Dynamic Spectrum Allocation for the Downlink of OFDMA-Based Hybrid-Access Cognitive Femtocell Networks

Lei Zhang, Tao Jiang, *Senior Member, IEEE*, and Kai Luo

***Abstract*—The cognitive femtocell has emerged as an exciting technology to solve the indoor coverage problem in future cellular networks. Recently, several technical issues for the cognitive femtocell have been studied, e.g., spectrum sharing and interference mitigation. However, the incentive method that is very important for practical hybrid access cognitive femtocell deployment has not been well investigated. In this paper, we propose a new dynamic spectrum allocation method for the hybrid access cognitive femtocell. In the proposed method, the macro base station (BS) allocates a portion of subchannels to the femto access point (FAP) to spur the FAP to serve the macro users (MUs). Then, the FAP allocates the subchannels and power to maximize the femtocell network utility, whereas the throughput of the served MUs is guaranteed. Moreover, we formulate the corresponding resource allocation problem as a sum-utility maximization problem and propose an optimization method to solve it via the dual decomposition method. Simulation results show that both the wireless service provider and the femtocell could benefit from the proposed method.**

***Index Terms*—Cognitive femtocell networks, dual decomposition, dynamical spectrum allocation, hybird access.**

I. Introduction

DURING the last decade, the number of wireless communication applications has grown by orders of magnitude in the cellular network. Simultaneously, more and more cellular traffic originates from indoors. A recent survey by ABI has shown that more than 50% voice traffic and 70% data traffic take place in indoor environments such as homes, offices, and airports [1]. However, the shadowing and multipath fading effects are serious in the indoor environment due to wall penetration. Accordingly, the poor quality of service (QoS) is received by the indoor users. For instance, another survey shows that 30% of business users and 45% of household users obtain poor QoS inside buildings [2]. To solve the indoor coverage problem, the femtocell has emerged as an exciting technology in future cellular networks [3]. On the one hand, femtocells could improve the received signal strength for the indoor users due to the short transmission distance. On the other hand, compared with building more macro base stations (BSs) to satisfy the increasing demands of indoor users, femtocells reduce capital and operational expenditures for the operators since femtocells are small, inexpensive, and low-power BSs that are generally deployed by the indoor users and connected to their own wired backhaul connection [3]. As a result, the use of femtocells has drawn much attention by the operators since femtocells could solve the indoor coverage problem with a little expenditure. In 2011, about 2.3 million femtocells were deployed by many major cellular operators, such as Vodafone, AT&T, and Softbank, and it is expected to increase to 50 million by 2014 [4].

The access control mechanisms in femtocells can be divided into three categories: open access, closed access, and hybrid access [3]. For the open-access mode, any wireless users including macro users (MUs) and femto users (FUs) could access to the femto access point (FAP) to transmit data. In general, open access is a superior approach from a network capacity point of view and from the MU's point of view [3]. However, the performance of the FUs is degraded since the resource of the FAP is limited and shared by the MUs. Conversely, for the case of closed access, only the FUs that are authorized by the FAP could access to the FAP to transmit data, whereas the MUs are not allowed to access. Therefore, the performance of the FUs is guaranteed for the closed access. However, in the case of closed access, the interference to the MUs caused by the femtocell is strong when the MUs are far away from the macro BS but close to the FAP. Moreover, the spectrum utilization of closed access is lower than that of open access. Hybrid access is a tradeoff between open access and closed access, where the MUs are permitted to access the FAP when the performance of the FUs are guaranteed. However, how to spur the FAP to share their limited resource with the MUs, such as subchannels and power, is still a problem in hybrid-access femtocells.

Cognitive radio (CR) is regarded as one of the most promising technologies in the future wireless communications [5]–[7]. In cognitive radio networks, cognitive users could access to the idle licensed spectrum of primary users to improve the spectrum efficiency [8]. Moreover, the cognitive users could adapt their

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L. Zhang is with the School of Electronics Information and Communications, Huazhong University of Science and Technology, Wuhan 430074, China, and also with Hubei Polytechnic University, Huangshi, 435003, China.

T. Jiang and K. Luo are with the School of Electronics Information and Communications, Huazhong University of Science and Technology, Wuhan 430074, China.

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transmission parameters by spectrum sensing to mitigate the interference. Recently, the femtocell networks that integrate with cognitive radios have drawn much attention. First, for the femtocell network, it works on the licensed cellular spectrum to seamlessly integrate with the cellular network. Thus, the spectrum insufficiency problem is becoming more serious due to the busy traffic and limited spectrum of cellular networks. Second, since the FAPs are generally deployed by the indoor users and the location of FAPs are not controlled by the cellular operator, the cross-tier and intratier interference problems are key challenges in the two-tier femtocell networks [9], [10]. In cognitive femtocell networks, the FAPs that are equipped with CR technology could dynamically sense spectrum usage by the macrocell and surrounding FAPs, adapt their transmission to avoid cross-tier and intratier interference to the macrocell and surrounding femtocells, and optimize the overall usage of the spectrum [3], [11].

In this paper, we propose a dynamic spectrum allocation method to motivate both the wireless operator and the FAP to adopt hybrid access in the cognitive femtocell. In the proposed method, the wireless operator allocates a part of the spectrum resource to the FAP to spur the FAP to serve the MUs. However, there are still several problems that need to be addressed in this method. First, how can the wireless operator be spurred to allocate a part of spectrum resource to the FAP? Second, to maximize the femtocell network utility while guaranteeing the throughput of the served MUs, how does the FAP allocates the resource to the MUs and the FUs, such as subchannels and power? To address these problems, we formulate these problems as optimization problems and employ the dual decomposition method to derive the optimal solution. The main contributions of this paper are as follows.

- A dynamic spectrum allocation method is proposed to spur both the wireless operator and the FAP to adopt hybrid access in the cognitive femtocell. In the proposed method, on the one hand, the wireless operator saves a portion of subchannels while guaranteeing the performance of the MUs. On the other hand, the FAP obtains more spectrum resource to improve the performance of the FUs.
- A protocol is designed to implement the proposed dynamic spectrum allocation problem. Moreover, the corresponding resource allocation of the FAP is formulated as an optimization problem, and the dual decomposition method is employed to derive the optimal solution.
- Simulations are conducted to evaluate the proposed dynamic spectrum allocation method, and the results show that both the wireless operator and the femtocell could benefit from the proposed method. Thus, the proposed method is an effective solution to the incentive problem of the hybrid access cognitive femtocell.

The remainder of this paper is organized as follows. We review the related work in Section II. In Section III, a system model is presented. Then, we propose a dynamic spectrum allocation method in the cognitive femtocell in Section IV. In Section V, we formulate the proposed method as an optimization problem and employ the dual decomposition method to derive the optimal solution. The simulations are presented in Section VI. We draw our conclusions in Section VII.

II. Related Work

The femtocell has emerged as one of the exciting technologies that could solve the poor indoor coverage problem with a little expenditure [12]. An overview of three access control mechanisms, which are open access, closed access, and hybrid access, was given in [13]. In [14], Lin *et al.* discussed the business mode in femtocells and proposed three deployment frameworks, i.e., wireless service provider deployment, end-user deployment, and joint deployment. The unique characteristics, corresponding challenges, and potential solutions of three deployment frameworks are investigated. Game theory has been widely applied to femtocell, and economic benefits are considered in several studies. In [15], a Stackelberg game was employed to analyze the cooperation and competition between the wireless service provider and the femtocell holders. A utility-aware refunding frame was proposed to spur the femtocell holders to serve the MUs from the economic aspect. Within the framework, the wireless service provider can provide certain refunding to the femtocell holder if it serves the MUs. In [16], Chen *et al.* discussed the utility-aware refunding frame with traffic uncertainty further. In [17], Li *et al.* proposed a new resource allocation method to improve the performances of the FUs and neighboring MUs in the open-access femtocells. In [18], the concept of contract was introduced to analyze the access permission and spectrum trading between the wireless operator and FAPs. In [19], a distributed uplink power control algorithm was proposed, and it was applied to the hybrid spectrum access strategy in two-tier femtocell networks. The proposed algorithm can provide QoS support for all users while maximizing the network throughput. In [20], the femtocell scenario where a wireless operator lacks a fixed-line network infrastructure and collaborates with a fixed-line operator was considered. A hybrid cooperation framework based on sequential game and Nash bargaining was proposed for a mobile operator and a fixed-line operator to provide femtocell services.

In cognitive femtocells, the FAPs that are equipped with CR technology could dynamically sense spectrum usage by the macrocell and surrounding FAPs, adapt their transmission to avoid cross-tier and intratier interference, and optimize the overall usage of the spectrum [3], [21]. In [10], the problem of cross-tier interference in femtocell networks was discussed, and cognitive radio technology was employed to mitigate cross-tier interference. With the cognitive radio technology, a strategic game was proposed to mitigate intratier interference. In [22], the problem of streaming scalable videos in cognitive femtocell was discussed. Various design factors across multiple layers were considered, and the problem was formulated as a multistage stochastic programming problem. In [23], resource block allocation in the downlink of cognitive FAPs was considered. The macro BS was considered the primary user, and the cognitive FAPs were formulated as multiple secondary users. The static game framework was employed to solve the resource allocation problem. In [25], several downlink spectrum sharing schemes were proposed according to the different availability of

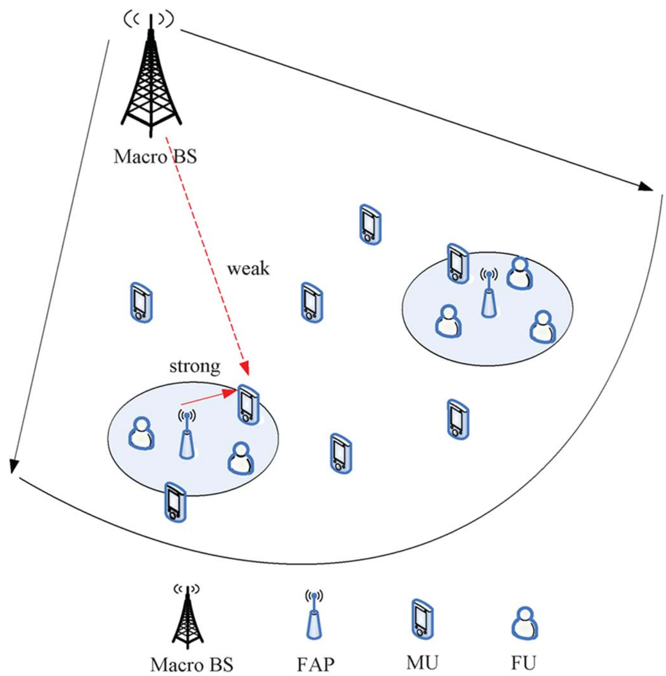


Fig. 1. System scenario.

sensing information in the cognitive FAPs, and corresponding capacities were derived. In [26], the competition of the cognitive FAPs for spectrum resource was investigated, and a game-theoretic framework to solve the resource allocation problem was employed.

However, as far as we know, there is no work that considers the incentive method in the hybrid-access cognitive femtocell from the technical perspective. In this paper, we propose a dynamic spectrum allocation method to spur both the wireless operator and the FAP to adopt hybrid access in the cognitive femtocell. Moreover, to maximize the femtocell network utility while guaranteeing the throughput of the served MUs, we formulate the corresponding resource allocation problem as a sum-utility maximization problem and propose an optimization framework to solve it by the dual decomposition method.

III. System Model

As shown in Fig. 1, we consider a centralized OFDMA-based two-tier network architecture with a macro BS and a number of FAPs, where the FAPs are deployed by the indoor users and connected to the macro BS by the wired backhaul, such as cable and fiber. Compared with Wi-Fi, the FAPs work on the licensed cellular spectrum and use the cellular standard to seamlessly integrate with the cellular network. Moreover, the same spectrum overlay model as the model in [23] and [24] is employed in this paper. In spectrum-overlay-based cognitive femtocells, the FAPs that are equipped with CR technology could dynamically sense the utilized channels by the macrocell and surrounding femtocells and occupy the spectrum holes of the licensed cellular spectrum to avoid cross-tier and intratier interference to the macrocell and surrounding femtocells [23], [24]. For tractability of analysis, perfect spectrum sensing is assumed in this paper.

TABLE I
List of the Main Variables

M	Number of MUs in the femtocell network
N	Number of FUs in the femtocell network
B	Bandwidth of a subchannel
S	Log-normal shadowing factor
P_{FAP}	The maximum total transmission power of a FAP
s	Total number of sensed subchannels
c	Total number of negotiation channels
c_m	Number of negotiation channels of m-th MU
D_m	The minimum rate of m-th MU
$R_{i,j}$	Achievable rate of j-th user on subchannel i
h_j	Attenuation factor of j-th user
Φ	Set of MUs in the femtocell network
Ω	Set of FUs in the femtocell network
Ψ	Set of users in the femtocell network
Υ	Set of available subchannels in the femtocell network
n_0	Noise power density
m, n	Indexs of a MU and a FU
i	Index of an available subchannel
j	Index of a user in the femtocell network
d_m, d_n	Demands of m-th MU and n-th FU
$U_n(x)$	Utility function of n-th FU
k_1	Upper-bound of the FUs' utility function
k_2	Reflection of the average demand level of the FU and fairness rules
$p_{i,j}$	Transmission power of j-th user on subchannel i
$\mu_{i,j}$	Subchannel allocation indicator of j-th user on subchannel i
f	Fairness of whole network
w	Number of floors in the path
r	Transmission range
l	Iteration number during dual decomposition procedure

We consider the OFDMA-based downlink transmission in the given network scenario. There are a total of M MUs and N FUs in a femtocell. Let the set of the MUs and the set of the FUs in a cognitive femtocell be denoted $\Phi = \{1, 2, \ldots, M\}$ and $\Omega = \{1, 2, \ldots, N\}$, respectively. $m \in \Phi$ represents the index of a MU, and $n \in \Omega$ represents the index of an FU. The set of indoor end users that contains both MUs and FUs is denoted $\Psi = \{1, 2, \ldots, M + N\}$, and each indoor end users is indexed by j, where $j \in \Psi$. The indoor end users communicate with the serving FAP by employing OFDMA technique, in which consecutive subcarriers are bundled into a subchannel. The bandwidth of each subchannel is denoted B, and each subchannel is indexed by i. The FAP initializes the set of available subchannels via spectrum sensing in each slot, and the number of the available subchannels via spectrum sensing is denoted k. The transmission power of the FAP is denoted P_{FAP}, and transmission power to the jth indoor end user on subchannel i is denoted $p_{i,j}$. We denote $\mu_{i,j}$ as the binary function capturing the assignment of subchannel i to the jth end user, and $\mu_{i,j} = 1$ means that the subchannel i is allocated to the jth end user. Otherwise, $\mu_{i,j} = 0$. A list of the main variables used in this paper is given in Table I.

IV. Dynamic Spectrum Allocation Method

Here, a dynamic spectrum allocation method is proposed to spur both the wireless operator and the FAP to adopt hybrid access in the cognitive femtocell network. As shown in Fig. 1, the signal-to-noise ratio (SNR) of the link between the MU and the FAP is much better than that of the link between the MU and the macro BS due to the short transmission distance, less wall penetration, and shadowing effects. To achieve the same QoS of the MU, the indoor communications consume less subchannels compared with the outdoor communications. Motivated by this observation, we propose a dynamic spectrum allocation method to spur both the wireless operator and the FAP to adopt hybrid access in the cognitive femtocell. In the proposed method, the wireless operator allocates a part of spectrum resource to the FAP to spur the FAP to serve the MU. Both the wireless operator and the femtocell could benefit from the proposed method. On one hand, the FAP could provide a better service to the FUs due to more available subchannels. On the other hand, the macro BS could improve its spectrum efficiency by saving a part of the spectrum.

To implement the dynamic spectrum allocation method, a corresponding protocol is designed, and the details of the protocol are presented as follows.

Step 1: The mth MU goes into the area that the FAP covers and initializes a data transmission call via the control channel; the FAP receives the request and reports it to the macro BS.

Step 2: The macro BS calculates the number of subchannels q_m that the mth MU needs according to the mth MU's requirement D_m and the resource allocation method of the macro BS.

Step 3: The macro BS negotiates with the FAP to spur it to serve the mth MU. The macro BS notifies the FAP that it will allocate c_m subchannels, which are a part of q_m subchannels to the FAP if the FAP could satisfy the mth MU's requirement. We call the subchannels that the macro BS allocates to the FAP negotiation channels. Note that $c_m = \lfloor \alpha q_m \rfloor$, where α is a controllable system parameter of the macro BS. $\lfloor x \rfloor$ obtains the nearest integer less than or equal to x.

Step 4: The FAP decides whether to serve the mth MU or not, according to the profit of the femtocell. If the FAP finds that the network utility of the femtocell could increase by H percent when it serves the mth MU, the FAP decides to serve the mth MU. H is a controllable system parameter of the FAP. Otherwise, the FAP will not serve the mth MU, and the macro BS needs to allocate more subchannels to the FAP to spur it to serve the mth MU.

Note that the procedure of the proposed method and spectrum sensing can be conducted by the femtocell simultaneously since the negotiation process of the protocol can be conducted on the wired backhaul between the macro BS and the FAP.

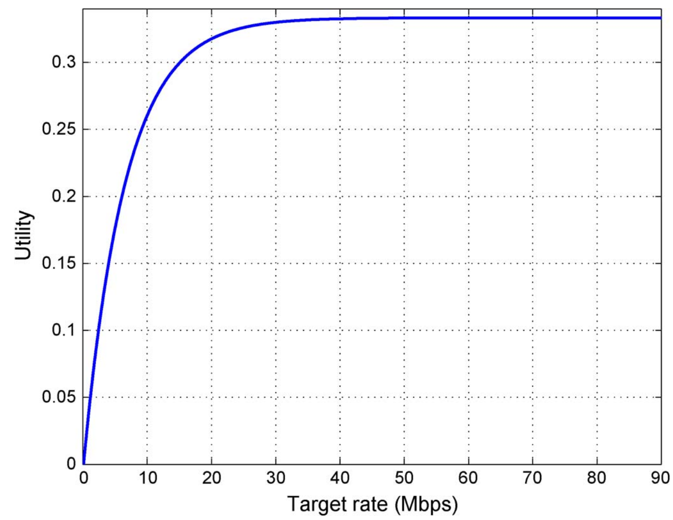


Fig. 2. Utility function.

Therefore, the corresponding resource allocation strategy of the FAP can be formulated as follows:

$$\max \sum_{n\in\Omega} U_n(\lambda_n) \tag{1}$$

$$\text{s.t.} \sum_{j\in\Psi} \mu_{i,j} \le 1 \qquad \forall i \in \Upsilon \tag{2}$$

$$\sum_{i\in\Upsilon}\sum_{j\in\Psi} p_{i,j} \le P_{\text{FAP}} \tag{3}$$

$$\lambda_m \ge D_m \tag{4}$$

where $\Upsilon = \{1, 2, \ldots, k+c\}$, and c represents the total number of negotiation channels in our proposed method, i.e.,

$$c = \sum_{m\in\Phi} c_m. \tag{5}$$

$U_n(\cdot)$ is the utility function. It is a concave and increasing function of data rates that reflects user satisfaction [27] and can be denoted as follows:

$$U_n(\lambda_n) = \begin{cases} k_1(1 - e^{-k_2\lambda_n}), & \text{if } \lambda_n \ge 0 \\ -\infty, & \text{if } \lambda_n < 0 \end{cases} \tag{6}$$

where λ_n is the achievable rate of the nth FU, $\lambda_j = \sum_{i\in\Upsilon} \mu_{i,j} \cdot R_{i,j}$, and $R_{i,j}$ is the achievable rate of the jth user on subchannel i, which can be calculated by $R_{i,j} = B\log_2(1 + \text{SNR}_{i,j})$. k_1 represents the utility function's upper limit, the value of k_2 is chosen to let utility equal to $0.9k_1$ when the user achieves the target rate t. Given t, $k_2 = \ln(0.1)/-t$. As shown in Fig. 2, we give an example of the utility function where $t = 15$ Mb/s, $k_1 = 1/3$, and $k_2 = 7.675 \times 10^{-8}$. $U_n(\cdot)$ is an increasing function. When the achievable rate is smaller than the target rate $t = 15$ Mb/s, the utility increases fast. Since the utility increases slowly when the achievable rate exceeds the target rate, allocation of more resource to the end users that satisfy the target rate will make little contribution to the utility function, and it can guarantee the fairness among the users.

The constraint in (2) denotes that each subchannel can be allocated to only one user. Equation (3) indicates the power constraint of the FAP, and (4) means that the FAP should guarantee the requirement of the served MUs if it makes a deal with the macro BS.

V. Optimization of the Proposed Method

The optimization problem of (1) is a mixed-binary-integer programming problem, and it is nonconvex. However, since the time-sharing condition is satisfied in the OFDMA systems with a large number of subcarriers, the duality gap is proved to be zero [27]–[29]. Therefore, in this paper, the Lagrangian dual method is employed to derive the optimal solution of (1).

First, we introduce a new variable d_n, which represents the application layer demand of nth FU and rewrite (1) as

$$\begin{aligned} \max \quad & \sum_{n\in\Omega} U_n(d_n) \\ \text{s.t.} \quad & \text{(2)–(4)} \\ & d_n \le \lambda_n. \end{aligned} \tag{7}$$

Since $U_n(\cdot)$ is an increasing function, the objective of (7) is maximized when $d_n = \lambda_n$. Thus, problems (1) and (7) have the same solution.

Second, we denote the Lagrange multipliers θ_n and θ_m. Then, the dual function is

$$g(\boldsymbol{\theta}) = \begin{cases} \max & \sum\limits_{\substack{n\in\Omega \\ m\in\Phi}} [U_n(d_n) + \theta_n(\lambda_n - d_n) \\ & \qquad\qquad + \theta_m(\lambda_m - D_m)] \\ \text{s.t.} & \text{(2)–(3).} \end{cases} \tag{8}$$

The dual function consists of two sets of variables: the variable d_n of the application layer, and the variables λ_m and λ_n of the physical layer. Therefore, the problem of (8) can be divided into two subproblems. The first subproblem is a utility maximization problem, corresponding to a rate adaptation problem in the application layer, i.e.,

$$g_{\text{appl}}(\boldsymbol{\theta}) = \max \sum_{\substack{n\in\Omega \\ m\in\Phi}} \left[U_n(d_n) - \theta_n d_n - \theta_m D_m\right]. \tag{9}$$

For simplicity, we rewrite (9) as

$$g_{\text{appl}}(\boldsymbol{\theta}) = \max \sum_{n\in\Omega} U_n(d_n) - \sum_{j\in\Psi} \theta_j d_j \tag{10}$$

where

$$\sum_{j\in\Psi} \theta_j d_j = \sum_{m\in\Phi} \theta_m D_m + \sum_{n\in\Omega} \theta_n d_n. \tag{11}$$

The second subproblem is a joint subchannel and power allocation problem in the physical layer, i.e.,

$$g_{\text{phy}}(\boldsymbol{\theta}) = \begin{cases} \max & \sum\limits_{j\in\Psi} \theta_j \lambda_j \\ \text{s.t.} & \text{(2)–(3)} \end{cases} \tag{12}$$

where

$$\sum_{j\in\Psi} \theta_j \lambda_j = \sum_{m\in\Phi} \theta_m \lambda_m + \sum_{n\in\Omega} \theta_n \lambda_n. \tag{13}$$

Due to the fact that the sum-utility maximization problem of (7) has zero duality gap in the OFDMA systems, it can be solved by minimizing the dual objective as

$$\begin{aligned} \min \quad & g(\boldsymbol{\theta}) \\ \text{s.t.} \quad & \boldsymbol{\theta} \ge 0. \end{aligned} \tag{14}$$

Then, the problem of (14) can be solved by the subgradient-based method, and the corresponding steps could be summarized as follows.

Step 1: Initialize $\boldsymbol{\theta}^0$.
Step 2: Given $\boldsymbol{\theta}^{(l)}$, solve the problems (10) and (12) separately to obtain the optimal values d_j^* and λ_j^*, respectively.
Step 3: Employ a subgradient to update $\boldsymbol{\theta}$

$$\theta_j^{(l+1)} = \left[\theta_j^{(l)} + \nu_j^{(l)}(d_j^* - \lambda_j^*)\right]^+ \tag{15}$$

where function $[x]^+ = 0, x \le 0$. Otherwise, $[x]^+ = x$;
Step 4: Return to **step 2** until convergence.

Note that, it has been proven that, in [27] and [30], the given subgradient method is guaranteed to converge to the optimal dual variable with a diminishing step rule. The dual variable θ_j can be considered the price of achievable rate, and it coordinates the demand of application layer and the supply of physical layer. On the one hand, from (15), we can observe that if the price θ_j increases when $\lambda_j^* < d_j^*$, the higher price θ_j will spur the physical layer to allocate more resources to obtain more revenues. On the other hand, the higher price θ_j will spur the application layer to reduce traffic demand.

A. Solutions of Subproblems

Here, efficient methods are proposed to solve the given two subproblems in the application layer and the physical layer, respectively.

1) Solutions of Subproblem in Application Layer: Since the objective of the FAP is to maximize the sum utility of the FUs while guaranteeing the QoS of the MUs, the optimal solution is obtained when $\lambda_m = D_m$. Moreover, since $U_n(\cdot)$ is a concave function of d_n, $(U_n(d_n) - \theta_n d_n)$ is also a concave function of d_n. Therefore, we can find the optimal d_n^* by taking the derivative of (10) with respect to d_n and set it to zero. The optimal d_j^* is given as

$$d_j^* = \begin{cases} D_m, & j \in \Phi \\ \left[-\frac{1}{k_2} \ln \frac{\theta_m}{k_1 k_2}\right]^+, & j \in \Omega. \end{cases} \tag{16}$$

2) Solutions of Subproblem in Physical Layer: To solve the problem of (12), we also introduce Lagrange multiplier σ to relax the power constraint of the FAP. The dual function is given as follows:

$$a(\sigma) = \begin{cases} \mathbf{max} & \sum_{j\in\Psi} \theta_j \lambda_j + \sigma \left(P_{\mathrm{FAP}} - \sum_{i\in\Upsilon} \sum_{j\in\Psi} p_{i,j} \right) \\ \mathbf{s.t.} & (2). \end{cases} \tag{17}$$

Since σP_{FAP} is constant in (12) when σ is given, we transform (12) as follows:

$$\begin{aligned} \mathbf{max} \quad & \sum_{j\in\Psi} \theta_j \lambda_j - \sigma \sum_{i\in\Upsilon} \sum_{j\in\Psi} p_{i,j} \\ \mathbf{s.t.} \quad & (2). \end{aligned} \tag{18}$$

Since the subproblem in the physical layer also has a zero duality gap [27], [29], we can solve the problem of (12) via the dual problem, i.e.,

$$\begin{aligned} \mathbf{min} \quad & a(\sigma) \\ \mathbf{s.t.} \quad & \sigma \geq 0. \end{aligned} \tag{19}$$

Similar to the problem of (14), we can derive the optimal primal variables via the subgradient method, and its steps include the following.

Step 1: Initialize $\sigma^{(0)}$.
Step 2: Given $\sigma^{(l)}$, solve the problem (18) to obtain the optimal values $\mu^*_{i,j}$ and $p^*_{i,j}$.
Step 3: Employ a subgradient to update σ:

$$\sigma^{(l+1)} = \left[\sigma^{(l)} + \varepsilon^{(l)} \left(\sum_{i\in\Upsilon} \sum_{j\in\Psi} p_{i,j} - P_{\mathrm{FAP}} \right) \right]^+ \tag{20}$$

where σ can be considered a pricing variable that accounts for the cost of power. From (20), we can observe that the cost σ increases when $\sum_{i\in\Upsilon} \sum_{j\in\Psi} p_{i,j} > P_{\mathrm{FAP}}$, and the higher cost σ will spur the FAP to allocate less power to avoid the decrease of utility of (18). Otherwise, σ decreases.

Step 4: Return to **step 2** until convergence.

B. Overview of the Algorithm

The overall sum-utility maximization problem can be solved by using the proposed dual decomposition method. When updating the values of $\boldsymbol{\theta}$ in the subgradient method, we need to obtain the solutions of both the application-layer subproblem and the physical-layer subproblem. The application-layer subproblem is easy to solve since it is a concave problem. For the subproblem of the physical layer, we introduce the dual variable to relax the power constraint and derive the optimal solutions via the dual decomposition due to the zero gap in the OFDMA systems. The maximal utility of the femtocell network is reached when the values of $\boldsymbol{\theta}$ are convergent. The flowchart of the proposed dual decomposition method for (1) is shown as follows.

Algorithm 1 Dual decomposition

1: Initialize $\boldsymbol{\theta}^{(0)}$;
2: Given $\boldsymbol{\theta}^{(l)}$, solve the problem (10) in the application layer to obtain the optimal values d^*_j;
3: Initialize $\sigma^{(0)}$;
4: Given $\sigma^{(l)}$, solve the problem (12) in the physical layer to obtain the value $p_{i,j}$;
5: Using function (20) to perform a subgradient update for σ, where $\varepsilon^{(l)}$ follows a diminishing step size rule;
6: Return to **3** until convergence;
7: Using the optimal $p^*_{i,j}$ to obtain the optimal λ^*_j;
8: Using (15) to perform a subgradient update for $\boldsymbol{\theta}$, where $\nu^{(l)}_j$ follows a diminishing step size rule;
9: Return to **1** until convergence.

VI. Simulations

A. Simulation Scenario

Here, simulations are conducted to evaluate the performance of the proposed method. The transmission radius of the FAP is set to be 15 m, and $N = 3$ FUs are in the coverage of the FAP. The maximum transmission power of the FAP is assumed to be $P_{\mathrm{FAP}} = 0.05$ W. The noise power density is set to be $n_0 = -204$ dB/Hz, and the bandwidth of each subchannel that contains 50 consecutive subcarriers is $B = 1$ MHz. To guarantee the QoS of each MU, the minimum date rate requirement of each MU is set to be $D_m = 10$ Mb/s.

The path loss factors of wireless subchannels between indoor end users and the FAP are modeled based on the ITU model as follows [20], [31]:

$$h_j = 10^{-3.7} r^{-3} 10^{-1.83w\left(\frac{w+2}{w+1} - 0.46\right)} 10^{-S/10} \tag{21}$$

where r (in meters) is the transmission range, S is the lognormal shadowing factor with the standard deviation of 8 dB, and w is the number of floors in the path and is set to be 2 in the simulations.

To evaluate the performance of the proposed method, we consider the other three methods to compare with the proposed method.

- **Optimal allocation for traditional hybrid access (OP-THA)**: This is the optimal method where the FAP allocates resource to both FUs and MUs using the dual decomposition method. This scheme is based on traditional hybrid access, in which the incentive mechanism is not considered.
- **Equal allocation for closed access (EA-CA)**: This is the basic method that the FAP allocates resource, such as subchannels and power, equally to each user. In addition, this scheme is based on closed access.
- **Optimal allocation for closed access (OP-CA)**: This is the optimal method wherein the FAP allocates resources to each user using the dual decomposition method. This scheme is based on closed access.

- **Dynamic spectrum allocation for hybrid access (DSA-HA)**: This is the optimal resource allocation method in our proposed DSA method, in which the network utility of the femtocell is maximized, and the throughput of the served MUs is guaranteed. This scheme is based on hybrid access.

The following performance metrics, i.e., network utility, network throughput, and fairness, are employed to evaluate the performance of the femtocell for the given methods.

- **Network utility**: This is the sum of utilities of all FUs in the femtocell. It reflects the satisfactory level of the FUs in the femtocell, which is a nonnegative number but not greater than 1.
- **Network throughput**: This is the throughput of the femtocell, i.e., the sum throughput of all FUs.
- **Fairness**: The Jain's index [32] is employed to evaluate the fairness of the whole network, which is defined as

$$f = \frac{\left(\sum_{n=1}^{N} \lambda_n\right)^2}{N \sum_{n=1}^{N} (\lambda_n)^2} \tag{22}$$

where λ_n is the achievable rate of the nth FU. The index $f \in [1/N, 1]$, and a larger f means a fairer system.

B. Simulation Results

1) General Comparisons: Here, the number of subchannels sensed by the FAP is assumed to follow the uniform distribution, where $s \in [1, 6]$. Since the resource allocation algorithm of the macro BS is not our focus in the proposed method, for simplicity, we assume the number of subchannels that the mth MU needs in the macro cellular networks also follows the uniform distribution, where $q_m \in [2, 8]$.

In our proposed method, since its performance is the same as closed access if the FAP declines the MUs to access, we repeat the simulations until the MUs are severed by the FAP for 1000 times. For simplicity, the FAP would serve the MUs as long as the utility of FUs could be increased, which means H is an infinitesimal. Our main focus is to investigate whether the QoS of the MUs can be guaranteed and how much benefits could be obtained by the femtocell in these 1000 frames.

As shown in Fig. 3, we have the following observations.

- Since the incentive mechanism is not considered in the traditional hybrid access method and the FAP needs to share its' resource to the MUs, compared with the other three methods, the OP-THA achieves the poorest performances, such as network utility of femtocell, femtocell network throughput, and fairness.
- The OP-CA method that employs the dual decomposition method achieves a larger network utility than the EA-CA method. It proves that the dual decomposition method is an efficient way to solve the joint resource allocation problem. Furthermore, the network utility of the DSA-HA method is the best among the three schemes since more available subchannels could be employed in the femtocell in the DSA-HA method.

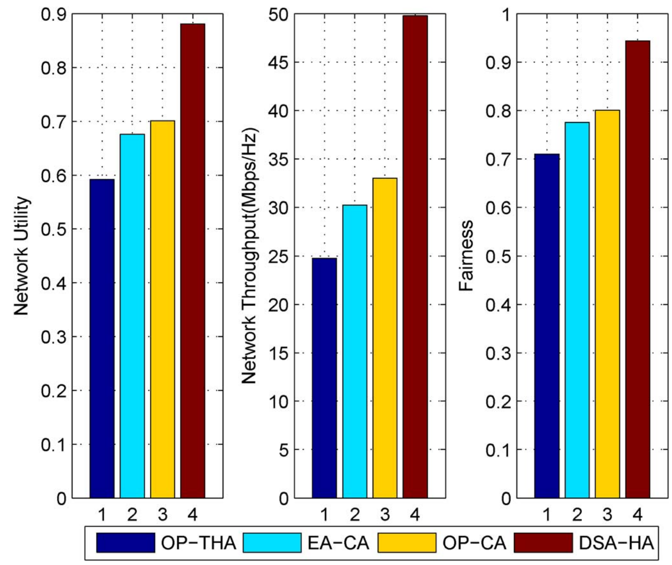


Fig. 3. Performances with different schemes.

- Compared with the EA-CA method, the OP-CA method could achieve a larger network throughput than that of the EA-CA method. The reason behind this phenomenon is that the variety of the FUs on different subchannels is utilized in the OP-CA method. Compared with the OP-CA method, the DSA-HA method achieves more network throughput due to more available subchannels.
- Since the number of available subchannels obtained by spectrum sensing may be limited in the closed-access framework, both the EA-CA and OP-CA methods cannot achieve high fairness. For example, if the FAP allocates five subchannels to three FUs, we can never obtain good fairness because of the relatively large difference among the rates of these FUs. However, with a larger number of available subchannels obtained from the macro BS, which indicates the larger achievable rate of each user, this difference can be diminished. For example, in the DSA-HA method, the number of available subchannels increases to eight since the FAP serves the MUs. At this time, with the increased achievable rate for each MU, the difference of achievable rate for each MU is decreasing.

As shown in Fig. 4, we investigate the achievable rate of each user for the DSA-HA method. The achievable rates of FUs are different due to different channel conditions. The QoS of the MU can be guaranteed by the femtocell in our proposed DSA-HA method since the achievable rate of the MU nearly equals to the minimal rate requirement, which is set to be $D_m = 10$ Mb/s. Note that, since the objective of the FAP is to maximize the sum utility of all the FUs while guaranteeing the QoS of the MUs, the optimal solution is obtained when $\lambda_m = D_m = 10$ Mb/s.

In Fig. 5, we investigate the spectrum usage of the MUs that are located inside the femtocell in 1000 frames. The first bar

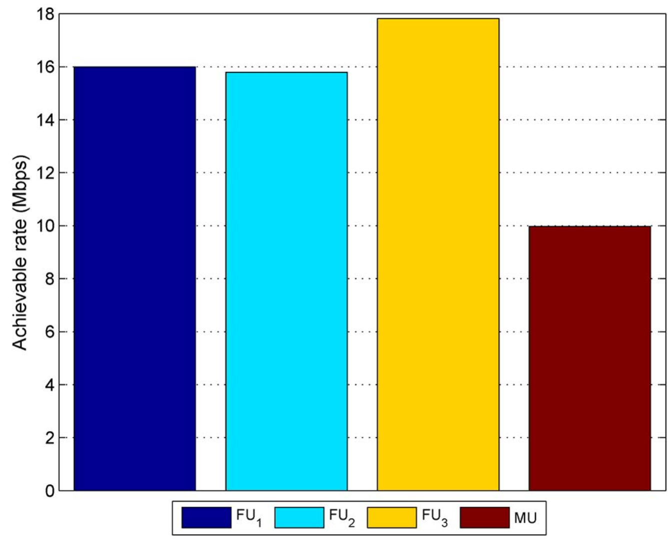


Fig. 4. Achievable rates of each end user with the proposed DSA-HA method.

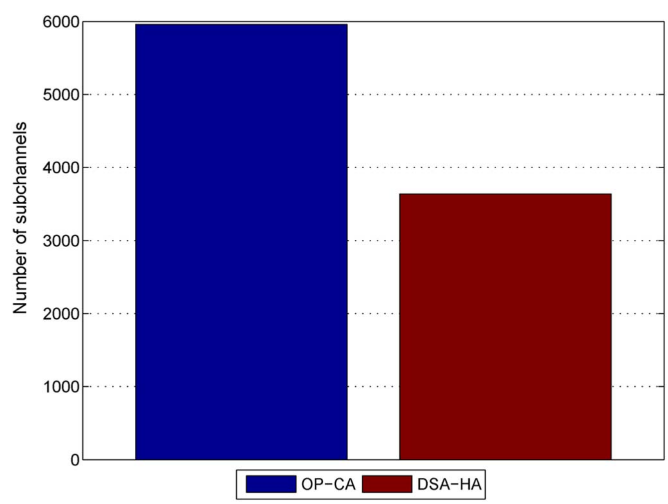


Fig. 5. Number of subchannels used by the MUs that locate inside the femtocell with different schemes.

shows the total number of subchannels would be occupied by the MUs that locate inside the femtocell in the OP-CA method, and the second bar shows the total number of subchannels would be employed by the FAP to serve the MUs in the DSA-HA method. The subtraction of these two bars is the number of subchannels that the macro BS would save in the DSA-HA method compared with the OP-CA method. As shown in Fig. 5, the total number of subchannels occupied by the MUs that locates inside the femtocell in 1000 frames is 5956 in the OP-CA method, and the total number of subchannels would be required by the FAP to serve the MUs in the DSA-HA method is only 3640. Obviously, the DSA-HA method could save 2316 subchannels for the macro BS since the FAP just uses 3640 subchannels. Compared with the OP-CA method, nearly 39% subchannels are saved for the macro BS; thus, the spectrum efficiency of the macro BS is improved in our proposed DSA-HA method.

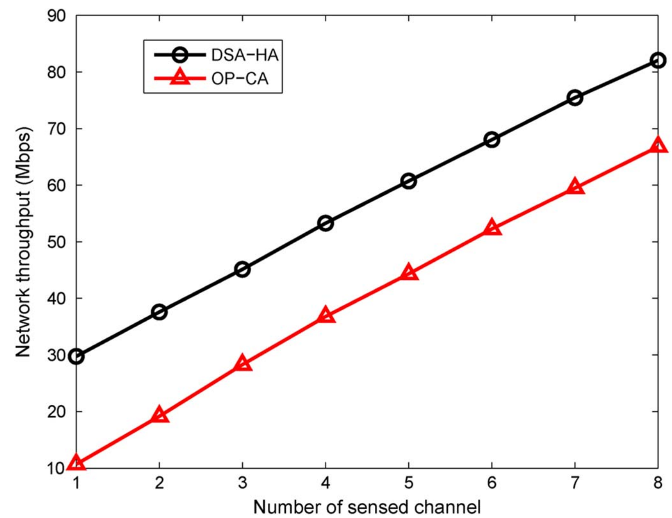


Fig. 6. Network throughput with different number of sensed channels.

In conclusion, the overall performance including network utility, network throughput, and fairness of the DSA-HA method is much better than that of other two methods. Both the wireless service provider and the femtocell benefit from the proposed method.

2) Impact of Sensing Ability: The sensing ability of the cognitive femtocell, which is reflected by the number of sensed subchannels s, is an important factor that affects the overall performance greatly. Here, we analyze the impact of s, whereas the total number of negotiation channels is a constant, where $c = 4$. As shown in Fig. 6, it is obvious that the network throughput increases as s grows because the FAP could allocate more subchannels to the FUs. Meanwhile, the network throughput of the DSA-HA method always larger than that of the OP-CA method. The main reason is that the FAP can obtain more available subchannels in the hybrid access when allowing the qualified MUs to access to the femtocell.

As shown in Fig. 7, the network utilities of both the OP-CA and the DSA-HA methods increase as s grows due to more spectrum resources. In addition, the utility gap between these two schemes decreases with larger s. This is because the utility of the FUs increases slowly when the achievable rate is larger than the target rate. Therefore, it is more likely that the FAP would not serve the MUs if the FAP senses enough available subchannels. However, in a real situation, particularly in busy cellular networks, the idle subchannels obtained by spectrum sensing are few, and the achievable rate of each FU is low most of the time. Thus, the proposed DSA-HA method is more suitable to the femtocell.

3) Impact of the Number of Negotiation Channels: The number of negotiation channels c is also a significant factor in our proposed method. Here, we particularly analyze the impact of c while the number of sensed subchannels is a constant, where $s = 3$ and $s = 5$, respectively. As shown in Fig. 8, for the given $s = 3$ or $s = 5$, with the larger c, the DSA-HA method could achieve the larger network utility. However, since the OP-CA method does not allow any MUs to access to the femtocell, the network utility of the OP-CA method has no

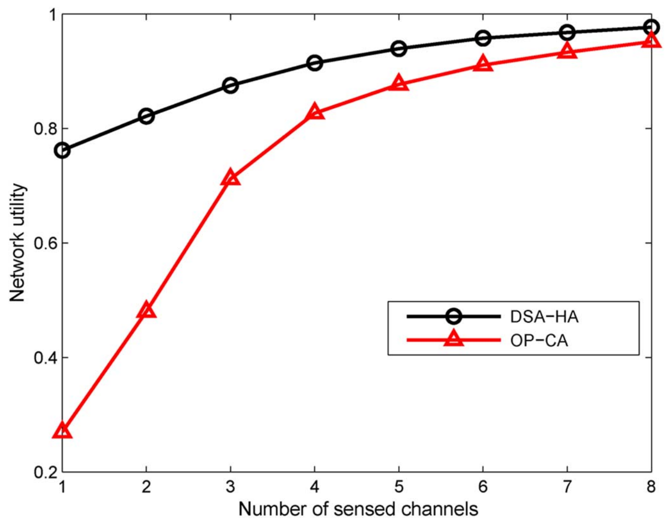


Fig. 7. Network utility with different number of sensed channels.

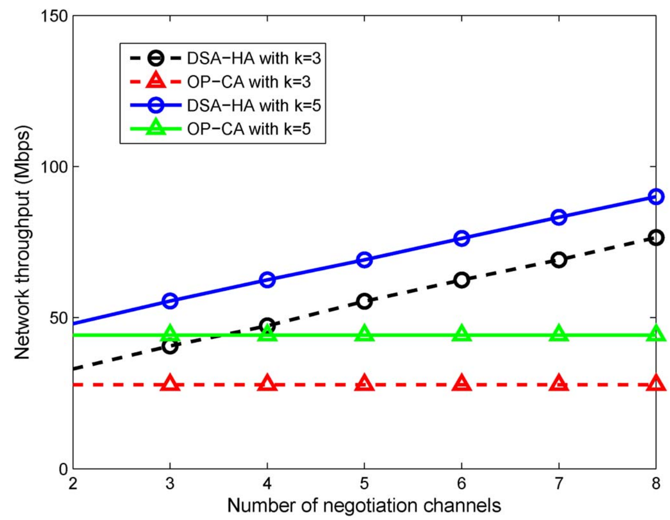


Fig. 9. Network throughput with different number of negotiation channels.

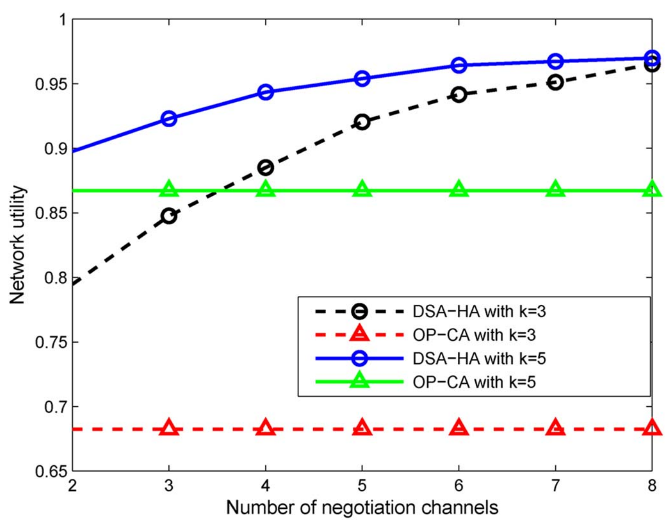


Fig. 8. Network utility with different number of negotiation channels.

relation with c, and it stays constant in the figure. Thus, the gap of network utility between the DSA-HA method and the OP-CA method with the same s becomes larger with more negotiation channels. Moreover, the gap of network utility between the DSA-HA method with $s = 5$ and the OP-CA method with $s = 5$ is always less than the gap of network utility between the DSA-HA methodwith $s = 3$ and the OP-CA method with $s = 3$. We could conclude that whether the FAP would serve the MUs not only depends on the number of negotiation channels but depends on the sensing performance of the FAP as well. The FAP probably does not allow the MU to access even if the number of negotiation channels is considerable since the FAP could obtain enough available subchannels via spectrum sensing.

In Fig. 9, the network throughput of the DSA-HA method keeps increasing when the FAP could obtain more negotiation channels. Meanwhile, the network throughput of the OP-CA method stays constant. Judging from Figs. 8 and 9, compared with the OP-CA method, both the network utility and network throughput can be largely improved in the DSA-HA method.

VII. Conclusion

In this paper, we have proposed a dynamic spectrum allocation method to spur both the wireless operator and the FAP to adopt hybrid access in the cognitive femtocell. In the proposed method, the macro BS saves a portion of spectrum while guaranteeing the performance of the MUs, and the FAP obtains more spectrum resource to improve the performances of the FUs. The corresponding resource allocation of the FAP was formulated as an optimization problem, and the dual decomposition method was employed to derive the optimal solution. Simulation results showed that both the wireless service provider and the femtocell could benefit from the proposed method.

References

[1] T. Zahir *et al.*, "Interference management in femtocells," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 293–311, Jun. 2013.

[2] J. Cullen, "Radioframe presentation," in *Proc. Femtocell Eur.*, London, U.K., Jun. 2008.

[3] J. G. Andrews, H. Claussen, M. Dohler, S. Rangan, and M. C. Reed, "Femtocells: Past, present, and future," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 1033–1046, Apr. 2012.

[4] "Femtocell market status," Informa Telecoms & Media, London, U.K., Femtoforum Whitepaper, 2011.

[5] Y. C. Liang, K. C. Chen, G. Y. Li, and P. Mähönen, "Cognitive radio networking and communications: An overview," *IEEE Trans. Veh. Technol.*, vol. 60, no. 7, pp. 3386–3407, Sep. 2011.

[6] S. Yin, D. W. Chen, Q. Zhang, M. Y. Liu, and S. F. Li, "Mining spectrum usage data: A large-scale spectrum measurement," *IEEE Trans. Mobile Comput.*, vol. 11, no. 6, pp. 1033–1046, Jun. 2012.

[7] T. Jiang, Z. Wang, L. Zhang, D. Qu, and Y.-C. Liang, "Efficient spectrum utilization on TV band for cognitive radio based high speed vehicle network," *IEEE Trans. Wireless Commun.*, vol. 13, no. 10, pp. 5319–5329, Oct. 2014.

[8] L. Zhang, T. Jiang, Y. Zhang, and Y. Cao, "Grade of service of opportunistic spectrum access based cognitive cellular networks," *IEEE Wireless Commun.*, vol. 20, no. 5, pp. 126–133, Oct. 2013.

[9] X. Y. Wang, P.-H. Ho, and K.-C. Chen, "Interference analysis and mitigation for cognitive-empowered femtocells through stochastic dual

control" *IEEE Trans. Wireless Commun.*, vol. 11, no. 6, pp. 2065–2075, Jun. 2012.

[10] S.-Y. Lien, Y.-Y. Lin, and K.-C. Chen, "Cognitive and game-theoretical radio resource management for autonomous femtocells with QoS guarantees," *IEEE Trans. Wireless Commun.*, vol. 10, no. 7, pp. 2196–2206, Jul. 2011.

[11] G. Gur, S. Bayhan, and F. Alagöz, "Congtive femtocell networks: An overlay architecture for localized dynamic spectrum access," *IEEE Wireless Commun. Mag.*, vol. 17, no. 4, pp. 62–70, Aug. 2010.

[12] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell networks: A survey," *IEEE Commun. Mag.*, vol. 46, no. 9, pp. 59–67, Sep. 2008.

[13] G. De La Roche, A. Valcarce, D. López-Pérez, and J. Zhang, "Access control mechanisms for femtocells," *IEEE Commun. Mag.*, vol. 48, no. 1, pp. 33–39, Jan. 2010.

[14] P. Lin, J. Zhang, Y. J. Chen, and Q. Zhang, "Marcro-femto heterogeneous network deployment and management: From business models to technical solutions," *IEEE Wireless Commun. Mag.*, vol. 18, no. 3, pp. 64–70, Jun. 2011.

[15] Y. J. Chen, J. Zhang, and Q. Zhang, "Utility-aware refunding framework for hybrid access femtocell network," *IEEE Trans. Wireless Commun.*, vol. 11, no. 5, pp. 1688–1697, May 2012.

[16] Y. J. Chen, J. Zhang, and Q. Zhang, "Incentive mechanism for hybrid access in femtocell network with traffic uncertainty," in *Proc. IEEE ICC*, Sep. 2013, pp. 6333–6337.

[17] L. Li, C. Q. Xu, and M. X. Tao, "Resource allocation in open access OFDMA femtocell networks," *IEEE Wireless Commun. Lett.*, vol. 1, no. 6, pp. 625–628, Dec. 2012.

[18] J. K. Yin, G. F. Sun, F. Yang, X. Y. Gan, and X. B. Wang, "Incentive mechanism for access permission and spectrum trading in femtocell network," in *Proc. IEEE ICC*, Sep. 2013, pp. 5959–5963.

[19] H. N. Vu and L. B. Le, "Hybrid access design for femtocell networks with dynamic user association and power control," in *Proc. IEEE VTC–Fall*, Sep. 2012, pp. 1–5.

[20] P. Lin, J. Zhang, Q. Zhang, and M. Hamdi, "Enabling the femtocells: A cooperation framework for mobile and fixed-Line operators," *IEEE Trans. Wireless Commun.*, vol. 12, no. 1, pp. 158–167, Jan. 2013.

[21] S. Al-Rubaye, A. Al-Dulaimi, and J. Cosmas, "Cognitive femtocell: Future wireless networks for indoor applications," *IEEE Veh. Technol. Mag.*, vol. 6, no. 1, pp. 44–51, Mar. 2011.

[22] D. L. Hu and S. W. Mao, "On medium grain scalable video streaming over femtocell cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 641–651, Apr. 2012.

[23] A. Attar, V. Krishnamurthy, and O. N. Gharehshiran, "Interference management using cognitive base-stations for UMTS LTE," *IEEE Commun. Mag.*, vol. 49, no. 8, pp. 152–159, Aug. 2011.

[24] O. N. Gharehshiran, A. Attar, and V. Krishnamurthy, "Collaborative subchannel allocation in cognitive LTE femto-cells: A cooperative game-theoretic approach," *IEEE Trans. Commun.*, vol. 61, no. 1, pp. 325–334, Jan. 2013.

[25] S.-M. Cheng, W. C. Ao, F.-M. Tseng, and K.-C. Chen, "Design and analysis of downlink spectrum sharing in two-tier cognitive femto networks," *IEEE Trans. Veh. Technol.*, vol. 61, no. 5, pp. 2194–2207, Jun. 2012.

[26] J. W. Huang and V. K. Krishnamurthy, "Cognitive base stations in LTE/3GPP femtocells: A correlated equilibrium game-theoretic approach," *IEEE Trans. Commun.*, vol. 59, no. 12, pp. 3485–3493, Dec. 2011.

[27] T. Ng and W. Yu, "Joint optimization of relay strategies and resource allocations in cooperative cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 328–339, Feb. 2007.

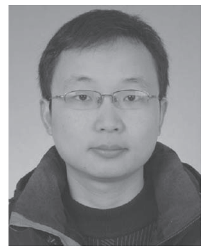
[28] K. W. Choi, E. Hossain, and D. I. Kim, "Downlink subchannel and power allocation in multi-cell OFDMA cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 7, pp. 2259–2271, Jul. 2011.

[29] Y. Cao, T. Jiang, C. G. Wang, and L. Zhang, "CRAC: Cognitive radio assisted cooperation for downlink transmissions in OFDMA-based cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 9, pp. 1614–1622, Oct. 2012.

[30] S. Boyd, L. Xiao, and A. Mutapcic, "Subgradient methods," Stanford Univ., Stanford, CA, USA, Lecture notes of EE392o, Autumn Quart. 2003–2004.

[31] "Guidelines for evaluation of radio transmission technologies for IMT-2000," Int. Telecommun. Union (ITU), Geneva, Switzerland, Recommendation ITU-R M.1225, 1997.

[32] R. Jain, *The Art of Computer Systems Performance Analysis: Techniques for Experimental Design, Measurement, Simulation and Modeling*. New York, NY, USA: Wiley, 1991.



Lei Zhang received the B.S. and M.S. degrees in electrical information and communication engineering from Huazhong Normal University, Wuhan, China, in 2004 and 2009, respectively, and the Ph.D. degree in information and communication engineering from Huazhong University of Science and Technology, Wuhan, in June 2014.

He is currently a Lecturer with Hubei Polytechnic University, Huangshi, China. His research interests include cognitive radio networks, femtocells, and Long-Term Evolution.

Tao Jiang (M'06–SM'10) received the B.S. and M.S. degrees in applied geophysics from China University of Geosciences, Wuhan, China, in 1997 and 2000, respectively, and the Ph.D. degree in information and communication engineering from Huazhong University of Science and Technology, Wuhan, in April 2004.

From August 2004 to December 2007, was with several universities, such as Brunel University London, Uxbridge, U.K.; and the University of Michigan-Dearborn, Dearborn, MI, USA. He is currently a Chair Professor with the School of Electronics Information and Communications, Huazhong University of Science and Technology. He is the author or coauthor of over 200 technical papers in major journals and conferences and six books/chapters in the areas of communications and networks.

Dr. Jiang served or is serving as a Symposium Technical Program Committee member for several major IEEE conferences, including the IEEE Conference on Computer Communications, the IEEE Global Communications Conference (IEEE GLOBECOM), and the IEEE International Conference on Communications. He was invited to serve as the Technical Program Committee Symposium Chair for the 2013 IEEE GLOBECOM and the 2013 IEEE Wireless Communications and Networking Conference. He served or currently serving as an Associate Editor for several technical journals in communications, including the IEEE TRANSACTIONS ON SIGNAL PROCESSING, IEEE COMMUNICATIONS SURVEYS AND TUTORIALS, the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, and the IEEE INTERNET OF THINGS JOURNAL. He received the National Natural Science Foundation of China Distinguished Young Scholars Award.

Kai Luo received the B.Eng. degree from Huazhong University of Science and Technology, Wuhan, China, in 2006 and the Ph.D. degree from Imperial College London, London, U.K., in 2013, under the supervision of Prof. A. Manikas.

In 2013, he joined the Institute of Electronics, Chinese Academy of Sciences, Beijing, China. Since 2014, he has been a Lecturer with the School of Electronics Information and Communications, Huazhong University of Science and Technology, Wuhan. His research interests include array signal processing and radar and multiple-input–multiple-output communications.