1 \le z_c \le r_c, \text{ for } c \in N_{\text{nG}} \tag{15}$$

$$d_c \le D_q, \text{ for } c \in n_q. \tag{16}$$

The expression of the objective function (8) aims at maximizing the total PRB efficiency over the network. Equations (9)–(16) are the model constraints, as described below. Inequality (9) represents the requirement of a tree structure considered in our model, where $S \subseteq V$ and $E(S) = \{(i, j) \in E_1 | i, j \in S\}$. Since neighboring femtocells will connect to the same FMS, the inequality (10) shows that any interfering neighbor will also connect to the same FMS v_1. The inequalities (11) and (12) give the upper bound of the allocated PRBs. To prevent the co-tiered interference, (13) ensures that the same PRBs cannot be allocated to neighboring femtocells. The constraints (14)–(16) guarantee QoS requirements of a connection c. The optimization OPT-FF solution by using integer linear programming (ILP) incurs huge computational complexities. An ILP problem is an NP-complete problem. The general optimal approach often requires brute-force search and suffers from huge computational complexity. In the PRB allocation problem, the system parameters include the huge number of traffic requests, available PRBs, and femtocells, which incur high complexities. Therefore, the optimality is to be approximated through our proposed greedy approach in the next section.

We solve the resource allocation problem by the notion where the assignment of PRBs is subject to interference constraints such that no two neighboring femtocells share the same PRBs. Although the graph coloring algorithm has widely been applied in resource planning in multicell, the problem under investigation in this paper is different from the conventional graph coloring formulation. In the conventional graph coloring problem, all vertices must be colored; moreover, one vertex can only be assigned a single color. If we model the proposed problem as a graph coloring problem, several PRBs will be grouped as a block with the same color. Certain blocks can only be allocated to the corresponding femtocells since one color can only be assigned to one vertex in accordance with the graph coloring algorithm. However, during the whole operating time of a femtocell network, the requested numbers and durations of PRBs change for each femtocell. The number of allocated PRBs for every femtocell may be different. Therefore, the graph coloring algorithm cannot be directly applied to model the current problem of investigation.

In addition to the classical graph coloring algorithm, there exist variations of graph coloring algorithm. The

TABLE II
COMPARISONS BETWEEN OUR PROBLEM AND RELATED GRAPH COLORING PROBLEMS

		Comparison		
		Objective	**Constraint A**	**Constraint B**
Problem	Graph coloring	Minimize the number of colors	A vertex can only be assigned one color	All vertices have to be colored
	Max-coloring [37]	Minimize the sum of the weights of the heaviest vertices in the color classes	A vertex can only be assigned one color with its own weight	All vertices have to be colored
	GB-DFR [33]	Minimize the number of colors	A vertex can only be assigned one color	All vertices have to be colored
	GC-DSA [32]	Minimize the number of colors	A vertex can only be assigned one color	All vertices have to be colored
	OPT-FF (proposed)	Maximize the number of colors	A vertex can be assigned different number of colors	Not all vertices have to be colored

vertex-weighted version of the coloring problem is studied as the max-coloring problem. The max-coloring problem is to minimize the sum of colors, where all vertices are weighted by the assigned color. If we model the proposed problem as the max-coloring problem, assigning PRBs to a femtocell is restricted since a vertex can only be assigned one color. In contrast, the proposed interference graph considers the assignment of all available PRBs, temporally varying traffic load, and QoS requirements. The PRBs are flexible and no longer banned from specific femtocells. The optimization formulation attempts to find the maximum PRB efficiency within a limited resource frame. The limited resources are considered in the proposed method such that not all femtocells will be assigned PRBs, whereas vertices need to be colored in the graph coloring problem and the weighted version of the graph coloring problem. Furthermore, the same PRB may be allocated to different femtocells in different time frames. The allocation of PRBs is more flexible in the proposed method. Table II shows comparisons on the objective and constraints among the proposed problem, graph coloring problem, max-coloring problem [37], GB-DFR [33], and GC-DSA [32]. Due to the foregoing differences between graph-coloring-based approaches and ours, it is difficult to directly apply graph coloring and their variations on the femto interference avoidance problem, and this observation motivates our formulation in this paper.

V. PROPOSED METHOD

In this section, a greedy algorithm is proposed as a solution for the resource allocation problem. The proposed algorithm is conducted in the self-organization process, including self-configuration and self-optimization. Both processes are specifically designed for femtocell networks. The self-configuration process is briefly introduced as follows. After the operation of a femtocell is initialized, the femtocell connects to the network of its operator through the backhaul connection. The femtocell registers and authenticates itself to the network with a femtocell ID provided by the network operator. At this point, the radio parameters of the femtocell are initialized with a default configuration. Several fundamental information and network configuration parameters are initialized automatically. Since femtocells must be aware of the presence of neighboring cells, neighboring lists are required to be configured in the default configurations. There are three ways to obtain neighboring information [4]. Two methods including scanning the air interface and broadcasting message are limited by the coverage area of the femtocells. For example, if two femtocells are hidden cells to each other, users located in the cell edge of these two overlapping femtocells will suffer from intercell interference. The last method is to periodically report overlapping cells through the FUEs located at the overlapping area. However, this mechanism increases the power consumption of end users. To get neighboring information with hidden cells, we simply modified the original sensing process. The femtocell will execute the following neighboring information process in self-configuration.

Neighboring Information Process: The execution of the process is to find the list of neighboring femtocells and hidden femtocells.

Step 1.1. As the femtocell h_i is initialized, the default configuration is adopted in the femtocell. The femtocell h_i broadcasts a message denoted as ENTER_MSG(TxFemtoID) to notify its neighbors that a femtocell with femtocell ID TxFemtoID has entered the network. The message is transmitted by double regular power through the air interface.

Step 1.2. The neighboring femtocells of h_i receiving ENTER_MSG(TxFemtoID) will return a message denoted as NEIGHBORING_MSG(RxFemtoID) with femtocell ID RxFemtoID to h_i. The message can be sent through either wire connection by FMS or wireless connection with double regular power.

Step 1.3. The femtocell h_i waits for a period of time to receive NEIGHBORING_MSG(RxFemtoID). During this waiting time, the femtocell h_i collects the femtocell ID of its neighbors.

Step 1.4. After the waiting time, the femtocell h_i constructs a list of its neighboring femtocell ID.

Next, the femtocell moves toward the process of self-optimization when the self-configuration has been completed. As shown in Fig. 2, the femtocell will update its neighboring information periodically. Since the femtocell might operate normally, leave the network, or move to different locations at any time, it is important to update their neighboring list dynamically. The femtocell in self-optimization updates its neighboring femtocell ID, which is triggered by the following event.

Event 1: Periodic Neighboring Information Updating: This event is executed when the periodic neighboring information updating timer reaches its expired value. After neighboring information update, the timer will be reset. The periodic neighboring information update consists of four steps, the same as Steps 1.1, 1.2, 1.3, and 1.4.

In the self-optimization process, the femtocell is ready to serve the FUEs. When the FUE generates or requests a connection to the femtocell, the femtocell processes and delivers the information of the connection to the FMS. The FMS is responsible for resource allocation and coordination of femtocells. Since the request indicates the QCI of the traffic, the QoS characteristics are taken into account according to the LTE specifications, such as GBR, delay, data rate, and the requested number of PRBs [5]. Because QCI requirements vary in different connections, the self-optimization loop provides flexibilities in accommodating different requirements. After receiving requests/requirements of the FUE, the femtocell determines whether the service can be supported by current available resources. The femtocell will determine whether the PRB will be allocated by the following conditions. First, if the femtocell is available to serve the connections, the entire requested PRBs of the FUE are granted. Second, the femtocell can only support partial PRBs; therefore, the type of QCI and GBR is considered to reduce the required number of PRBs in Table I. In this situation, the most economical number of requested PRBs will be granted, where the requested PRBs are confirmed and redefined by the femtocell. A request of a connection from a femtocell composed of its femtocell ID, the list of neighboring femtocell ID, and the QCI constraints of the connection will be passed to the FMS. Third, if the available PRBs cannot meet the demand of requested connection, the connection will be dropped. In other words, the throughput of the femtocell must be controlled such that the model constraint (10) is satisfied.

The FMS processes the serving queue and the resource allocation. When a request for a connection arrives at the FMS, this request will be put in the serving queue with first-in–first-out buffers. In case of high-loading (HL) scenarios, the current waiting time is constantly checked to verify the delay constraint of the QCI. Supposing that the waiting time is over time constraint, the request will be dropped. Otherwise, the request will be served by the following resource allocation algorithm. The existing works rely on femtocells to handle the interference problem by using resource allocation techniques. Additional interference avoidance techniques are required to be operated by the femtocell for PRB allocation. In contrast, we follow the design rationale, where femtocells are low-cost devices with limited computational capability, and attempt to offload the computing burden from the femtocells. We propose a greedy based resource allocation scheme of femtocell-to-femtocell interference (RAFF) to tackle the PRB allocation problems at the FMS.

Since the FMS is responsible for avoiding the interference, the neighboring list of the requesting femtocell is queried by the FMS in the beginning of the resource allocation scheme. Then, RAFF will be executed by the FMS to find PRB allocations during self-optimization, as shown in Algorithm 1. Since PRBs are controlled by FMS, the most commonly used resources can simply be reused. By reusing the PRB as much as possible, the PRB efficiency will be improved, and the required bandwidth will be reduced. The RAFF is described as follows. First, the FMS will gather the latest statistics information of PRBs, including the PRB efficiency and the number of available PRBs. Next, the FMS estimates if the total bandwidth can be handled. If the total bandwidth can be accommodated, the FMS will allocate PRBs to this request of the connection by using the PRBs of the highest PRB efficiency. Otherwise, the GBR or non-GBR of the connection will be adopted to allocate the partial PRBs. When the QCI of the connection is GBR, the number of allocated resources needs to satisfy the demand for the requested numbers of PRBs. If the connection is non-GBR, the allocated PRBs just have to meet the required PRBs of the QCI. When the configurations of neither GBR nor non-GBR match the PRB requirements, the scheme will put this request of the connection back in the queue and wait for the next resource allocation process.

Algorithm 1: RAFF: Resource allocation under constraints of interference avoidance, QoS guarantee and resource reuse.

i) Initial setup: before executing the process of self-optimization, a femtocell needs to configure itself. The RAFF algorithm starts when the femtocell is in self-optimization and already set up its neighboring information. The femtocell provides its neighboring information to the FMS. This configuration is obviously admissible.

ii) Admissible connection: the QCI of a connection is defined with the permissible delay, the required number of PRBs, and the GBR. Resource allocation is allowed when the delay is shorter than the delay constraint of the QCI. Otherwise, the required number of PRBs and GBR jointly considered with the affordable total throughput of the FMS can determine the number of allocated PRBs. Only feasible configurations are considered, such that the model constraints (12), and (14)–(16) are satisfied.

iii) Allocation function: an allocation is evaluated by using the optimization formulation in (8). To avoid the interference, the femtocells must be aware of the presence of neighboring cells and their spectrum allocation, and therefore, so the neighboring information will be updated continuously. The PRBs used by neighboring cells will be eliminated from the allocated PRBs to satisfy the model constraint (13). Moreover, the resource efficiency of all the available PRBs is prioritized to reuse the PRBs. The allocated PRBs are selected from the highest prioritized resources by using (5).

iv) Stopping criterion: the resource allocation algorithm stops after the request of the connection is dropped or PRBs are allocated.

In the end, after the request of the connection is processed, the FMS returns the allocation results through the femtocell to the FUE to complete the resource allocation process. If resources are allocated to the FUE, the connection is established between FUE and FMS through the femtocell. During the connection, the femtocell periodically collects the broadcast messages by executing Event 1 in periodic neighboring information updating and sends a report of neighboring list to the FMS. Upon receipt of the neighboring list, the FMS selects the allocated resources to avoid interference.

The proposed method is designed to perform the resource allocation algorithm by the FMS. When the scheme is to establish an uplink connection, a communication between the femtocell and the FMS is additionally required compared to the conventional methods. Therefore, the time scale of the associated signaling affects the waiting time of the FUE to establish an uplink connection. Instead, when the scheme starts to establish a downlink connection, the proposed method will not cause signaling impact according to the specification of 3GPP LTE [5], where no extra communication is required since the femtocell by default needs to establish a connection through the FMS to the Internet. The interface signals between a femtocell and a FMS are well defined by 3GPP LTE. In the specification [38], a timeout value is defined to retransmit the signal for establishing the connection when the signaling delay is too long. The timeout value is settable by the operator according to the network condition; therefore, the delay incurred in the signaling can be supported. Although the communication between the femtocell and the FMS in the uplink causes delay, the proposed method can maintain interference avoidance and QoS.

VI. Complexity Analysis

We analyze and compare the complexity of the proposed scheme with existing schemes. The original statement of low complexity refers to the design of femtocells without considering the FMS. Most existing works rely on femtocells to handle the interference problem in resource allocations. Therefore, the femtocells require additional interference avoidance techniques to allocate PRBs, which incur complexities in the femtocells. In contrast, our proposed approach deals with the interference problems by the FMS since the FMS can be managed by the service provider and femtocells are customer-deployed low-cost devices with limited computational capability. Consequently, no additional allocation techniques are needed in femtocells. Due to the possible confusion, the description of low complexity in Section V is removed. Instead of the femtocell complexity, the orders of the overall complexities are compared as follows.

We analyze and compare the complexity of the proposed and existing schemes. The proposed scheme aims to find the maximum number of allocated PRBs for all femtocells. It requires to sort Q PRBs for M femtocells, where M represents the number of femtocells, and B is the number of PRBs. Hence, the total number of operations is approximated to $(4M + MQlogQ)$, yielding a complexity of $O(MQlogQ)$. The DFP algorithm [34] estimates the interference of resources among femtocells so that the interference of assigned resources can be mitigated. The corresponding number of operations is $(QM^2 - QM)/2$, yielding the complexity of $O(QM^2)$. The exact number of operations required by the adaptive FFR algorithm [11] is difficult to obtain due to the interference metrics and the heuristic nature of the algorithm. The number of operations is approximated to $(M^3 - M^2 + 2M - 2)$. Therefore, the complexity of the adaptive FFR algorithm is $O(M^3)$. The DRA scheme proposed by Sundaresan and Rangarajan [12] needs to iteratively hash resources of each femtocell. If there are more neighboring femtocells, hash collision occurs more often. When hash collision occurs, the DRA uses a iterations to find the reallocated resources. The number of operations is $(2 + a(3M + QM/10))$, and the complexity is $O(QM)$. The complexities of the foregoing schemes are summarized in Table III, and the number of operations required by those schemes is compared in Fig. 6. Although the proposed algorithm requires more operations than the DRA algorithm, the proposed RAFF achieves throughput improvement compared with DRA. Moreover, interference can be avoided by the proposed method, as demonstrated in the next section.

TABLE III
Complexity Comparison of Resource Allocation Schemes

Algorithm	Number of operations	Complexity
DFP [34]	$(QM^2 - QM)/2$	$\mathcal{O}(QM^2)$
Adaptive FFR [11]	$M^3 - M^2 + 2M - 2$	$\mathcal{O}(M^3)$
DRA [12]	$2 + a(3M + QM/10)$	$\mathcal{O}(QM)$
RAFF (proposed)	$4M + MQ\,log\,Q$	$\mathcal{O}(MQ\,log\,Q)$

M: number of femtocells; Q: number of PRBs

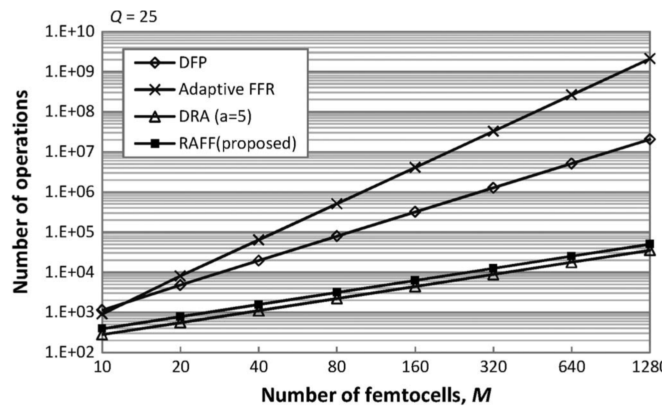

Fig. 6. Number of operations under different number of femtocells.

TABLE IV
System Parameters

Parameter	Value
Map Range	100 *m* × 100 *m*
Number of Femtocell	100
Radius	10 *m*
Deployment	Uniform random distribution
Neighbors	1 ~ 22
Antenna Pattern	Omni-directional
Frame Structure	FDD
Bandwidth	5 *MHz*
Subframe Duration	0.5 *ms*
Number of Available PRBs	25 *(in frequency domain)*
Modulation	64 *QAM*
Spectral Efficiency	3.7 *b/s/Hz*

TABLE V
PARAMETERS FOR THE BEARER QOS PROFILE

QCI	Required Data Rate	# of Required PRB	Proportion	Arrival Rate *(connection/hr)*	Holding Time *(sec)*	
					Mode Value	Expected Value
1	8kbps	1	50.88%	12	10	60
2	64kbps~700kbps	3~24	11.72%	12	30	120
3	64kbps~512kbps	3~17	18.54%	12	300	600
4	128kbps~384kbps	5~13	3.97%	360	0.1	0.1
5	128kbps~384kbps	5~13	1.59%	60	10	20
6	128kbps~700kbps	5~24	10.81%	0.5	900	7200
7	8Kbps ~ 3.4Mbps	1~110	0.83%	12	300	600
8	8Kbps ~ 3.4Mbps	1~110	0.83%	12	300	600
9	8Kbps ~ 3.4Mbps	1~110	0.83%	12	300	600

VII. SIMULATION RESULT

We evaluate the performance of the proposed RAFF by adopting the system parameters of 3GPP LTE, which are listed in Table IV. The scenario consists of an area of 100-m^2 uniformly random distributed femtocells with a coverage radius of 10 m in this area. The coverage areas of femtocells may overlap with one another in the deployment. We arrange a certain number of femtocells that were 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 for each simulation, where the average numbers of neighbors are 1.40, 4.10, 4.80, 6.30, 7.08, 7.69, 8.49, 9.63, 10.44, and 11.88, respectively. All the femtocells are controlled by an FMS in charge of allocating resources. The five performance metrics are specified by the QCIs listed in Table V. The required data rate and the number of required PRBs need to meet the requirement in 64 quadrature amplitude modulation wireless channel quality in 3GPP specification [5]. Since different QCIs apply to different types of applications, we generate traffics corresponding to various applications in mobile phone networks. The proportion of each QCI is in accordance with the application statistics [38]. The arrival rate is assumed to be Poisson distribution, and the holding time is assumed to be lognormal distribution, as shown in Table V [39], [40]. The next parameter metric is the delay constraint, as shown in Table I. For example, the application of QCI 4 could be computer games using real-time data transmissions, whose arrival rate is up to several times per second, but each transmission duration is short. The delay constraint is stringent due to the nature of real-time interactions (50 ms). Furthermore, the parameter of GBR in Table I should also be considered.

The arrival rates in Table V are intended for home or office usage; therefore, we called it low-loading (LL) scenario in our simulation. In addition, we assume HL scenario for crowded public environments, such as department stores or subway stations. The main idea of HL is to increase the arrival rate of each QCI to ten times the arrival rate in LL. From the simulation results under HL conditions, the improvements of the proposed method are more significant. Different types of connections are generated to analyze the performances of the system for each QoS under different loadings. In the following, we compare the proposed RAFF with DRA [12] with respect to the average throughput, connection rejection rate, PRB efficiency, frame usage, and performance in QoS categories.

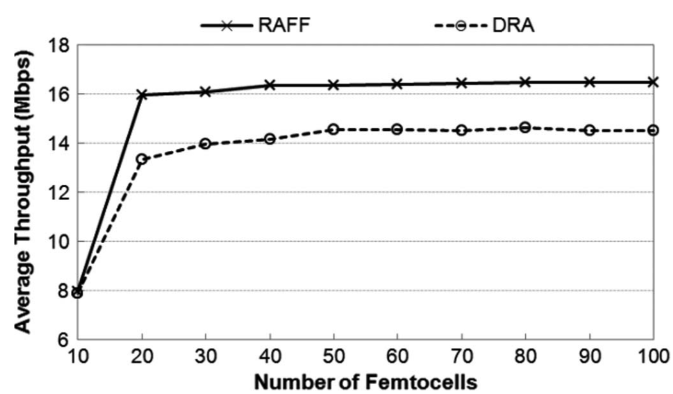

Fig. 7. Average throughput in HL scenario.

The average throughput under different numbers of femtocells in the HL scenario is illustrated in Fig. 7. When the number of femtocells is 10, the resource frame is not full yet, and resources are still sufficient to provide services. The average throughputs of the proposed RAFF and the DRA are similar. However, when the number of femtocells is more than 20, the network is congested, and the resources allocated by RAFF and DRA are limited by the size of the resource frame. Therefore, the average throughputs are relatively stable. Compared with DRA, the proposed RAFF achieves 13% improvement in the average throughput.

As long as there are enough resources for allocation, the assigned PRBs will not be limited by the interference with the DRA. Since the DRA utilizes random resource allocation, a PRB could be allocated by different femtocells. However, the proposed RAFF assigns each PRB orderly so that there will be no interference for each connection. Fig. 8 shows the average interfered connection ratio for different numbers of femtocells in the LL and HL scenarios. When network congestion occurs with distributed more than 20 femtocells, the increase of the average interference ratio of the DRA is slight. The proposed RAFF can completely avoid the interfering resources in contrast

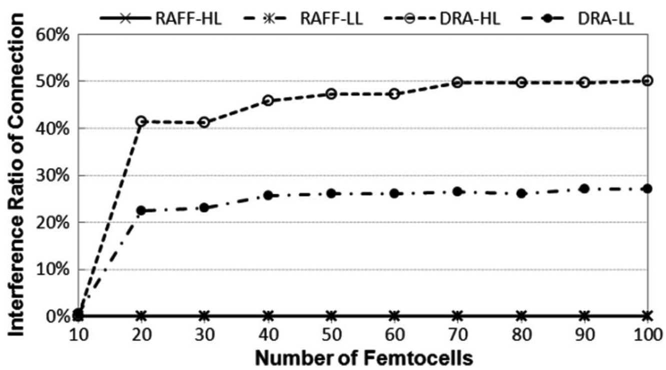

Fig. 8. Interference ratio of all connections.

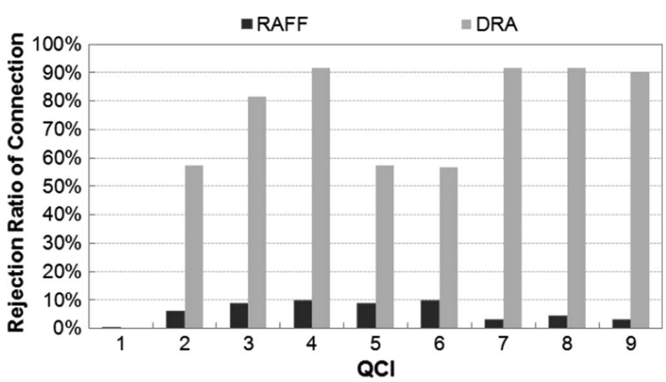

Fig. 9. Performances of rejection ratio of connections in all QCI in HL scenario.

to the average interfered connection ratio that is 20–30% in the LL scenario and 40–50% in the HL scenario in the DRA.

To compare the performance under nine QCIs, we set QCI-related parameters with the number of PRBs, GBR, proportion of application statistics, arrival rates, and holding rates. The rejection ratio of connection and the success ratio of PRB allocation are demonstrated in Figs. 9 and 10. The average rejection rates of every QCI connections under HL scenario are shown in Fig. 9. In both RAFF and DRA, the rejection of connections restricts to the throughput of the femtocell and the FMS. Otherwise, RAFF also has to include the rejection of connections when there is no interference-free PRB in a resource frame. Compared with DRA, the proposed RAFF keeps the rejection rates of connections under 10% in all QCIs. This improvement is contributed by the fact that the femtocells and the FMS dynamically allocate PRB in RAFF. Furthermore, we also calculate the average success rates of PRB allocations for every QCI connection under the HL scenario with uniformly randomly distributed 100 femtocells, as shown in Fig. 10. The average success ratio of PRB allocations is the ratio of the total PRBs allocated by FMS and the total PRBs requested by the femtocell in every QCI connection. The proposed RAFF maintains the success ratio up to 90% in all QCIs. Because of the variable nature of traffic demands, the required PRBs are variable in QCI 7–9. Both the FMS and the femtocell can adjust the allocated PRBs in RAFF. Therefore, our adaptive approach improves the system performance.

The average PRB efficiency with respect to the number of femtocells is shown in Fig. 11. The proposed RAFF improves

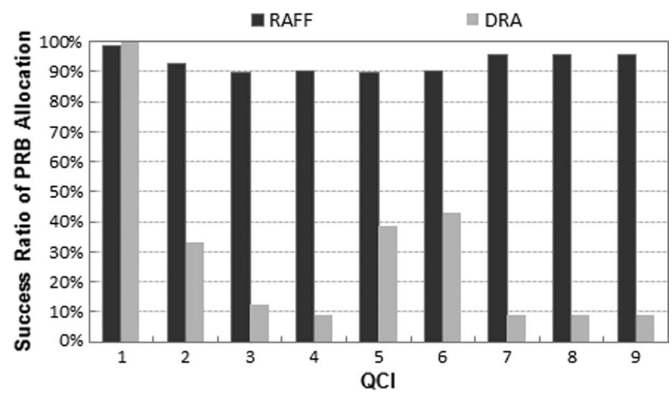

Fig. 10. Performances of success ratio of PRB allocation in all QCI in HL scenario.

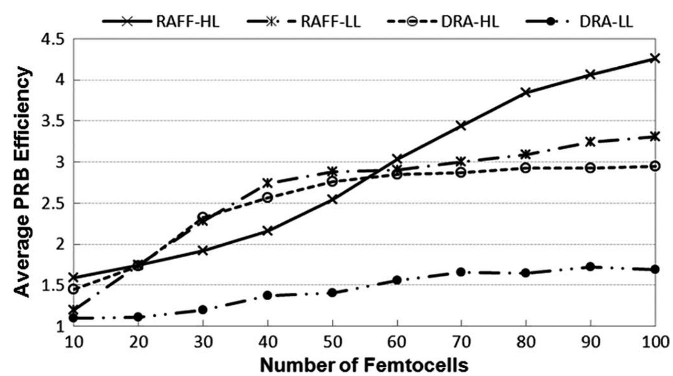

Fig. 11. Average PRB efficiency.

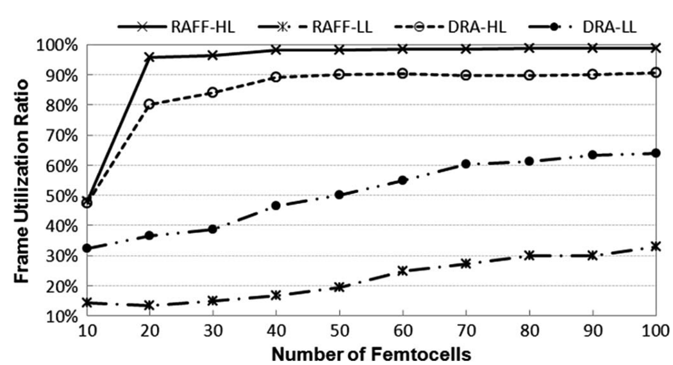

Fig. 12. Frame utilization ratio.

82% in the average PRB efficiency in the LL scenario. In the settings of this paper, the proposed method does not allocate interfered resources. Since noninterfered resources are limited in the HL scenario, the RAFF has lower average PRB efficiency compared with DRA when the number of femtocells is between 30 and 50; however, the average PRB efficiency still improves 13% by RAFF.

The average frame utilization ratio is shown in Fig. 12. Whenever the number of femtocells are deployed, there are abundant noninterfering PRBs for the femtocells to allocate in the LL scenario. The proposed RAFF in the LL scenario reduces the average frame utilization ratio by 55% compared with DRA. In the HL scenario, the proposed method only increases 11% frame utilization ratio.

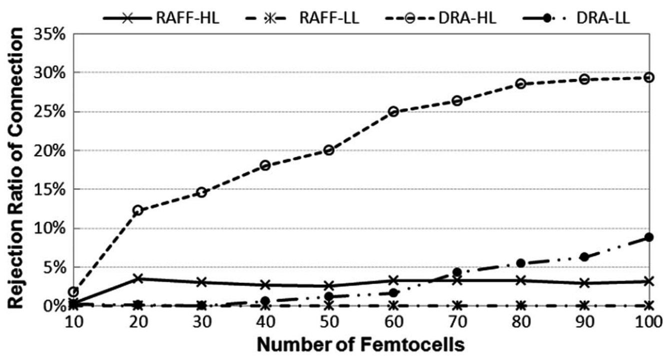

Fig. 13. Rejection ratio of connection.

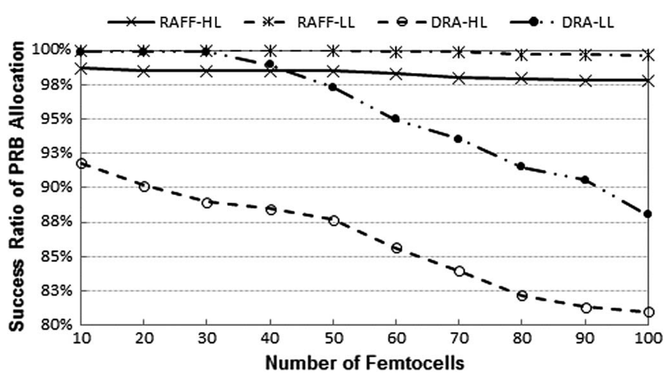

Fig. 14. Success ratio of PRB allocation.

Fig. 13 shows the rejection ratio of connections in different numbers of femtocells. In both HL and LL scenarios, the proposed method achieves 86% improvement and maintains a rejection ratio of less than 5%. Fig. 14 also shows the success ratio of PRB allocation in both HL and LL scenarios. In HL scenarios, the proposed RAFF improves 14% of the success ratio of PRB allocation compared with DRA. In addition, the improvement of RAFF is up to 5% in LL scenarios. The success ratio of PRB allocation is maintained at 98% in both scenarios.

VIII. Conclusion

To mitigate the co-channel and co-tiered interference and the high demand for PRB efficiency in femtocell networks, in this paper, we have explored the usage of FMS to assist the allocations of OFDMA resources. To exploit the spectrum resource and increase the PRB efficiency in the femtocells, we focus on the design of the efficient resource management scheme, where the resource usages are not predefined but dynamically allocated with QoS considerations. We propose the RAFF scheme to increase the spectrum efficiency and eliminate interference while maintaining the QoS requirements. Simulation results show that our mechanism provides 13% improvement in average throughput. Moreover, the rejection ratios of all QCIs are below 10%, and the success ratios of PRB allocations of all QCIs are higher than 90% in the HL scenario. Furthermore, the average PRB efficiency improves by 82% in the LL scenario and 13% in the HL scenario.

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