Revenue Improvement for Wireless Service Providers in Hybrid Macrocell–Femtocell Networks

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***Abstract*—Femto base stations (FBSs) are cost-effective choices for wireless service providers (WSPs) to provide better indoor coverage and capacity in cellular networks. With the introduction of femtocells, spectrum allocation among macro base stations (MBSs) and numerous FBSs becomes challenging. WSPs will allocate resources among hierarchical infrastructures to mitigate mutual interference and maximize WSPs' revenue from service provisioning. In this paper, we propose a channel allocation and service provision framework to help WSPs allocate resources and increase revenue. The spectrum allocation and revenue maximization problem is formulated as a convex problem, and a centralized method is proposed to efficiently solve it. We also propose a distributed algorithm called LD (based on Lagrangian decomposition) to achieve a near-optimal solution with low computational and communication complexity, which can be used when the system is on a large scale. The simulation results show that our scheme can significantly improve the system's revenue.**

***Index Terms*—Channel allocation, distributed algorithm, hybrid networks, revenue maximization, wireless service providers (WSPs).**

I. Introduction

NEXT-GENERATION wireless cellular networks, particularly networks that operate at high frequencies, face the severe problem of poor indoor coverage and capacity. Due to the high attenuation that is suffered at these frequencies, indoor users usually receive a low signal-to-interference-plus-noise ratio (SINR), which cannot support high-data-rate applications. To overcome poor reception inside buildings, tiny base stations (BSs) for the home or enterprise, called femto base stations (FBSs) [1]–[4], have been introduced. Femtocells are the areas covered by low-power low-cost BSs installed inside houses, which can provide exceptional service in residential or enterprise environments, with a typical coverage range of tens of meters. They also have extensive autoconfiguration and self-optimization capabilities to enable a simple plug-and-play deployment and are designed to automatically be integrated into an existing macrocell network.

An FBS serves nearby users with wireless links and connects to the Internet through wired backhaul such as the Digital Subscriber Line (DSL). Due to the short sender–receiver distance from the users, its power level is very low, which reduces the interference that it causes to nearby devices while keeping the receiver signal strengths of its users uncompromised. Therefore, the smaller size of femtocells creates abundant opportunities for spatial reuse: Concurrent transmissions over the same channel among femtocells can be executed. Through careful allocation, the system capacity can be improved, and eventually, more revenue can be made.

In existing work, many researchers assume that FBSs are installed by home users in an unplanned manner. Most of these researchers [5], [6] suppose that FBSs operate in licensed bands as secondary users. They have to avoid harmful interference to licensed macro users. Some researchers [7] assume that FBSs can access television white space and macrocells' licensed bands. The shortcomings of these approaches are that FBSs cannot guarantee quality of service due to the lack of dedicated spectrum and coordination. Even if the FBSs can sense the environment, autoconfigure, and self-optimize, the overall performance of the femtocells may not be satisfying.

Different from the aforementioned user-deployed scenario, more attention is paid to the scenario with wireless service provider (WSP)-deployed FBSs. It has many advantages over the user-deployed case, such as the available dedicated spectrum, planned deployment, and the possibility of network optimization and coordination. It involves interference management, channel allocation, and revenue maximization, which is of interest to WSPs. The problem is how to schedule the resource and provide services to maximize its revenue, which becomes far more complicated than traditional cellular network planning. Currently, the challenges have not yet satisfactorily been overcome for the following reasons.

- Interference management and channel allocation are usually coupled. Revenue maximization is associated with the provided throughput and is thus related to channel and power policies. The interference can be managed by either dynamic power control in the nonorthogonal scheme (where all BSs operate in cochannels) or channel allocation in orthogonal schemes. Problems that involve power control in multichannel networks are usually mixed-integer problems [8], whose optimal solutions can

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hardly be efficiently found. Problems that are formulated based on the orthogonal spectrum scheme can somehow be easier but probably with capacity loss due to the avoidance of any elaborate power control.

- Another challenge arises, because femto and macro users have the same priority, whereas in user-deployed cases, femto users are secondary and transparent to the macrocell service. The accessing control (assigning users to BSs) and the service provision to users are more complex than before, because there are additional numerous FBSs and femto users to be arranged.
- The conditions of hybrid networks can be dynamic. When there are limited users, scheduling can very efficiently be obtained by a centralized algorithm. However, for a large number of users, the communication and computational overheads of the centralized algorithm can be unaffordable. A distributed algorithm may be more suitable in this case. Previous works do not usually simultaneously provide the centralized algorithm and the distributed algorithm.

In this paper, we consider the scheduling of WSP-deployed FBSs. The WSP first negotiates with householders to deploy its FBSs in the home. The FBSs provide open access, which means that nearby outdoor users may also be served by them. Thus, cellular networks are enhanced by numerous FBSs. We achieve WSP's revenue maximization by two-tier channel allocation to provide service and manage any interference. Our scheme benefits both users and the WSP. The femto-accessing users get better coverage and data capacities at lower prices. The shorter transmission distances and abundant spectrum spatial reuse make femto users cut down on the required spectrum; thus, more spectrum can be consumed by macro-accessing users. The WSP can surely make greater profit by the increment of system capacity. With regard to the challenges, our considerations are listed as follows.

1) We intend to manage the interference and maximize the revenue by channel allocation. Therefore, the orthogonal spectrum scheme is adopted. Our scheme splits the spectrum into orthogonal time-frequency blocks and assigns them to the BSs.
2) Our scheme gives two-tier allocation results, i.e., the usage of channels for all BSs and their users. The interference graph is leveraged to prevent any macro–femto interference and alleviates the femto–femto interference. Users who access the same BS orthogonally share the spectrum allocated to it.
3) The problem is formulated as a convex optimization. We provide both centralized and distributed algorithms to meet the needs from the system's different scales.

The main contributions of this paper are threefold. First, a novel spectrum allocation framework for hybrid macrocell–femtocell networks is proposed to enable fair spectrum allocation among BSs and users. This involves the following two factors: 1) interference management and 2) revenue maximization. Second, we propose a centralized algorithm and a distributed algorithm to solve the optimization problem under different conditions. Third, the numerical results show that the proposed framework works well and benefits both the WSP and end users.

The rest of this paper is organized as follows. In Section II, the state-of-art femtocells management papers are summarized, and a comparison with this paper is made. We give a detailed description of the system model in Section III and the formulation in Section IV. We discuss the centralized and distributed algorithms in Section V, and a performance evaluation is given in Section VI. Finally, in Section VII, we give our conclusions.

II. Related Work

In this section, we review some of the literature about femtocell management in hybrid macrocell–femtocell networks and classify them into user-deployed and WSP-deployed cases.

In the user-deployed case, FBSs aim at serving their users better. Each FBS has a fixed set of users as service objects (so-called closed access). Many researchers have studied the interference management problem under the scenario with power control methods. Jo *et al.* [9] addressed two interference mitigation strategies by open- and closed-loop control. Yun and Shin [6] proposed CTRL, which is a distributed and self-organizing femtocell architecture, to manage the femto–macro interference. However, although both of them protected the macro users' transmissions, they did not guarantee the satisfaction of the femto users' demands. Chandrasekhar *et al.* [5] modeled the femto users' power control problem as a noncooperative game and proved the Pareto optimality of the Nash equilibrium. Even so, the game model could not give the optimal overall system performance. Sundaresan and Rangarajan [10] studied the resource management problem in orthogonal frequency-division multiple-access (OFDMA) femtocells. Rather than using power control, they adopted the hash-based distributed scheme in the isolated allocation case and the location-based scheme in the coupled allocation case. However, they focused only on the BS-level channel allocation and ignored the diversity of end users, such as demand, subscription, and link quality. The user-deployed FBSs cannot guarantee the performance of femto users for the lack of dedicated spectrum and coordination. In addition, the scheduling of the cellular networks does not take FBSs into account. Thus, the overall system performance can hardly achieve the optimum.

There are also works that discuss WSP-deployed FBSs. In this case, the WSP can employ central control over the system. Kishore *et al.* [11] proposed a framework to estimate the uplink capacity in the macrocell–microcell networks, but they considered only a macrocell and a single embedded microcell. Chandrasekhar and Andrews [12] gave the uplink capacity analysis and interference avoidance strategy under the assumption of stochastic deployed femtocells and users. However, neither guaranteed the optimal system performance. Shetty *et al.* [13] studied an economic framework of the femtocells to maximize the WSP's revenue without considering rigid technical details. The simple interference model that it adopted could not well describe the real case. Furthermore, none of these three works considered multichannel scheduling in the cellular network. Xia *et al.* [14] discussed the operation modes of femtocells. They concluded that code-division multiple-access femtocells should be configured for open access whereas OFDMA or time-division multiple-access femtocells should adapt to the user density. However, they did not consider the economic issues of the system and ignored the femtocell–femtocell interference.

Compared with the existing work on WSP-deployed FBSs, our scheme enables the WSP to maximize its revenue by jointly considering the economic and technical aspects. Our centralized algorithm works well in a small-scale system and gives an optimal solution. The distributed algorithm is designed for large-scale systems, and its results are near optimal.

III. System Model

In this section, we describe the network scenario and the system model.

Consider a single-legacy macrocellular OFDMA network[1] with a central macro base station (MBS) and N_u subscribing users either indoor or outdoor. All the users can access the MBS (consider only downlink service) and pay for their capacity at unit price P_m. Now, the WSP can negotiate with householders to be allowed to deploy the BSs by promising better indoor services and a preferential femto-accessing price P_f for unit data service. Suppose that N_f FBSs are eventually deployed. We assume that P_m and P_f are constant from a long-term point of view. The WSP makes channel allocation of the time-frequency blocks to BSs and their users such that its aggregate revenue from macro and femto accessing is maximized.

Assume that FBSs are open accessed. Suppose that each user accesses the BS that provides the highest received SINR. Let T_{f_i} be the set of users who subscribe to FBS B_i and T_m be the set of users who subscribe to the MBS. Note that, in our scheme, we define the femto-accessing users as femto users and the macro-accessing users as macro users, regardless of whether they are located indoors or outdoors.

All the BSs operate on the WSP's licensed bands such that any external noise can be avoided. Assume that the power levels on channels are fixed for BSs. There are N_c orthogonal channels of the macrocell $C = \{C_1, \ldots, C_{N_c}\}$. We adopt the orthogonal spectrum allocation. Any pair of BSs that may interfere each other will be allocated time-frequency orthogonal blocks of spectrum. For pairs that do not cause much interference to each other, we can assign them the same spectrum blocks to improve the efficiency.

The system works in a frame-synchronized manner. The channel conditions are assumed to be fixed within a frame and are slow fading through frames. The channels can be reallocated every several frames for the reduction of overhead. At the beginning of an allocation, the BSs collect the users' demands, link qualities (SINRs), and subscription information. Then, the allocation is made, and the BSs execute the instructions. To give a valid allocation, the WSP has to take into account the interference avoidance and service provision constraints, which are introduced in the next section.

[1]Assume that the traditional intercellular spectrum plan [15] is applied to reduce the intermacrocell interference. Now, FBSs within the same macrocell can share part of the spectrum with the MBS. Our scheme intends to optimally redistribute the spectrum in an intramacrocell way.

IV. Problem Formulation

In this section, we formulate the scenario by formally describing the constraints and the optimization target. The objective function consists of the revenue from the macro- and femto-accessing parts. In each part, the revenue is proportional to the demand that is satisfied, given that the price is fixed. We aim at maximizing the total revenue from the two parts under the constraints. The interference constraints leverage the interference graph to manage the BS-level interference. The service provision constraints model the channel allocation from the BSs to the end users.

A. Interference Avoidance Constraints

We leverage the interference avoidance constraints to manage the BS-level interference. According to our formulation, the cross-tier (macro–femto) interference can completely be avoided, and the femto–femto interference can be mitigated.

Assume that the MBS could interfere with any FBS as it transmits at a high power level; therefore, we make the allocation orthogonal between the macro and femto tiers. Any pair of FBSs is defined to be an interfering pair if their mutually received signal strengths are larger than the predefined threshold β. β can be chosen according to the system parameters, for example, the density and power levels of BSs.

We adopt the interference graph technique. The channel usages of BSs are expressed as a matrix $\{\alpha_{ij}\}$, where $\alpha_{ij} \in [0, 1]$ represents the time portion of a frame when C_j is allocated to FBS B_i. Let $\alpha_{mj} \in [0, 1]$ be the time portion usage of the MBS on C_j. To manage the interference, the sum of the usages of the interfering BSs on the same channel should not exceed unit one (normalized). The constraints should be satisfied to manage the interference, i.e.,

$$\alpha_{ij} + \sum_{B_k \in A_i} \alpha_{kj} + \alpha_{mj} \leq 1 \tag{1}$$

for all $i = 1, \ldots, N_f$ and $j = 1, \ldots, N_c$. A_i is the set of B_i's "left of" and interfering femto neighbors. A similar form of constraint has been employed in previous works [16], [17]. B_k is in A_i if and only if B_k is to the left of B_i and the two FBSs form an interfering pair. For ease of understanding, the "left of" formulation imposes an order among FBSs. MBS can interfere with all FBSs, and therefore, every FBS has to involve $\{\alpha_{mj}\}$ in its constraints. Thus, we have, in total, $N_f N_c$ constraints in this form as the interference avoidance constraints.

The advantages of the "left of" constraint are threefold. First, it is less restrictive than ordinary constraints formulation, although it may not be the optimal formulation.[2] A less-restrictive formulation can lead to a better result of the optimization problem. Fig. 1 compares the differences of the constraint formulations. Second, the "left of" formulation can guarantee an interference-free channel allocation for adjacent BSs in the

[2]With ordinary constraints formulation, each FBS involves any interfering BSs into its constraints. Therefore, it is more restrictive than "left of" ones. The optimal constraints are the least restrictive ones, which also guarantee an interference-free allocation.

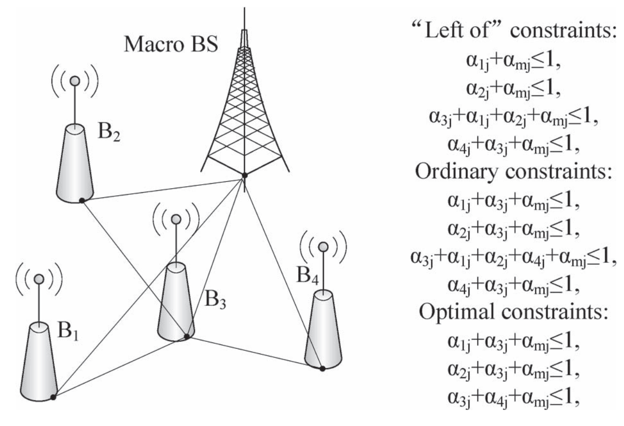

Fig. 1. Illustration of the constraints.

interference graph. (For nonadjacent BSs, we calculate their potential interference.) Third, this formulation can be applied to any topology. However, we do not find a general formulation of the optimal constraints.

B. Service Provision Constraints

The service provision constraints ensure that the total spectrum resource consumed by users who subscribe to a BS does not exceed the amount allocated to the BS. Denote $\nu_{ij} \in [0, 1]$ as the time portion that user U_i is served by its associating BS on channel C_j. The following service provision constraints hold for all i, j:

$$\sum_{U_k \in T_{f_i}} \nu_{kj} \leq \alpha_{ij}, \sum_{U_k \in T_m} \nu_{kj} \leq \alpha_{mj}. \quad (2)$$

C. Optimization Problem

Assume that every user U_i raises demand d_i at the beginning of the frame. It would not pay for additional throughput that exceeds d_i. The WSP can charge it $\min\{t_i, d_i\}P$, where $t_i \geq 0$ is the provided throughput, and P is P_f or P_m, depending on its subscribing BS.

The throughput of user U_i is the aggregation of the Shannon channel capacities through time $\sum_{j=1}^{N_c} \nu_{ij} W_j \log(1+\gamma_{ij})$, where W_j is the bandwidth of channel C_j, and γ_{ij} is the SINR of U_i on channel C_j, i.e.,

$$\gamma_{ij} = \begin{cases} \frac{p_f H_{ij}}{I_{ij}+I_m+N_0 W_j}, & \text{for femto user } U_i \\ \frac{p_m H_{ij}}{I_m+N_0 W_j}, & \text{for macro user } U_i \end{cases} \quad (3)$$

where p_f and p_m are FBSs' and MBS's transmission power levels, H_{ij} is the attenuation factor, N_0 is the thermal noise power density, and I_{ij} and I_m are the received aggregate interference from other FBSs in the same macrocell and other macrocells, respectively. I_{ij} is approximately evaluated by the worst case that all nonadjacent FBSs in the interference graph generate aggregate interference to U_i. I_m is calculated by counting the interference from the first-tier (six neighboring) macrocells in the worst case [15].

The overall system revenue consists of the parts from the macro and femto service provision. The objective is to maximize the overall revenue under the interference avoidance and service provision constraints. The optimization problem can be summarized as follows:

$$\begin{aligned} \text{maximize } & P_m \sum_{macro\ user\ U_i} \min\left\{\sum_{j=1}^{N_c} \nu_{ij} W_j \log(1+\gamma_{ij}), d_i\right\} \\ & + P_f \sum_{femto\ user\ U_i} \min\left\{\sum_{j=1}^{N_c} \nu_{ij} W_j \log(1+\gamma_{ij}), d_i\right\} \\ \text{subject to } & \alpha_{ij} + \sum_{B_k \in A_i} \alpha_{kj} + \alpha_{mj} \leq 1 \text{ for all } i, j \\ & \sum_{U_k \in T_{f_i}} \nu_{kj} \leq \alpha_{ij}, \sum_{U_k \in T_m} \nu_{kj} \leq \alpha_{mj} \text{ for all } i, j \\ \text{variables } & \{\alpha_{ij}\}, \{\alpha_{mj}\}, \{\nu_{ij}\} \in [0, 1]. \end{aligned} \quad (4)$$

V. Centralized and Distributed Algorithms

In this section, we provide the analysis and algorithms for (4). We first give a centralized algorithm to achieve optimality for small-scale networks and then propose a low-complexity distributed algorithm for large-scale networks.

A. Concavity and the Centralized Method (CM)

Theorem 1: The problem (4) is convex.

Proof: Note that the provided throughput for a user is linear and concave on the variables. The minimization operation preserves the concavity [18], and the nonnegative weighted sum of the users' throughput is also concave. More obviously, the domain of the problem $[0, 1]^n$ is a convex set, and the inequality constraints are convex. Thus, it is a typical convex optimization problem. ■

CM is designed as follows. The BSs pass their optimization-related parameters to a central node, and the computation is executed on a single node. The parameters are the demand vectors of associated users and their SINR levels. The central node derives the results by the mature convex optimization techniques.

Algorithm 1: CM.

Require: The identity of BSs and interference graph, the price P_m and P_f, and the channel bandwidth $\{W_j\}$.

1: Each FBS B_i passes T_{f_i}, $\{\gamma_{ij}\}$, and d_i to the MBS in a predetermined order (assume that the MBS is the centralized node).

2: The MBS computes the solution $\{\alpha_{ij}\}$, $\{\alpha_{mj}\}$, $\{\nu_{ij}\}$ using a convex optimization method. Then, it sends $\{\alpha_{ij}\}$ and $\{\nu_{kj}\}(U_k \in T_{f_i})$ to FBS B_i.

The total number of values exchanged in this case is limited by $\delta_{CM} = (N_f + 3N_{f_u})N_c$, where N_{f_u} is the number of femto users. The parameters and results can be passed through the wired backhaul or the wireless interface. A wired interface will increase the packets delay and uncertainty due to Internet traffic conditions. The information exchange can also be implemented on the wireless link. Frequency or time division can be employed, and various techniques such as cooperative relay and interference cancelation can be used to improve the communication efficiency.

The CM algorithm can efficiently find the optimal results at low communication and computational cost, given that the system scale is not very large. However, it needs a centralized node to take all the computation tasks, which may be time consuming and not robust enough for network failures in large systems. The communication overhead also rapidly increases with the system scale.

B. Distributed Algorithm

In case there are a great many users, the CM algorithm can be impractical, because the communication and computational cost rapidly increases. We propose a distributed algorithm, called LD, which is based on the Lagrangian decomposition, to serve in this case.

We need to put the interference avoidance constraints into the Lagrangian, because we will later decompose the problem to subproblems at each BS to reduce the computational cost on the single node. Only the coupled (interference avoidance) constraints where variables $\{\alpha_{ij}\}$ and $\{\alpha_{mj}\}$ of different BSs are coupled together need to be moved to the objective function. The service provision constraints involve local variables for each BS and can thus be preserved in the subproblems.

Define the Lagrangian that is associated with the problem (4) as

$$\begin{aligned} \text{maximize } & L\left(\{\alpha_{ij}\},\{\alpha_{mj}\},\{\nu_{ij}\},\{\lambda_{ij}\}\right) \\ &= P_m \sum_{\text{macro } \mathrm{U_i}} \min\left\{\sum_{j=1}^{N_c} \nu_{ij} W_j \log(1+\gamma_{ij}), d_i\right\} \\ &\quad + P_f \sum_{\text{femto } \mathrm{U_i}} \min\left\{\sum_{j=1}^{N_c} \nu_{ij} W_j \log(1+\gamma_{ij}), d_i\right\} \\ &\quad - \sum_{j=1}^{N_c}\sum_{i=1}^{N_f} \lambda_{ij}\left(\alpha_{ij} + \sum_{B_k\in A_i} \alpha_{kj} + \alpha_{mj} - 1\right) \\ \text{subject to } & \sum_{U_k\in T_{f_i}} \nu_{kj} \le \alpha_{ij}, \sum_{U_k\in T_m} \nu_{kj} \le \alpha_{mj} \text{ for all } i,j \end{aligned} \tag{5}$$

where $\lambda_{ij} \ge 0$ is the Lagrange multiplier with the constraint $\alpha_{ij} + \sum_{B_k\in A_i} \alpha_{kj} + \alpha_{mj} \le 1$.

Because the objective function is not strictly concave, we add the auxiliary terms to it before implementing the decomposition. The terms themselves should be strictly concave, e.g., $-\epsilon \sum_{i=1}^{N_f}\sum_{j=1}^{N_c} \alpha_{ij}^2$, where $\epsilon > 0$. All the constraints are kept unchanged, and the Lagrangian in (5) becomes

$$L\left(\{\alpha_{ij}\},\{\alpha_{mj}\},\{\nu_{ij}\},\{\lambda_{ij}\}\right) - \epsilon \sum_{i=1}^{N_f}\sum_{j=1}^{N_c} \alpha_{ij}^2. \tag{6}$$

The dual function $g(\{\lambda_{ij}\})$ of (6) is defined as the minimum value of its Lagrangian over $\{\alpha_{ij}\}$, i.e.,

$$\sup_{\{\alpha_{ij}\}} \left(L\left(\{\alpha_{ij}\},\{\alpha_{mj}\},\{\nu_{ij}\},\{\lambda_{ij}\}\right) - \epsilon \sum_{I=1}^{N_f}\sum_{j=1}^{N_c} \alpha_{ij}^2 \right). \tag{7}$$

The strong duality of (6) can be guaranteed by the Slater constraint qualification. In fact, the strong duality always holds in this case, because (6) is feasible. Therefore, the solution to the dual problem is the same as the solution of the primal one (6), i.e.,

$$\begin{aligned} &\text{minimize} && g\left(\{\lambda_{ij}\}\right) \\ &\text{subject to} && \{\lambda_{ij}\} \ge \mathbf{0}. \end{aligned} \tag{8}$$

Now, the decomposition method can be applied to (8) to conduct two levels of optimization.

At the lower level, we arrange the terms in (7) with local variables in the same BS together to form the subproblems. The local variables for FBS B_i are $\{\alpha_{ij}\}$ and $\{\nu_{kj}|U_k \in T_{f_i}\}$ for all j. Similarly, the local variables for the MBS are $\{\alpha_{mj}\}$ and $\{\nu_{kj}|U_k \in T_m\}$ for all j. Each FBS B_i solves the subproblem as

$$\begin{aligned} \text{maximize} \quad & P_f \sum_{U_i\in T_{f_i}} \min\left\{\sum_{j=1}^{N_c} \nu_{ij} W_j \log(1+\gamma_{ij}), d_i\right\} \\ & - \sum_{j=1}^{N_c}\left(\lambda_{ij}(\alpha_{ij}-1) + \sum_{B_i\in A_k} \lambda_{kj}\alpha_{ij}\right) - \epsilon\sum_{j=1}^{N_c}\alpha_{ij}^2 \\ \text{subject to} \quad & \sum_{U_k\in T_{f_i}} \nu_{kj} \le \alpha_{ij} \quad \text{for all } j \\ \text{variables} \quad & \{\alpha_{ij}\}, \{\nu_{kj}|U_k\in T_{f_i}\} \text{ for all } j \end{aligned} \tag{9}$$

to get the optimal value $g_i(\{\lambda_{ij}\})$. Similarly, the MBS solves the problem to get the optimal value $g_m(\{\lambda_{ij}\})$as

$$\begin{aligned} \text{maximize} \quad & P_m \sum_{U_i\in T_m} \min\left\{\sum_{j=1}^{N_c} \nu_{ij} W_j \log(1+\gamma_{ij}), d_i\right\} \\ & - \sum_{j=1}^{N_c}\sum_{i=1}^{N_f} \lambda_{ij}\alpha_{mj} - \epsilon\sum_{j=1}^{N_c}\alpha_{mj}^2 \\ \text{subject to} \quad & \sum_{U_k\in T_m} \nu_{kj} \le \alpha_{mj} \quad \text{for all } j. \\ \text{variables} \quad & \{\alpha_{mj}\}, \{\nu_{kj}|U_k\in T_m\} \quad \text{for all } j. \end{aligned} \tag{10}$$

The BSs can optimize (9) and (10) in a parallel manner, because the variables in the subproblems are all local information.

At the higher level, we need to update the Lagrange multipliers to ensure the consistency of the Lagrange multipliers on the neighboring BSs. In particular, one simple way is

$$\lambda_{ij}(t+1) = \left[\lambda_{ij}(t) + s(t)\left(\alpha_{ij}(t) + \sum_{B_k\in A_i} \alpha_{kj}(t) + \alpha_{mj}(t) - 1\right)\right]^+ \tag{11}$$

where $s(t) > 0$ is the step size in the tth iteration. In general, the values of $\{s(t)\}$ should carefully be selected, because they affect the convergence, converging speed, and gap to the optimal solution. Theoretically, $s(t)$ should be constant (small enough) or diminishing $(1 + m/t + m)$, where m is a fixed nonnegative number [19].

Now, we give the distributed algorithm LD. It takes several iterations of a two-level optimization to give the near-optimal solution. We denote the variables and parameters in iteration t with an additional suffix t.

Algorithm 2: Distributed algorithm based on Lagrangian decomposition.

Require: A nonnegative initial value of the partial Lagrange multiplier $\{\lambda_{ij}(0)\}$ and $\epsilon(0).t \leftarrow 0$.

1: **repeat**

2: Given $\{\lambda_{ij}(t)\}$, each BS solves its subproblems.

3: Every femto B_i sends $\{\alpha_{ij}(t)\}$ to all BSs in A_i. They receive the neighboring FBSs' messages. They also send $\{\alpha_{ij}(t)\}$ and $g_i(\{\lambda_{ij}\})$ to the MBS.

4: The MBS gathers the information to compute $\epsilon(t+1)$. It sends $\epsilon(t+1)$ and $\{\alpha_{mj}(t)\}$ to all FBSs.

5: Femto B_i updates its Lagrange multipliers by (11).

6: $t \leftarrow t + 1$

7: **until** $g_i(\{\lambda_{ij}\})$ and $g_m(\{\lambda_{ij}\})$ are changed by no more than the predefined threshold.

8: The BSs unify $\{\alpha_{ij}\}$ to strictly obey the interference constraints and correct the optimal value by auxiliary terms.

The two levels of subproblem optimizations are iteratively conducted, and in the end, we achieve the optimal solution to (6); however, the problem of interest is (5). We can compensate by subtracting the auxiliary terms, but the bias of the solution to the original problem (5) cannot completely be corrected. Thus, ϵ should not be large enough to induce much deviation. In the simulation, we also find that, if ϵ is too small, the convergence is very slow. We suggest making ϵ dynamic and assign $\epsilon(t+1)$ with the value $(\eta M(t))/(\sum_{i=1}^{N_f}\sum_{j=1}^{N_c}\alpha_{ij}(t)^2)$, where $M(t)$ is the optimal system revenue in the current iteration, and η is a small constant. The idea is to make the auxiliary terms proportional to the current system revenue $M(t)$.

For the selection of parameters such as $s(t)$ and $\epsilon(t)$, we have to trade off the gap to the optimal value and the convergence speed. We can binary search the domains of the parameters to find the proper values such that the gap is tolerable and the convergence is fast enough. The search results can be used for a long time, because our algorithm is not sensitive to these parameters. $\{\lambda_{ij}\}$ can be initialized as zero.

Now, we analyze the communication cost. At step 4, each B_i sends out $N_c(N_{b_i} + 1) + 1$ real numbers, where N_{b_i} is the cardinality of A_i. At step 5, the MBS sends out $N_f(N_c + 1)$ real numbers. Considering that, in practice, LD stops after limited iterations, let the number be N_i. Thus, the total real numbers exchanged in the process is about $\delta_{LD} = N_i(N_c\sum_{i=1}^{N_f} N_{b_i} + 2N_cN_f + 2N_f)$, which is irrelevant to the number of femto-accessing users N_{f_u}. Comparing δ_{CM} and δ_{LD}, we find that LD is preferable when there are numerous femto-accessing users, because the communication cost may not increase too much, and the computational cost on any single BS is significantly reduced.

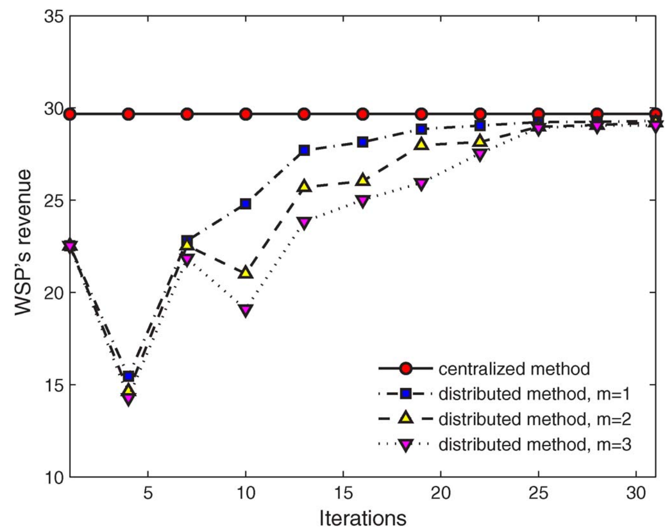

Fig. 2. Influence of the step size to the convergence.

The disadvantages of LD are given as follows. First, it is less efficient than CM with a small system. Second, LD is relatively harder to implement. Third, LD is based on iterations and gives a near-optimal result, whereas CM gives the optimal result.

VI. Evaluation

In this section, we conduct simulations in MATLAB and use the CVX tool [20] to show the performance of the two algorithms and the advantages of hybrid networks. We evaluate the convergence process of LD. Then, our scheme is compared with some baseline schemes to show its superiority. Finally, we run the scheme under various system parameters to verify its universal validity.

Consider a macrocell with a 500-m radius. In addition, the MBS is deployed at the center. $N_f = 20$ femtocells and $N_u = 100$ users are randomly located. We assume that each FBS has at least one indoor user located at home and the remaining $N_u - N_f = 80$ users are located anywhere in the macrocell network. The other default values of parameters are given as follows: $N_c = 20$ and $W_i = 0.2$ MHz for $i = 1, \ldots, 10$ and 0.4 MHz for $i = 11, \ldots, 20$, $P_m = 1$ per megabit, $P_f = 0.3$ per megabit, $p_m = 0.2$ W on each channel, $p_f = 0.1$ W on each channel, $N_0 = -174$ dBm/Hz, $\{\lambda_{ij}(0)\} = \mathbf{0}$, $\epsilon(0) = 1$, $\eta = 0.04$, and $s = 2/t + 1$. The femto user U_i's demand d_{f_i} is set to random at [0, 5] Mb, and the macro user U_i's demand d_{m_i} is random at [0, 1] Mb. The performance results are all averaged over 100 evaluations to smooth out any random factors such as the shadowing effect, demand diversity, or location variation.

Assume that the outdoor and indoor path losses are $28 + 35\log_{10}(r)$ dB and $38.5 + 20\log_{10}(r)$ dB, respectively, where r is the transmitter–receiver distance (in meters). The wall loss $L_w = 10$ dB will be counted if the BS and the user are separated by walls. The shadow fading S is log-normal distributed, with a standard deviation of 8 dB for outdoors and 4 dB for indoors.

Figs. 2 and 3 show that the convergence of our distributed algorithm is fast and the gap to the optimal value is small. Fig. 2 shows the impact of a series of step sizes on the convergence.

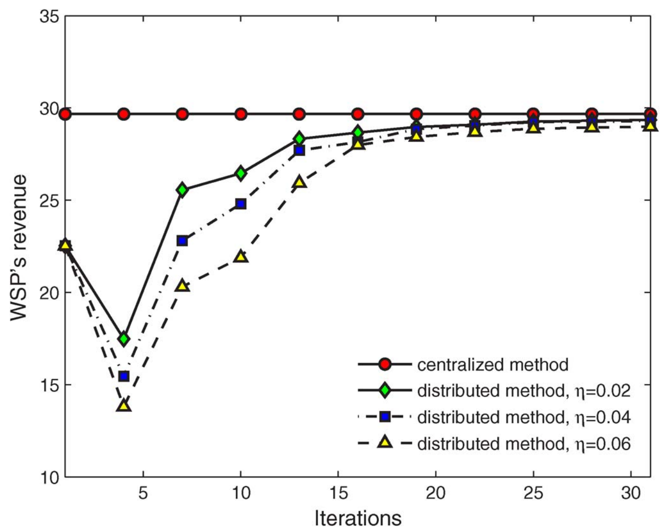

Fig. 3. Influence of the auxiliary terms.

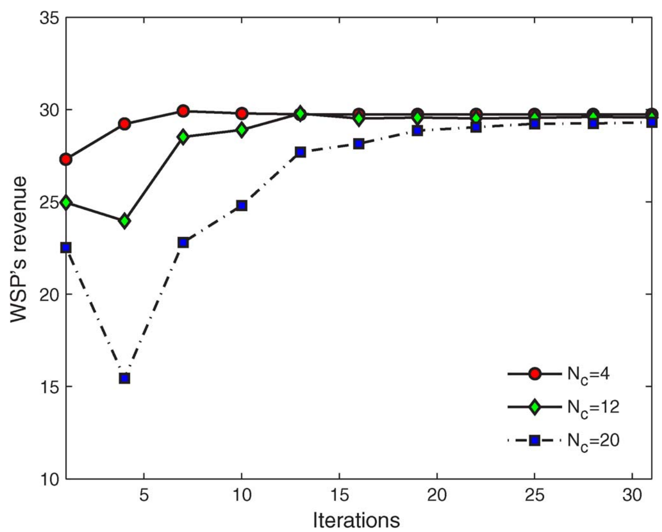

Fig. 4. Performance of LD in systems with different N_c values.

The value of m has little impact on the convergence speed and the gap to the optimal value. This confirms that the diminishing step size $1 + m/t + m$ can guarantee convergence. Fig. 3 shows the impact of the different auxiliary terms. The influence on the convergence speed is little. A larger η induces a larger slightly gap to the optimal value. All these results show that the distributed algorithm is robust to the selection of parameters. Fig. 4 shows the convergence progress of LD with different N_c values.[3] The convergence for a large-scale system is slower, but we can stop the algorithm after several iterations to get a near-optimal solution.

Table I makes a comparison of the two algorithms' computational overhead in different scenarios. For the first two cases, on the average, each BS needs $100.136/21 = 4.768$ and $198.781/41 = 4.848$ s to run LD, respectively. LD takes longer to give the results. However, for larger systems, in the last two cases, LD performs better than CM in the average computation, where the CM process is time consuming.

We compare our scheme with some baseline schemes, including fixed allocation and no FBS scheduling. In the fixed allocation, macro and femto accessing are preallocated ω and $1 - \omega$ portions of the spectrum, respectively. An FBS equally shares the $1 - \omega$ portion with its interfering neighbors. In the traditional scenario without FBSs, the MBS uses the entire spectrum to serve the users. Figs. 5 and 6 show the results under $d_{f_i} \in [0, 5]$, $d_{m_i} \in [0, 1]$, and $d_{f_i} \in [0, 20]$, $d_{m_i} \in [0, 4]$, respectively. Based on the two figures, our scheme always

TABLE I
COMPUTATIONAL OVERHEAD OF TWO ALGORITHMS

Total computation time (seconds)	20 FBSs, 100 users, 4 channels	40 FBSs, 200 users, 4 channels	60 FBSs, 300 users, 4 channels	60 FBSs, 300 users, 8 channels
CM	1.763	3.961	6.983	13.476
LD	100.136	198.781	289.410	295.064

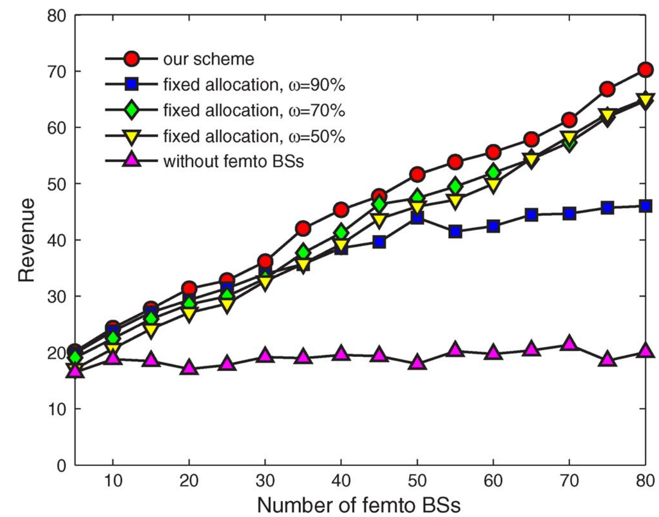

Fig. 5. Comparison with the baseline schemes with the default users' demand.

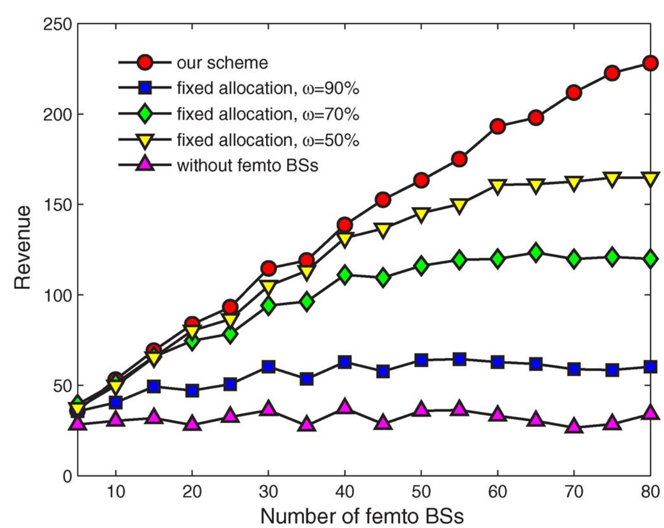

Fig. 6. Comparison with the baseline schemes with larger users' demand.

[3]The total bandwidth of the macrocell and the total power on each BS are kept the same. The convergence values of the three curves can be different, because the cases (with fading effect) are different.

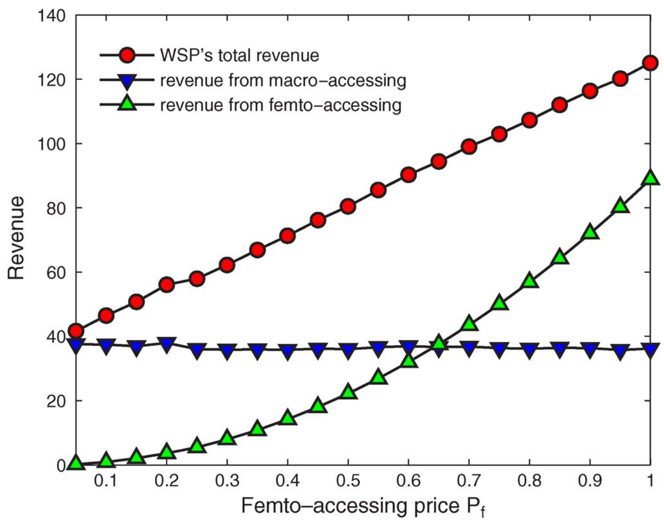

Fig. 7. Prices affect the service provision priority.

achieves the highest system revenue. If there are many FBSs and indoor users, the allocations that involve FBSs are definitely better than with macro allocation only. The figures also show that the performance gap between the fixed allocation schemes and our scheme increases with the number of FBSs in the large-demand case.

Although prices P_m and P_f are assumed to be fixed in the scheduling, they can affect the system performance. We fix $P_m = 1$ and change P_f. In Fig. 7, the overall revenue increases with P_f, and the main contribution comes from the femto accessing. The WSP tends to allocate more spectrum to FBSs such that more revenue can be generated. The revenue from macro accessing is slightly reduced, because the little spectrum that it vacates can spatially be reused to satisfy many femto users' demands.

VII. Conclusion

In this paper, we have proposed a novel channel scheduling scheme for hybrid macro–femto networks. It can jointly solve interference management and service provision problems, which are both closely related to channel scheduling. Based on the WSP's current fixed prices, our scheme gives the optimal allocation, which maximizes the WSP's revenue. CM is a cost-efficient way of obtaining the optimal result when the scale of the system is moderate. We also propose a distributed algorithm, called LD, to achieve the near-optimal result when CM is not suitable due to the large scale of the system. Our scheme can efficiently handle general cases, dense or sparse networks, and high or moderate users' demands. Extensive simulation results confirm our conclusions and again demonstrate that the femtocell technique dramatically improves the cellular capacity and spectrum efficiency.

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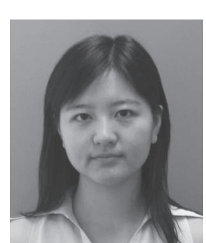

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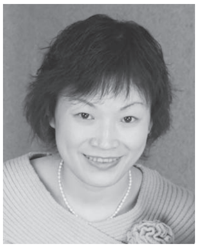

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