IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received June 5, 2018, accepted July 2, 2018, date of publication July 17, 2018, date of current version August 20, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2856627

A Price-Based Optimization Strategy of Power Control and Resource Allocation in Full-Duplex Heterogeneous Macrocell-Femtocell Networks

FANZI ZENG[1], QIAO LI[1], ZHU XIAO[1,2], (Member, IEEE), VINCENT HAVYARIMANA[1,3], AND JING BAI[4], (Member, IEEE)

[1]College of Computer Science and Electronic Engineering, Hunan University, Changsha 410082, China
[2]State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an 710071, China
[3]Department of Applied Sciences, Ecole Normale Supérieure, Bujumbura 6983, Burundi
[4]Key Laboratory of Intelligent Perception and Image Understanding of the Ministry of Education, School of Artificial Intelligence, Xidian University, Xi'an 710071, China

Corresponding author: Zhu Xiao (zhxiao@hnu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grants 61502162, Grant 61702175, Grant 61772184, and Grant 61772401, in part by the Fund of State Key Laboratory of Geoinformation Engineering under Grant SKLGIE2016-M-4-2, in part by the Hunan Natural Science Foundation of China under Grant 2018JJ2059, and in part by the Open Fund of State Key Laboratory of Integrated Services Networks under Grant ISN17-14.

ABSTRACT In this paper, we investigate the problem of resource allocation and cross-tier interference mitigation in full-duplex orthogonal frequency division multiple access -based heterogeneous networks consisting of macrocell and underlaying femtocells. First, we design a price mechanism to maximize the utility of both macro base station and femtocell base stations under finite interference constraint. We then propose a triple optimization strategy for power control, subcarrier allocation, and price regulation to mitigate the cross-tier interference. For the macrocell, the barrier method is proposed to implement the price-based resource allocation and ensure the utility maximization. For the femtocells, we propose a Lagrangian optimization algorithm based on KKT conditions to solve the power control and subcarrier allocation, in which a closed-form solution is derived to tackle the dual multiplier problem. Simulation results demonstrate that the resource allocation algorithm can effectively neutralize the cross-tier interference and maximize the utility of the heterogeneous macrocell-femtocell networks.

INDEX TERMS Heterogeneous networks, OFDMA, full-duplex communications, resource allocation, price mechanism.

I. INTRODUCTION

With the development of communication technology, next-generation wireless communication systems are facing unprecedented challenges due to ever-increasing demand for high data traffic and wireless service from rapidly growing global subscribers [1]. To address this problem, heterogeneous small cell networks are regarded as one of the most promising ways to improve the overall capacity and network performance [2]. Compared with macrocell-centric networks, small cells including femtocell base stations (FBSs) and picocell base stations (PBSs) can significantly increase the system capacity and enhance the coverage of networks. In the heterogeneous small cell networks, such as the macrocell-femtocell HetNets, FBSs are set up individually by users and their deployment may be unknown to the macrocell base stations (MBS), thus, the inter-cell interference becomes a major issue [2]. In [3], Zhu *et al.* proposed a novel framework for multi-tier HetNets to characterize the coverage performance and energy efficiency. In particular, when the small cells share the same spectrum with the macrocell, it will lead to cross-tier interference. Moreover, small cells share the spectrum resources and hence improve the spectrum utilization. However, this causes inter-tier interference between various small cells. Both the inter-tier and cross-tier interference can reduce the network performance. Therefore, resource allocation plays a very important role in the interference management.

A. RELATED WORKS

In recent years, the full-duplex (FD) communication technology has been considered as an up-and-coming solution to address the interference mitigation and resource allocation in the HetNets. For FD communications, the users can be allowed to simultaneously transmit and receive on the same channel, and it can theoretically double system throughput [4] compared with half-duplex (HD) communications, provide flexible access mode [5], feedback delay reduction [6], end to end delay reduction [7], guarantee the physical layer secrecy and MAC layer secrecy [8] and increase the utility of network protocols [9]. However, the self-interference (SI) in FD system can easily saturate the wireless link of the receiver. Thank to the development of analog and digital signal processing, SI can be well controlled to the level under −110dB [10], which makes the FD communications become feasible. In addition, there is interference on the same channel in the FD communication system. In order to fully excavate the potential of FD communications, there is a severe need for reasonable resource allocation method. In [11], Nam *et al.* proposed an iterative algorithm of power and subcarrier allocation optimization to maximize the overall data rate of the system. The local Pareto optimal value can be obtained while the shortage is without considering the interference of SI and inter-node. In [12], Nam *et al.* proposed a resource allocation approach to maximize the sum-rate in FD-OFDMA network system. However, the interference from the inter-node has not been considered. In Nam *et al.* [13] and Xiao *et al.* [14] proposed a joint optimization algorithm of user selection, power and subcarrier allocation to maximize the system throughput, which takes the advantages of SI and inter-node interference into account. However, these resource allocation researches are only based on single-cell FD-OFDMA networks.

Compared with the conventional high-power macrocell, the small cells have the characteristics of low power and low-cost, and the interference to macrocell will be relatively small. In [15], Xiao *et al.* developed a cell status prediction algorithm to obtain the optimal prediction outcome of the next status for the small cells. Moreover, because the SI of FD can be effectively controlled, the small cells networks with FD configuration have attracted more attentions. However, one of the most important problems is the existence of interference in macro-femto HetNets. In [16], Liu *et al.* considered the strategy of hybrid spectrum access, and studied the cross-tier interference caused by the uplink transmission of the femtocell users equipment (FUE) to the macrocell. In [17], Al-Kadri *et al.* derived the closed expression of the interception probability, the spatial density and SI cancellation capability, which are explicitly described based on the enhanced Inter-Cell Interference Coordination (eICIC) coordination. In [18], Han *et al.* proposed an interference cancellation FD assistance strategy and studied a user equipment between the cross-tier interference suppression by MBS to maximize the link data rate. In [19], Goyal *et al.* studied a multi-cell networks system, in which the base station (BS) was equipped with FD device under a complex interference environments. In [20], Atzeni and Kountouris proposed a FD framework which aimed at shedding light on the system-level gains of FD mode with respect to HD mode in terms of network throughput and provided design guidelines for the practical implementation of FD technology in large small-cell networks.

Recently, different aspects of price and economics of HetNets are investigated. In [21], Rahmati *et al.* investigated a price-based power allocation scheme for UEs using self-backhauled small cell access points (SAP). They employed a Stackelberg game to investigate the joint utility maximization problem of the SAP and UEs. In [22], Zeng and Zhong proposed a novel utility-based cooperative spectrum leasing scheme to maximize the throughput of secondary user (SU), while the purpose of primary user (PU) was to save energy and charge SU for spectrum leasing. Numerical results showed the utility of the PU and the SU can be improved.

Network resources, such as transmission power and subcarrier, must be appropriately allocated among different users to maximize network performance. In [23], Liu *et al.* proposed a power allocation scheme for two-tier macrocell-femtocell networks to maximize the user utility under the constraint of QoS. In [24], Xiao *et al.* aimed to maximize the throughput of the femtocell networks while avoiding severe inter-tier interference to the macrocell through designing joint subchannel assignment and power allocation in an OFDMA femtocell network. In [25], Khamidehi and Sabbaghian proposed a low-cost sub-optimal algorithm to implement power and subcarrier allocation in different scenarios for the uplink of femtocell networks. In [26], Liu *et al.* proposed novel transformations of the constraints and obtained constraints in the format of worst-case value-at-risk. In [27], Liu *et al.* proposed a noncooperative game framework to handle the different QoS of femtocell networks to improve security of a macrocell user. In [28], Li *et al.* proposed a power allocation scheme to maximize system capacity under pre-determined co-channel interference to primary user network. However, the above research on femtocells is based on the HD mode.

In summary, FD technology has become a new communication paradigm, which provides an effective way to enhance the capacity of wireless communication system. However, compared with the previous research on cross-tier interference, since the former BSs all adopt the HD mode, only the interference of FUE to macrocell users equipment (MUE) is considered. In the FD mode, for the macrocell, the MUE will be interfered by both the FUE and the FBS [29]. Therefore, how to deliberately cope with these two types of interference and maintain it at a reasonable level is still a challenging task.

B. CONTRIBUTIONS

In this paper, we focus on investigating resource allocation for FD-OFDMA communications in two-tier macro-femto HetNets, in which macrocell and femtocell share spectrum based on OFDMA technology, FBS has FD devices, MBS and its users are traditional HD modes. As a result of the introduction of FD, macrocell is subjected to two parts of cross-tier interference, both from users and FBS in femtocell. In order to mitigate cross-tier interference in FD-OFDMA HetNets, we develop a framework for joint subcarrier assignment, power allocation and price regulation to maximize the utility of both macrocell and femtocell under the interference constrain for the macrocell. The main contributions are summarized as follows:

- We propose a triple optimization strategy to formulate the price, power and subcarrier allocation with the purpose of maximizing the utility of both macrocell and femtocell. Because of the limited transmission power in the femtocell, reasonable power control is required, and the interference received by macrocell is also limited, hence the maximum interference threshold is given as a constraint. Moreover, the uniqueness of subcarrier allocation determines that the original optimization problem will be an integer program problem, which makes the solution of the problem complicated.
- For the utility maximization problem, we propose a joint triple optimization algorithm of power control, subcarrier allocation and price regulation to solve the cross-tier interference of femtocell to macrocell. Within the macrocell, we use the barrier method to handle the price-based resource allocation and ensure the utility maximization. Within the femtocell, we propose a Lagrangian optimization algorithm based on KKT conditions to solve the power control problem. For subcarriers, it is considered to assign subcarriers to the user pair that maximizes the femtocell utility. The simulation results show that the resource allocation algorithm can effectively suppress cross-tier interference and maximize the utility of macrocell and femtocell.

The remainder of this paper is organized as follows. The system model is described in Section II. The utility problems are described in Section III. The triple resource allocation optimization strategy is presented in Section IV. Section V gives the numerical results of resource allocation and performance evaluation. Section VI concludes the paper.

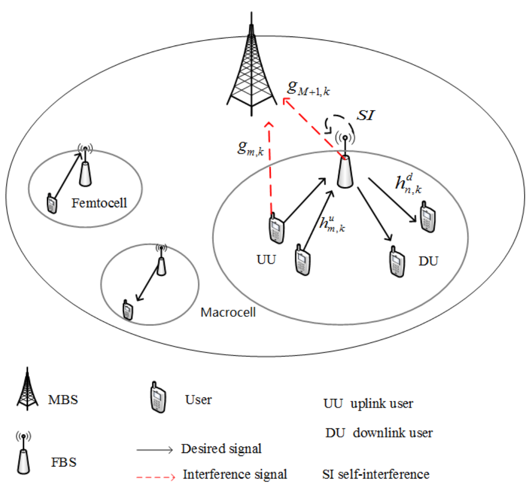


FIGURE 1. System mode for an FD OFDMA HetNets.

II. SYSTEM MODEL

We consider the FD communications in macro-femto HetNets, which is shown in Fig. 1. In the HetNets, multiple femtocells are deployed within the coverage of the macrocell and the OFDMA technology is used. The spectrum band is partitioned into K orthogonal subchannels. We assume that each femtocell provides wireless service for $\mathcal{M}$ uplink users (UUs) and $\mathcal{N}$ downlink users (DUs). For the sake of convenience, we assume the same number of UU and DU, i.e., $|\mathcal{M}| = |\mathcal{N}| = M$, it can guarantee one-to-one relationship between the users. In [12], without loss of generality, the authors assumed that the number of uplink nodes is equal to the number of downlink nodes. This assumption was given in the simulation experiment [24]. There is a broad consensus that configuring the FD in macrocell is not a good candidate because of the larger MBS power consumption and the large coverage requirements [30]. Therefore, in this study, it is assumed that only the FBS is equipped with FD equipment, all UUs and DUs adopt HD mode in order to ensure lower hardware complexity. The macrocell works in the frequency division duplex (FDD) multiple access mode, i.e., the MBS assigns two channels for its associated MUE for uplink and downlink transmissions, respectively.

Due to the random deployment of femtocells, the interference consists of three parts: cross-tier interference, intercell interference and intra-cell interference. Besides, the SI is added when the FBSs are equipped with FD device. Because of the current advancement from digital and analog circuits, SI can be well suppressed below the noise power level. We assume that femtocell adopts sparse deployment and inter-cell interference can be ignored. In other words, FBSs and FUEs in different cells no longer interfere with each other.

The cross-tier interference between macrocell and femtocell degrades network performance and reduces the quality of service (QoS) of MUE. In order to enable MBS to protect its MUE, we propose the interference price mechanism to cope with the cross-tier interference management of femtocell to macrocell. Due to the presence of the FD, the femtocell interference on the macrocell increases in two parts. Therefore, the charge for the interference price comes from the two parts, which allows MBS to better protect MUE under the interference power constraint. The main parameters are introduced in Table 1.

III. PROBLEM FORMULATION

A. MACROCELL PROBLEM FORMULATION

In this subsection, we study the interference management problem for macrocell. Let I_{th} denote the maximum interference threshold on sub-channel k. The aggregate interference from the user and FBS should not be lager than I_{th}. Unlike the study of cognitive radio networks, we assume that the maximum interference power constraint is applied to MBS, and protect users by collecting fees from femtocell. Then we obtain:

$$\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}(I_{m,k} + I_{M+1,k}) \leq I_{th}, \tag{1}$$

TABLE 1. Main parameters and variables.

Notation	Description
I_{th}	Maximum interference threshold
$I_{m,k}$	Interference from the FUE in the femtocell to the macrocell
$I_{M+1,k}$	Interference from the FBS in the femtocell to the macrocell
g_k	Interference channel gain vector from the considered femtocell to the MBS on sub-channel k
$g_{m,k}$	Interference channel gains associated with UU m
$g_{n,k}$	Interference channel gains associated with the FBS
P_{FUE}	Maximum available transmit powers at FUE
P_{FBS}	Maximum available transmit powers at FBS
$p^u_{m,k}$	Transmit powers of UU m on sub-channel k
$p^d_{n,k}$	Transmit powers of FBS for DU m on sub-channel k
μ_k	Interference price
$h^u_{m,k}$	Channel gains of uplink
$h^d_{n,k}$	Channel gains of downlink
σ^2_{SI}	Self-interference
σ^2_0	Power of the additive Gaussian noise
$x_{m,n,k}$	Binary indictor of sub-channel assignment

where $I_{m,k} = p^u_{m,k} g_{m,k}$ represents the interference from the FUE in the femtocell to the macrocell, and $I_{M+1,k} = p^d_{n,k} g_{n,k}$ represents the interference from the FBS in the femtocell to the macrocell, respectively. We define $p^u_{m,k}$ and $p^d_{n,k}$ as the transmission power of UU m and the FBS for DU n on sub-channel k, respectively. $m \in \{1, 2, \cdots, M\}$, $n \in \{1, 2, \cdots, N\}$ and $k \in \{1, 2, \cdots, K\}$ are the indices of UUs, DUs and subcarrier, respectively. $g_{m,k}$ and $g_{M+1,k}$ are the interference channel gains associated with UU m and the FBS, respectively. $g_k \triangleq [g_{1,k}, \cdots, g_{m,k}, g_{M+1,k}]$ should be the interference channel gain vector from the considered femtocell to the MBS on sub-channel k.

Therefore, for the macrocell, in order to protect the QoS of its own subscribers, interference costs are charged from the femtocells. The MBS's revenue comes mainly from the interference of FBS and FUE, which can be expressed by:

$$U_{mcell} = \sum_{k=1}^{K} \sum_{m=1}^{M} \sum_{n=1}^{N} \mu_k \left(I_{m,k} + I_{M+1,k} \right), \tag{2}$$

where μ_k is the corresponding interference price factor, in practice, the MBS can broadcast the interference price to the FBS and FUE. Given the condition of maximum tolerable interference constraint, MBS must satisfy the best interference price μ_k if we need to maximize the utility function. Therefore, the best value by solving the optimization problem can be given by:

$$\max U_{mcell}, \tag{3}$$

$$s.t. \sum_{k=1}^{K} \sum_{m=1}^{M} \sum_{n=1}^{N} \left(I_{m,k} + I_{M+1,k} \right) \le I_{th}, \tag{4a}$$

$$\mu_k \ge 0. \tag{4b}$$

B. FEMTOCELL PROBLEM FORMULATION

In this subsection, we consider the femtocells configured with FD. When the interference price provided by MBS is given, each femtocell needs to reasonably allocate subcarrier and adjust transmission power to maximize its utility. Define P_{FUE} and P_{FBS} as the maximum transmission powers of UU m and the FBS. Let $R^u_{m,k}$ and $R^d_{n,k}$ denote the data rate of the uplink and downlink in the femtocell, respectively. $r^u_{m,k}$ and $r^d_{n,k}$ are used to describe the signal to interference plus noise ratio (SINR), respectively. If the sub-channel k is assigned to UU m and DU n, the SINR at the FBS and DU n can be obtained as follows:

$$r^u_{m,k} = \frac{p^u_{m,k} h^u_{m,k}}{\sigma^2_{SI} + \sigma^2_0}, \tag{5}$$

$$r^d_{n,k} = \frac{p^d_{n,k} h^d_{n,k}}{\sigma^2_0}, \tag{6}$$

where $h^u_{m,k}$ is the channel gain between the UU m and the FBS in channel k, $h^d_{n,k}$ is the channel gain between the FBS and the nth DU in sub-channel k. The residual self-interference (RSI) can increase the noise power by σ^2_{SI} regardless of user's transmission power. N_0 denotes the noise power spectral density.

Due to the existence of path loss, the channel power gain attenuates with the increase of the distance between femtocell. In addition, the penetration loss is nontrivial since femtocells are always deployed indoor. Therefore, we assume that femtocell is deployed outdoors sparsely, the inter-tier interference between different femtocells can be ignored [31]. Based on the above SINR studies, the data rates of uplink and downlink in the femtocell are given by:

$$R^u_{m,k} = \log_2(1 + r^u_{m,k}), \tag{7}$$

$$R^d_{n,k} = \log_2(1 + r^d_{n,k}). \tag{8}$$

For each femtocell, the utility function contains two parts of cost and profit.The main source of its profit is the increase of data rate, which needs to increase its transmission power. However, the increase of transmission power brings more cross-tier interference, which makes the femtocell need to pay more price. The trade-off between profit and cost is mainly dependent on power, hence a reasonable power allocation strategy is needed to maximize their own utility. In addition, it will be affected by the subcarrier allocation. Mathematically, the utility function of femtocells can be formulated as:

$$U_{fcell} = x_{m,n,k} \left(R^u_{m,k} + R^d_{n,k} \right) - \mu_k \left(I_{m,k} + I_{M+1,k} \right). \tag{9}$$

We use binary variables $x_{m,n,k} \in \{0, 1\}$ as the channel assignment indication. When $x_{m,n,k} = 1$, it indicates that channel k is allocated to the UU m and DU n user pair in the femtocell. The goal of the femtocell is to maximize its own utility under power and subcarrier constraints, which can be formulated as follows:

$$\text{maximize } U_{fcell}, \tag{10}$$

$$s.t. \sum_{k=1}^{K} p^u_{m,k} \le P_{FUE}, \quad \forall m, \tag{11a}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{K} p_{n,k}^{d} \leq P_{FBS}, \tag{11b}$$

$$p_{m,k}^{u}, p_{n,k}^{d} \geq 0, \tag{11c}$$

$$\sum_{m=1}^{M}\sum_{n=1}^{N} x_{m,n,k} \leq 1, \quad \forall k, \tag{11d}$$

$$x_{m,n,k} \in \{0,1\}. \tag{11e}$$

Constraints (11a), (11b) and (11c) are used to guarantee the effectiveness of power allocation for the UUs and FBS. The constraints (11d) and (11e) ensure that each sub-channel is assigned to a user pair in the femtocell.

IV. A TRIPLE RESOURCE ALLOCATION OPTIMIZATION STRATEGY OF POWER CONTROL AND SUBCARRIER ALLOCATION

In this section, we decompose the triple resource allocation problem into the price management of the macrocell and the power control and subcarrier allocation of the femtocell. The utility maximization of femtocells is convex, hence the optimal power control can be obtained by solving the convex optimization problem. For the macrocell, the objective function is nonlinear, and it is difficult to achieve a closed solution. To solve this, we consider the combination of interior point method and Newton method to obatin the optimal price.

A. RESOURCE ALLOCATION PROBLEM OF FEMTOCELL

For a given price μ_k, the problem (9) becomes a subcarrier allocation problem. In principle, the subcarrier allocation is exclusive to a user pair. Therefore, the problem (9) becomes an integer optimization problem. To solve this, we first relax the constraints (4a) (4b) and allow multiple modes to share a subcarrier. The binary variable constraint (11e) is replaced with

$$x_{m,n,k} \geq 0, \quad \forall m \in M,\ n \in N,\ k \in K. \tag{12}$$

We have $x_{m,n,k} \in [0, 1]$. The objective function of the femtocell becomes a convex function with transmission power. Therefore, the objective function transforms into a convex optimization problem, which can be solved by using KKT conditions.

Lemma 1: Given the interference price μ_k, the optimal solution of FBS problem is given by

$$p_{m,k}^{u} = \frac{1}{\mu_k g_{m,k} + \xi_m} - \frac{\sigma_{SI}^2 + \sigma_0^2}{h_{m,k}^{u}}, \tag{13}$$

$$p_{n,k}^{d} = \frac{1}{\mu_k g_{M+1,k} + \psi} - \frac{\sigma_0^2}{h_{n,k}^{d}}. \tag{14}$$

The dual variable ξ_m, ψ can be iteratively obtained through the gradient descent search method [32].

$$\begin{cases} \xi_m^{[t+1]} = \left[\xi_m^{[t]} + \tau\left(\sum\limits_{k=1}^{K} p_{m,k}^{u} - P_{FUE}\right)\right]^{+}, \quad \forall m \\ \psi^{[t+1]} = \left[\psi^{[t]} + \tau\left(\sum\limits_{n=1}^{N}\sum\limits_{k=1}^{K} p_{n,k}^{d} - P_{FBS}\right)\right]^{+}, \end{cases} \tag{15}$$

where $[.]^{+} = \max(0, .)$, τ is the step size for each iteration, t is the index of iteration for the dual multiplier update. Therefore, each P_{FUE} and P_{FBS} can locally update the dual multiplier for link k.

Based on the expressions in (13) and (14), the power at iteration t can be updated as

$$p_{m,k}^{u[t+1]} = \frac{1}{\mu_k g_{m,k} + \xi_m^{[t]}} - \frac{\sigma_{SI}^2 + \sigma_0^2}{h_{m,k}^{u}}, \tag{16}$$

$$p_{n,k}^{d[t+1]} = \frac{1}{\mu_k g_{M+1,k} + \psi^{[t]}} - \frac{\sigma_0^2}{h_{n,k}^{d}}. \tag{17}$$

In (16), (17), ξ_m and ψ can be locally updated by the FBS or FUE on link k.

Proof of power solving see Appendix.

B. RESOURCE ALLOCATION PROBLEM OF MACROCELL

In this subsection, we derive the power solution under the given ξ_m and ψ. The optimal price μ that can be obtained by taking the derived power (13) and (14) into the corresponding macrocell utility function (3), which can be given by:

$$\text{maximize } U_{mcell} = \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\left\{2 - \frac{\xi_m}{\mu_k g_{m,k} + \xi_m} - \frac{(\sigma_{SI}^2 + \sigma_0^2)\,\mu_k g_{m,k}}{h_{m,k}^{u}} - \frac{\psi}{\mu_k g_{M+1,k} + \psi} - \frac{\sigma_0^2 \mu_k g_{M+1,k}}{h_{n,k}^{d}}\right\}, \tag{18}$$

$$s.t. \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\left\{\left[\frac{g_{m,k}}{\mu_k g_{m,k} + \xi_m} - \frac{(\sigma_{SI}^2 + \sigma_0^2)\, g_{m,k}}{h_{m,k}^{u}}\right] + \left[\frac{g_{M+1,k}}{\mu_k g_{M+1,k} + \psi} - \frac{\sigma_0^2 g_{M+1,k}}{h_{n,k}^{d}}\right]\right\} \leq I_{\text{th}}. \tag{19}$$

We can assume that the tolerable interference constraints are large enough. For macrocell, the best problem can be expressed as:

$$\text{minimize } U_{mcell} = \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\left\{\frac{\xi_m}{\mu_k g_{m,k} + \xi_m} + \frac{(\sigma_{SI}^2 + \sigma_0^2)\,\mu_k g_{m,k}}{h_{m,k}^{u}} + \frac{\psi}{\mu_k g_{M+1,k} + \psi} + \frac{\sigma_0^2 \mu_k g_{M+1,k}}{h_{n,k}^{d}}\right\}, \tag{20}$$

$$s.t. \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\left\{\left[\frac{g_{m,k}}{\mu_k g_{m,k} + \xi_m} - \frac{(\sigma_{SI}^2 + \sigma_0^2)\, g_{m,k}}{h_{m,k}^{u}}\right] + \left[\frac{g_{M+1,k}}{\mu_k g_{M+1,k} + \psi} - \frac{\sigma_0^2 g_{M+1,k}}{h_{n,k}^{d}}\right]\right\} \leq I_{\text{th}}. \tag{21}$$

Algorithm 1 Barrier Method

Require: Given a strict initial point μ, $s := s^{(0)} > 0$, $u > 1$, $\varepsilon > 0$.
1: Repeat:
2: Center point steps, calculate $\mu^*(s)$ by minimizing $sf_0(\mu) + \phi(\mu)$, begins at the point μ.
3: For $\forall m, n, k$,calculate $p^{u*}_{m,k}, p^{d*}_{n,k}$ according to (16) (17).
4: Update: $\mu = \mu^*(s)$.
5: Stop: if $1/s < \varepsilon$.
6: Increase s: $s = us$.

It can be seen that the problem of macrocell is a convex optimization problem, and there will be an optimal price μ^*. However, for the objective function (20), it is a nonlinear function of μ. The objective function and the constraint conditions for the price are convex, we propose to use the interior point method to solve the optimization problem. The objective function with inequality constraints is transformed into an unconstrained objective function. The method of interior point is described in Algorithm 1. We use (20) and (21) to transform the constrained objective function into an unconstrained condition as follows:

$$\text{minimize } sf_0(\mu) + \phi(\mu), \tag{22}$$

$$f_0(\mu) = \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\left\{\frac{\xi_m}{\mu_k g_{m,k} + \xi_m} + \frac{(\sigma_{SI}^2 + \sigma_0^2)\mu_k g_{m,k}}{h^u_{m,k}} + \frac{\psi}{\mu_k g_{M+1,k} + \psi} + \frac{\sigma_0^2 \mu_k g_{M+1,k}}{h^d_{n,k}}\right\}, \tag{23}$$

$$\phi(\mu) = -\log(-f_1(\mu)) = -\log\left(I - \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\left(\frac{g_{m,k}}{\mu_k g_{m,k} + \xi_m} + \frac{g_{M+1,k}}{\mu_k g_{M+1,k} + \psi}\right)\right), \tag{24}$$

$$I = I_{th} + \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\left(\frac{\sigma_0^2 g_{M+1,k}}{h^d_{n,k}} + \frac{(\sigma_{SI}^2 + \sigma_0^2) g_{m,k}}{h^u_{m,k}}\right). \tag{25}$$

We obtain the optimal solution by using the Newton's method [33] after transforming the objective function into an unconstraint function. In Newton's algorithm, we use backtracking linear search to determine the search step size. Given s, we can get a unique price value. By gradually changing the s value, we can get a series of price set $\mu = \{\mu_1, \mu_2, \cdots, \mu_k\}$.

The calculation of the interior point method is composed of inner and outer iterations, and the outer layer updates s: $s = us$, the inner layer uses Newton's method to solve the solution $sf_0(\mu) + \phi(\mu)$. With the increase of u value, the total amount of calculations (Newton's iterations) do not decrease significantly after a certain period of decline. The choice of the value of u is a trade-off between the number of inner iterations and outer iterations. When u is larger, the number of outer iterations decreases and the number of inner iterations increases, u value is smaller on the contrary. The general value of u between 10 to 20 is more appropriate.

When the price and power allocation are completed, the problem of subcarrier allocation becomes a $0-1$ solution, For subcarrier allocation, we consider assigning it to the user pairs that can ensure the maximized femtocell utility U^*_{fell} :

$$x^*_{m,n,k} = \begin{cases} 1, & \text{if } (m,n) = \arg\max U^*_{fell} \\ 0, & \textit{otherwise}. \end{cases} \tag{26}$$

We propose the price-based resource allocation strategy as shown in Algorithm 2, by which we first obtain fixed initial value of the dual multiplier, and then the best price allocation is determined by solving (20) and (21). The power allocation for fixed price allocation is determined by solving (16) and (17), the subcarrier assignment for fixed power allocation, the process is repeated until the specified Lagrange multiplier convergence condition is satisfied.

Algorithm 2 Joint Subcarrier Assignment, Power Control and Price Allocation

1: Initialize:
2: $t = 0$, $\xi^{[t]}_m \geq 0$, for $\forall m$, $\psi^{[t]} \geq 0$, and the tolerance $\delta \geq 0$.
3: Repeat:
4: Step 1: For $\forall m, n, k$,calculate μ^*_k by solving Algorithm 1.
5: Step 2: For $\forall m, n, k$,calculate $p^{u*}_{m,k}, p^{d*}_{n,k}$ according to (16) (17).
6: Step 3: For $\forall k$, calculate $x^*_{m,n,k}$ according to (26).
7: Step 4: Update $\xi^{[t+1]}_m$, $\psi^{[t+1]}$ according to (15).
8: Step 5: $t = t + 1$.
9: Step 6: Until $\left\|[\xi^{[t]}; \psi^{[t]}] - [\xi^{[t-1]}; \psi^{[t-1]}]\right\|_2 \leq \delta$.

V. SIMULATION RESULTS

In this section, we eveluate the performance of the joint resource allocation of power, price and subcarrier in the macro-femto HetNets. As shown in Fig. 1, multiple femtocells are deployed within the coverage of the macrocell. In the simulations, we assume that the MBS has a coverage radius of 500 meters. In each femtocell, there are 10 UUs and 10 DUs, and all the users are randomly distributed in the two-tier macro-femto HetNets. We consider the total bandwidth of 4 MHz, which is divided by 160 channels. The noise power spectral density $N_0 = -173 dBm/Hz$, the maximum interference threshold $I_{th} = 7.5 \times 10^{-14} W$ (−101.2dB). We set the transmission power of the MBS to $35dBm$, the transmission power of MUE varies from $10dBm$ to $30dBm$, depending on the distance from MUE to MBS. The power budget of an FBS and an FUE is set to 30*dBm* and 25*dBm*. We assume that the uplink channel, downlink channel and cross-tier interference channel all obey Rayleigh fading channel.

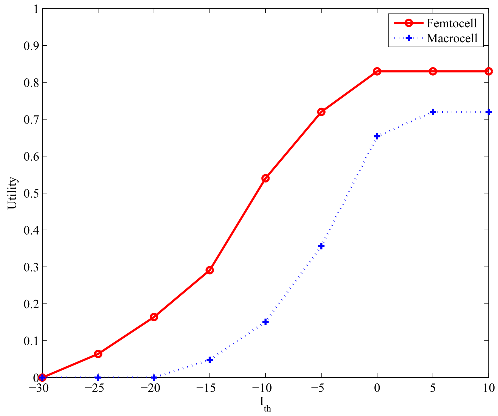


FIGURE 2. **Utility vs I_{th} under Macrocell and Femtocell.**

Fig. 2 shows the relationship between utility and the maximum interference constraint I_{th} under different cells. As I_{th} increases, the utility of macrocell and femtocells increases first and then reaches a steady level. The reason is that, first, MBS will give a larger initial price to femtocells, with the increase of I_{th}, the price will gradually become lower, and FBS will increase the transmission power so that the MBS's utility will eventually reach a stable level. For FBS, when I_{th} is large enough and the price fluctuation has no impact on its utility. At the same I_{th} value, femtocell's utility is higher than that of macrocell. Since the price adopted is uniform, macrocell can not impose different price to femtocells according to different channel gain, the utility of femtocell is relatively high.

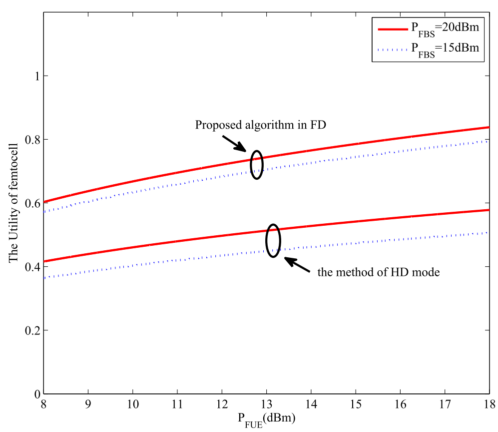


FIGURE 3. **The utility of femtocell vs P_{FUE}.**

Fig. 3 presents the relationship between the utility of femtocell and P_{FUE} under different P_{FBS}. It can be seen that the femtocell utility increases with the increase of P_{FBS} and P_{FUE}. The larger the P_{FBS}, the larger the corresponding femtocell utility function in the same P_{FUE}.

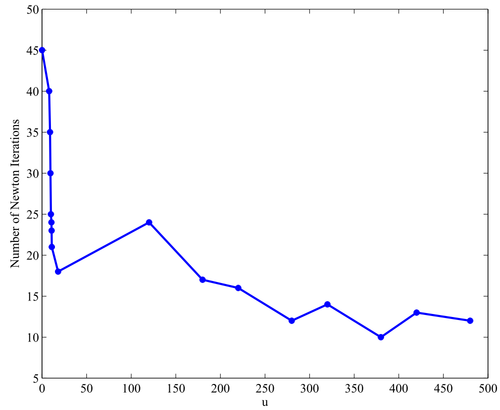


FIGURE 4. **Weighing the selection parameter *u*.**

Fig. 4 presents the changes of parameter u with the total iteration numbers of Newton steps. It can be seen that the curve in Fig. 4 exhibits a downward trend, however, it does not change monotonously. It indicates that there is a trade-off between the external iteration and the internal iteration. The total numbers of Newton steps will not change too much when the value of the u is greater than 120. As the value of u increases to over 280, the change of total iteration numbers tends to be slow. According to [34], the value of u is suggested from 3 to 100, since the it would not improve the performance with lager value of u.

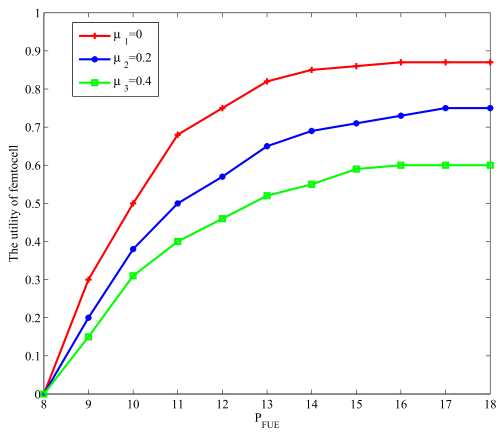


FIGURE 5. **The utility of femtocell vs P_{FUE} under different price μ.**

Fig. 5 shows the relationship between utility of femtocell, maximum interference power constraint and price. The utility of femtocell increases with the increasing of P_{FUE}. Moreover, the utility of femtocell eventually tends to achieve a stable level due to the price charged by macrocell. For femtocell, we can see that femtocell has the maximum utility when the interference price $\mu = 0$. When P_{FUE} is fixed, the utility function decreases as the price increases, namely, the larger μ, the smaller the utility.

Fig. 6 presents the performance of the FD mode. In Fig. 6, we study the relationship between utility of femtocell and number of FBS under different duplex modes. The proposed FD mode can achieve considerable gain when comparing

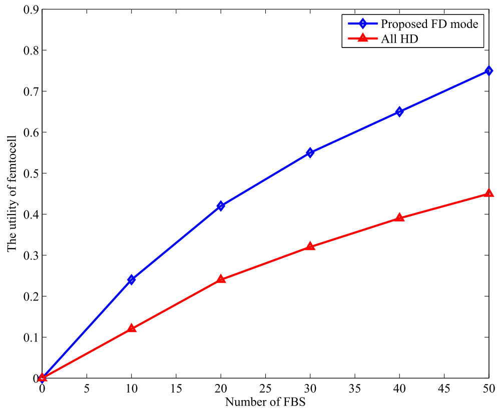


FIGURE 6. The utility of femtocell vs the number of FBS under different duplex modes.

with HD. This is because the power of each FBS and FUE is set to a proper value that not only improves the utility of femtocell but also mitigates cross-tier interference. It can be observed that the FD transmission can improve the spectrum utilization. In addition, the proposed FD transmission mode is more practical than HD transmission.

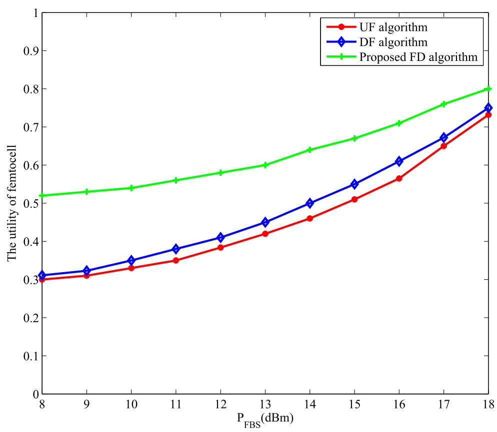


FIGURE 7. The utility of the femtocell vs P_{FBS} when $P_{FUE} = 18dBm$.

Fig. 7 illustrates the varying of utility of femtocell under various transmission power P_{FBS} when $P_{FUE} = 18dBm$. The proposed FD model is compared with the uplink-first (UF) and downlink-first (DF) algorithms [12]. The UF algorithm maximizes the uplink throughput and then calculates the downlink throughput. It is just the opposite of the UF algorithm in the DF algorithm. However, both the UF algorithm and the DF algorithm have not taken the SI into account. As shown in Fig. 7, the proposed FD algorithm outperforms the UF and DF algorithms. In overall, our proposed FD model algorithm takes into account the existence of SI, while the reference algorithms do not consider the existence of SI. Moreover, we propose the FD algorithm to maximize the resource allocation of the system by combining the uplink and downlink, which can maximize the utilization during the resource allocation.

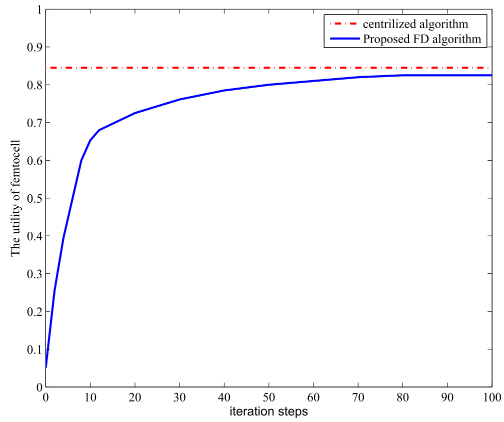


FIGURE 8. Convergence process of proposed FD algorithm.

Fig. 8 shows the numbers of iterations of the proposed FD algorithm based algorithm 2. From the figure, the gap between the FD algorithm and the centralized algorithm is narrow, which means the effectiveness of the proposed FD algorithm is equivalent to the centralized algorithm in terms of the femtocell utility. Furthermore, a significant decrease in femtocell utility gap between the centralized algorithm and the proposed FD algorithm. Thus, a tradeoff exists between acceptable utility value and iteration steps.

VI. CONCLUSION

In this paper, we propose a price-based resource allocation approach in FD OFDMA HetNets to mitigate the cross-tier interference to macrocell from FBS and FUE. In particular, in order to meet the interference constraint of MUEs, we propose a triple optimization strategy to achieve utility maximization. To achieve this, we utilize a Lagrange duality method and a subgradient iterative algorithm to solve the power control and subcarrier allocation, in which a closed-form solution is derived to tackle the dual multiplier problem. In addition, we design an interior point method that can quickly converge to the interference price. Numerical results show that the proposed method can effectively suppress cross-tier interference and achieve faster convergence. The future work will focus on investigating how the user mobility affects the performance of the FD heterogeneous networks.

APPENDIX

Proof: For the solution of femtocell power, we have assumed that the subcarrier allocation is completed, then the proof of the problem transformation is given as follows:

$$\max\ U_{fell} = \log(1 + r^u_{m,k}) + \log(1 + r^d_{n,k}) - \mu_k(g_{m,k}p^u_{m,k} + g_{M+1,k}p^d_{n,k}) \tag{27}$$

$$s.t.\ \sum_{k=1}^{K} p^u_{m,k} \leq P_{FUE}, \forall m, \tag{28}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{K} p^d_{n,,k} \leq P_{FBS}. \tag{29}$$

With Lagrange, the Lagrangian associated with this problem can be written as

$$\begin{aligned} L(\mathrm{P}, \xi, \psi) &= \log(1 + r_{m,k}^{u}) + \log(1 + r_{n,k}^{d}) \\ &\quad - \mu_k (g_{m,k} p_{m,k}^{u} + g_{M+1,k} p_{n,k}^{d}) \\ &\quad - \sum_{m=1}^{M} \xi_m \left(\sum_{k=1}^{K} p_{m,k}^{u} - P_{FUE} \right) \\ &\quad - \psi \left(\sum_{n=1}^{N} \sum_{k=1}^{K} p_{n,k}^{d} - P_{FBS} \right) \\ &\quad + \beta_1 p_{m,k}^{u} + \beta_2 p_{n,k}^{d}. \end{aligned} \tag{30}$$

Among them, ξ_m, ψ are the non-negative dual variable, the dual variable is defined $\Phi(\mathrm{P}, \xi, \psi) = \max_{\mathrm{P} \geq 0} L(\mathrm{P}, \xi, \psi)$ as the dual problem is $\min_{\xi, \psi \geq 0} \Phi(\mathrm{P}, \xi, \psi)$, and then use KKT conditions:

$$\frac{\partial L}{\partial p_{m,k}^{u}} = 0, \quad \frac{\partial L}{\partial p_{n,k}^{d}} = 0, \tag{31}$$

$$\xi_m \Big(\sum_{k=1}^{K} p_{m,k}^{u} - P_{FUE} \Big) = 0, \tag{32}$$

$$\psi \Big(\sum_{n=1}^{N} \sum_{k=1}^{K} p_{n,k}^{d} - P_{FBS} \Big) = 0, \tag{33}$$

$$\beta_1 p_{m,k}^{u} = 0, \quad \beta_2 p_{n,k}^{d} = 0, \tag{34}$$

$$p_{m,k}^{u}, p_{n,k}^{d} \geq 0, \tag{35}$$

$$\xi_m, \psi \geq 0, \tag{36}$$

$$\beta_1, \beta_2 \geq 0. \tag{37}$$

REFERENCES

[1] R. Li, Y. Chen, G. Y. Li, and G. Liu, "Full-duplex cellular networks," *IEEE Commun. Mag.*, vol. 55, no. 4, pp. 184–191, Apr. 2017.

[2] M. Kaneko, T. Nakano, K. Hayashi, T. Kamenosono, and H. Sakai, "Distributed resource allocation with local csi overhearing and scheduling prediction for OFDMA heterogeneous networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 2, pp. 1186–1199, Feb. 2017.

[3] Z. Xiao, H. Liu, V. Havyarimana, T. Li, and D. Wang, "Analytical study on multi-tier 5G heterogeneous small cell networks: Coverage performance and energy efficiency," *Sensors*, vol. 16, no. 11, p. 1854, 2016.

[4] L. Song, Y. Li, and Z. Han, "Resource allocation in full-duplex communications for future wireless networks," *IEEE Wireless Commun.*, vol. 22, no. 4, pp. 88–96, Aug. 2015.

[5] L. Wang, F. Tian, T. Svensson, D. Feng, M. Song, and S. Li, "Exploiting full duplex for device-to-device communications in heterogeneous networks," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 146–152, May 2015.

[6] D. Kim, S. Park, H. Ju, and D. Hong, "Transmission capacity of full-duplex-based two-way ad hoc networks with ARQ protocol," *IEEE Trans. Veh. Technol.*, vol. 63, no. 7, pp. 3167–3183, Sep. 2014.

[7] H. Ju, E. Oh, and D. Hong, "Catching resource-devouring worms in next-generation wireless relay systems: Two-way relay and full-duplex relay," *IEEE Commun. Mag.*, vol. 47, no. 9, pp. 58–65, Sep. 2009.

[8] G. Zheng, I. Krikidis, J. Li, A. P. Petropulu, and B. Ottersten, "Improving physical layer secrecy using full-duplex jamming receivers," *IEEE Trans. Signal Process.*, vol. 61, no. 20, pp. 4962–4974, Oct. 2013.

[9] M. O. Al-Kadri, A. Aijaz, and A. Nallanathan, "An energy-efficient full-duplex MAC protocol for distributed wireless networks," *IEEE Wireless Commun. Lett.*, vol. 5, no. 1, pp. 44–47, Feb. 2016.

[10] N. H. Mahmood, M. G. Sarret, G. Berardinelli, and P. Mogensen, "Full duplex communications in 5G small cells," in *Proc. 13th Int. Wireless Commun. Mobile Comput. Conf.*, 2017, pp. 1665–1670.

[11] C. Nam, C. Joo, and S. Bahk, "Joint subcarrier assignment and power allocation in full-duplex OFDMA networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 6, pp. 3108–3119, Jun. 2015.

[12] C. Nam, C. Joo, and S. Bahk, "Radio resource allocation with inter-node interference in full-duplex OFDMA networks," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2015, pp. 3885–3890.

[13] C. Nam, C. Joo, S.-G. Yoon, and S. Bahk, "Resource allocation in full-duplex OFDMA networks: Approaches for full and limited CSIs," *J. Commun. Netw.*, vol. 18, no. 6, pp. 913–925, 2017.

[14] S. Xiao *et al.*, "Joint uplink and downlink resource allocation in full-duplex OFDMA networks," in *Proc. IEEE Int. Conf. Commun.*, May 2016, pp. 1–6.

[15] Z. Xiao, T. Li, W. Ding, D. Wang, and J. Zhang, "Dynamic PCI allocation on avoiding handover confusion via cell status prediction in LTE heterogeneous small cell networks," *Wireless Commun. Mobile Comput.*, vol. 16, no. 14, pp. 1972–1986, 2016.

[16] W. Liu, X. Chen, and W. Wang, "Price-based uplink resource allocation for hybrid-spectrum femtocell networks," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2012, pp. 2665–2670.

[17] M. O. Al-Kadri, Y. Deng, A. Aijaz, and A. Nallanathan, "Full-duplex small cells for next generation heterogeneous cellular networks: A case study of outage and rate coverage analysis," *IEEE Access*, vol. 5, pp. 8025–8038, 2017.

[18] S. Han, C. Yang, and P. Chen, "Full duplex-assisted intercell interference cancellation in heterogeneous networks," *IEEE Trans. Commun.*, vol. 63, no. 12, pp. 5218–5234, Dec. 2015.

[19] S. Goyal, P. Liu, S. Hua, and S. Panwar, "Analyzing a full-duplex cellular system," in *Proc. Annu. Conf. Inf. Sci. Syst.*, 2015, pp. 1–6.

[20] I. Atzeni and M. Kountouris, "Full-duplex MIMO small-cell networks with interference cancellation," *IEEE Trans. Wireless Commun.*, vol. 16, no. 12, pp. 8362–8376, Dec. 2017.

[21] A. Rahmati, V. Shah-Mansouri, and M. Safari, "Price-based resource allocation for self-backhauled small cell networks," *Comput. Commun.*, vol. 97, pp. 72–80, Jan. 2017.

[22] F. Zeng and J. Zhong, "Utility-based cooperative spectrum leasing scheme for CR networks with hybrid energy supplies," *IET Commun.*, vol. 12, no. 5, pp. 509–517, 2018.

[23] Z. Liu, S. Li, H. Yang, K. Y. Chan, and X. Guan, "Approach for power allocation in two-tier femtocell networks based on robust non-cooperative game," *IET Commun.*, vol. 11, no. 10, pp. 1549–1557, 2017.

[24] S. Xiao, X. Zhou, Y.-W. Yi, G. Y. Li, and W. Guo, "Robust resource allocation in full-duplex-enabled OFDMA femtocell networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 10, pp. 6382–6394, Oct. 2017.

[25] B. Khamidehi and M. Sabbaghian, "Resource allocation for SC-FDMA femtocell networks," *IEEE Trans. Veh. Technol.*, to be published, doi: 10.1109/TVT.2017.2751077.

[26] Z. Liu, J. Wang, Y. Xia, R. Fan, H. Jiang, and H. Yang, "Power allocation robust to time-varying wireless channels in femtocell networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2806–2815, Apr. 2016.

[27] Z. Liu, P. Zhang, X. Guan, and H. Yang, "Joint subchannel and power allocation in secure transmission design for femtocell networks," *IEEE Syst. J.*, to be published, doi: 10.1109/JSYST.2016.2635153.

[28] Z. Li, F. Xiao, S. Wang, T. Pei, and J. Li, "Achievable rate maximization for cognitive hybrid satellite-terrestrial networks with AF-relays," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 2, pp. 304–313, Feb. 2018.

[29] L. Huang, S. Han, C. Yang, and G. Wang, "Full-duplex based successive interference cancellation in heterogeneous networks," in *Proc. IEEE Int. Symp. Pers., Indoor, Mobile Radio Commun.*, Sep. 2016, pp. 1–6.

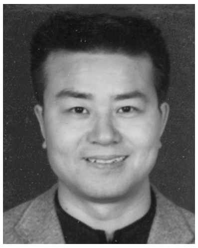
[30] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1637–1652, Sep. 2014.

[31] X. Kang, R. Zhang, and M. Motani, "Price-based resource allocation for spectrum-sharing femtocell networks: A Stackelberg game approach," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 538–549, Apr. 2012.

[32] M. Feng, S. Mao, and T. Jiang, "Joint duplex mode selection, channel allocation, and power control for full-duplex cognitive femtocell networks," *Digit. Commun. Netw.*, vol. 1, no. 1, pp. 30–44, 2015.

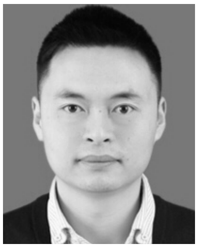
[33] H. Ramos and M. T. T. Monteiro, "A new approach based on the Newton's method to solve systems of nonlinear equations," *J. Comput. Appl. Math.*, vol. 318, pp. 3–13, Jul. 2017.

[34] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2006.



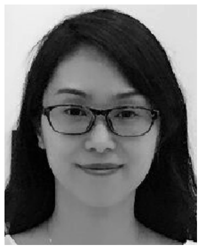
FANZI ZENG received the Ph.D. degree in signal and information processing from Beijing Jiaotong University, Beijing, China, in 2005. Since 2005, he has been with the College of Computer Science and Electronic Engineering, Hunan University, Changsha, China, where he is currently a Professor. In 2009, he was with the Department of Electrical and Computer Engineering, Michigan Technological University, Houghton, as a Visiting Scholar. His current research focuses on cognitive radio technology and artificial intelligence.

QIAO LI received the B.S. degree from Henan Normal University, China, in 2015. She is currently pursuing the M.S. degree in communication and information system with Hunan University. Her research interests include mobile communications and mobile computing.



ZHU XIAO (M'15) received the M.S. and Ph.D. degrees in communication and information system from Xidian University, China, in 2007 and 2010, respectively. From 2010 to 2012, he was a Research Fellow with the Department of Computer Science and Technology, University of Bedfordshire, U.K. He is currently an Associate Professor with the College of Computer Science and Electronic Engineering, Hunan University, China. His research interests include mobile communications, wireless localization, next-generation communications, and heterogeneous networks.

VINCENT HAVYARIMANA received the B.S. degree in mathematics from the University of Burundi, Bujumbura, in 2007, and the M.E. and Ph.D. degrees in computer science and electronic engineering from Hunan University, Changsha, China, in 2011 and 2016, respectively. He is currently a Lecturer and the Head of research service with Ecole Normale Supérieure, Burundi. His research interests include wireless communication, vehicular ad-hoc networks, and mobile computing.



JING BAI (M'10) received the B.S. degree in electronic and information engineering from Zhengzhou University and the Ph.D. degree in pattern recognition and intelligent system from Xidian University in 2004 and 2009, respectively. She is currently an Associate Professor with Xidian University. Her research interests include image processing, machine learning, and intelligent information processing.