Research Article

Game Theory Based Energy-Aware Uplink Resource Allocation in OFDMA Femtocell Networks

Jun Zhao,¹ Wei Zheng,¹ Xiangming Wen,¹ Xiaoli Chu,² Haijun Zhang,³ and Zhaoming Lu¹

¹ School of Information and Communication Engineering, Beijing Key Laboratory of Network System Architecture and Convergence, Beijing University of Posts and Telecommunications, Beijing 100876, China
² Department of Electronic Engineering, The University of Sheffield, Sheffield S1 3JD, UK
³ College of Information Science and Technology, Beijing University of Chemical Technology, Beijing 100029, China

Correspondence should be addressed to Jun Zhao; xfx_321@bupt.edu.cn

Received 12 December 2013; Accepted 10 February 2014; Published 13 March 2014

Academic Editor: Hongjian Sun

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Femtocell is a promising technique not only in operator networks but also in having potential applications for industrial wireless sensor networks. In this paper, we investigate energy efficient uplink power control and subchannel allocation in two-tier femtocell networks. Taking transmit power and circuit power into account, we model the power control and subchannel allocation problem as a supermodular game to maximize energy efficiency of femtocell users. To reduce the cochannel interference from femtousers to neighboring femtocells and macrocells, we introduce a convex pricing scheme to curb their selfish behavior. We decompose the resource allocation problem into two subproblems, that is, a distributed subchannel allocation scheme and a distributed power control scheme to reduce costs and complexity. Simulation results show that the proposed algorithm can improve user utilities significantly, compared with existing power control and subchannel allocation algorithms.

1. Introduction

According to the study of ABI, in recent years, more than 70% of the mobile data traffic happens indoors [1], where the coverage of macrocells is poor. Femtocell is a promising technique to improve the capacity and coverage of the indoor environment by shortening the distance of the transmitter and receiver [2]. Moreover, low power femtonode can be also an important technique in industry wireless sensor networks. However, due to the cochannel deployment of femtocells with macrocell, co-tier interference and cross-tier interference are serious [3]. On the other hand, in orthogonal frequency division multiple access (OFDMA) based femtocells, different users have different channel gains, and the system throughput can be maximized by appropriately allocating the resources, such as subchannels and power, which can be called multiuser diversity.

In order to obtain the above mentioned multiuser diversity and mitigate the cochannel interference, power control and subchannel scheduling are investigated in two-tier femtocell networks [4–8]. In [4], a noncooperative power allocation with SINR adaptation is used to alleviate the uplink interference suffered by macrocells; while in [5], a Stackelberg game based power control is formulated to maximize femtocell’s capacity under cross-tier interference constraints. However, subchannel allocation is not considered. In [6], a joint subchannel and power allocation algorithm is proposed to maximize total capacity in dense femtocell deployments. While in [7], a Lagrangian dual decomposition based resource allocation scheme with constraints on cross-tier interference in power allocation is used. In [9], the distributed subchannel and power allocation for cochannel deployed femtocells is modeled as a noncooperative game, for which a Nash equilibrium is obtained based on a time-sharing subchannel allocation. However, in these works, joint subchannel and power allocation with users’ QoS and cross-tier interference considerations is not studied. In [8], a distributed modulation and coding scheme, subchannel, and power allocation that supports different throughput constraints per user is proposed, but it does not consider two-tier networks.
Moreover, most of the existing literatures focus on capacity maximization of the femtocells. The energy consumption of femtocell networks cannot be ignored due to the massive deployment of femtocells. Meanwhile, in order to apply the adaptive advantage of wireless sensor networks better, we need to find an optimal resource allocation method to improve the energy efficiency of femtocells. In this paper, we investigate the energy efficient uplink power control and subchannel allocation in femtocell networks. Taking both transmit power and circuit power into account, we model the power control and subchannel allocation problem as a supermodular game to maximize energy efficiency of femtocell users. To reduce the cochannel interference from femtousers to neighboring femtocells and macrocell, we introduce a convex pricing scheme to curb their selfish behavior. We decompose the resource allocation problem into two subproblems, that is, a distributed subchannel allocation scheme and a distributed power control scheme to reduce costs and complexity. Simulation results show that the proposed algorithm can improve user utilities significantly, compared with existing power control algorithms.

The rest of the paper is organized as follows. Section 2 presents the system model and problem formulation. In Section 3, supermodular game based energy efficient resource allocation is proposed. The simulation results are provided in Section 4. Finally, Section 5 concludes the paper.

2. System Model

2.1. System Model. Our model involves a central macrocell and K random distributed indoor femtocell base stations. It is assumed that femtocells and macrocell use the same frequency, and there is only one scheduled active user during each signaling slot to avoid interference within a femtocell. Macrousers and femtousers are randomly distributed in the macrocell and femtocell, respectively. Let M and F denote the number of the active macrousers camping on macrocell and femtousers camping on a femtocell, respectively. All femtocells are assumed to be working in close access mode. The bandwidth of the OFDMA system B is divided into N subchannels. The channel fading of each subcarrier is assumed the same within a subchannel but may vary across different subchannels.

Let $h_{i,n}^k$ represent the channel gain of femtouser $i$ on subchannel $n$ in femtocell $k$. $p_{i,n}^k$ is femtouser $i$‘s transmit power on subchannel $n$ in femtocell $k$; $p_{m,n}^0$ is macrouser $m$’s transmit power on subchannel $n$ in the macrocell. $P_p = [p_{i,n}^k]_{K\times F}$ is the power allocation matrix of the $K$ femtocells on subchannel $n$; and $A_n = [a_{i,n}^k]_{K\times F}$ is the subchannel indication matrix, being $a_{i,n}^k = 1$ if subchannel $n$ is assigned to femtouser $i$ in femtocell $k$, and $a_{i,n}^k = 0$ otherwise. The Signal to Interference and Noise Ratio (SINR) of user $i$ on subchannel $n$ in femtocell $k$ can be described as

$$y_{i,n}^k = \frac{p_{i,n}^k h_{i,n}^k}{\sum_{k' \neq k} p_{i,n}^{k'} h_{i,n}^{k'} + p_{m,n}^0 h_{m,n}^0 + \sigma^2},$$

where $t_{i,n}^k = \sum_{k' \neq k} p_{i,n}^{k'} h_{i,n}^{k'} + p_{m,n}^0 h_{m,n}^0 + \sigma^2$ is the received interference of user $i$ on subchannel $n$, in which, $\sum_{k' \neq k} p_{i,n}^{k'} h_{i,n}^{k'}$ is cochannel interference caused by other neighboring femtocells; $p_{m,n}^0 h_{m,n}^0$ is the cochannel interference from macrocell to femtocell side. $\sigma^2$ is the additive white Gaussian noise (AWGN) power.

The received SINR of macrouser $m$ on subchannel $n$ is

$$\gamma_{m,n}^0 = \frac{p_{m,n}^0 h_{m,n}^0}{\sum_{k=1}^{K} p_{i,n}^k h_{i,n}^k + \sigma^2},$$

where $h_{m,n}^0$ denotes the channel gain of subchannel $n$ between macrocell BS and macrouser $m$. $\sum_{k=1}^{K} p_{i,n}^k h_{i,n}^k$ is the cochannel interference from femtocells. Based on Shannon theory, the maximum data rate of femtouser $i$ on subchannel $n$ in femtocell $k$ is described as

$$C_{i,n}^k = w \log_2 \left(1 + y_{i,n}^k\right),$$

where $w = B/N$ is the bandwidth of each subchannel, and $y_{i,n}^k$ is given by (1).

The capacity of macrouser $m$ on subchannel $n$ can be modeled as

$$C_{m,n}^0 = w \log_2 \left(1 + \gamma_{m,n}^0\right).$$

In this paper, SINR is selected as the QoS satisfaction indicator, to model the user’s QoS satisfaction (UQS), which is the best response of SINR; a UQS function is introduced in this section. This function should satisfy the rule of diminishing marginal returns; that is, UQS ($\beta_k$) increases with the increase of user’s SINR, but the increase of UQS decreases with SINR decrease of user $i$ in femtocell $k$. $\beta_k$ determines the center of the curve, which denotes the expectation value of user $i$’s QoS in femtocell $k$. For the same expectation value of QoS ($\beta_k = 0.7$), the UQS increases faster with a larger $\alpha_k$.
For the same QoS sensitivity ($\alpha^k = 15$), UQS increases with decreasing $\beta^k$. Therefore, the UQS function in (6) can well reflect the user’s QoS preferences.

Here, we consider energy efficiency in two-tier femtocell network; the utility function of user $i$ on subchannel $n$ can be defined as

$$U^k_{i,n} = \frac{f^k_{i,n}(\gamma_{i,n})}{p^k_{i,n} + P_c},$$

where $P_c$ is circuit power. Figure 2 shows the unpricing utility function of femtouser’s transmitting power.

### 3. Supermodular Game Based Energy Efficient Resource Allocation

#### 3.1. Game Framework.

According to game theory, we model the energy efficient resource allocation problem as a noncooperative game. $G = [\kappa, \{P_k\}, \{U_k(\cdot)\}]$, where $\kappa = \{1, \ldots, K\}$ is the set of femtocell players. In femtocell $k$, there is only one femtobase station as a central controller to coordinate the allocation of resources. Hence, we regard a femtocell and its users as a union, and the union competes with other unions formed by other femtocells and their users for the use of spectrum and power resource. $P_k = \{P_k\}$ represents the strategy space of union $k$, and its utility is $U_k = \sum_{i \in F} \sum_{n \in N} u^k_{i,n}$. In the game, each union aims to maximize its utility by allocating subchannels and power. As each subchannel is assigned to only one femtouser in each femtocell, therefore, for subchannel $n$, $G$ can be rewritten as $G_n = [\kappa_n, A_n \times P_m [u^k_{i,n}]]$, where $\kappa_n$ is the set of femtoplayers using subchannel $n$.

In $G_n$, each player tends to maximize its individual utility by transmitting at maximal power, which will cause unacceptable cochannel interference to both macrocell and neighboring femtocells. In order to achieve Pareto improvement and mitigate the co-tier and cross-tier interference, a pricing function is introduced.

![Figure 1: User’s UQS function.](image1)

![Figure 2: User’s utility function of transmitting power for fixed interference.](image2)
The authors in [12] introduce a penalty function that is proportional to each user’s transmit power. We use the convex pricing function $c_i e^{p_i(k)}$ as a more strict consideration. The utility function can be defined as

$$
\tilde{u}_{i,n}^k = \frac{f_{i,n}^k(y_{i,n}^k)}{p_{i,n}^k} - c_i e^{p_i(k)},
$$

(10)

where $c_i$ is the pricing function and its unit is bps/w$^2$. Let $\bar{G}_n = [\kappa_n, A_n, P_n, [a_{i,n}^k]]$ denote a $\kappa_n$-player noncooperative resource allocation game with pricing (NCRAGP).

**Definition 1.** Given the fixed $p_{i,n}^k$ and $a_{i,n}^k$, the optimal subchannel and power allocation policy of user $i$ is defined as

$$(p_{i,n}^*, a_{i,n}^*) = \arg \max_{(p_{i,n}^*, a_{i,n}^*)} \tilde{u}_{i,n}^k (p_{i,n}^k, a_{i,n}^k | p_{-i,n}^k, a_{-i,n}^k),
$$

(11)

where $p_{i,n}^k$ and $a_{i,n}^k$ represent the power and channel allocation strategy vectors of subchannel $n$ in femtocells other than femtocell $k$.

The joint optimization of subchannel and power allocation in (11) is a NP-hard problem. In order to reduce the computational complexity, we divide the problem into two subproblems. Firstly, we propose a subchannel allocation policy. Secondly, an optimal power allocation algorithm is developed based on the given subchannel allocation.

### 3.2. Energy Efficient Subchannel Allocation Policy

In this subsection, we propose a subchannel allocation method under the condition that the power allocation is given. The difference between our algorithms and the one that is in [12] is that we focus on the femtocell maximization of energy efficiency rather than throughput. We use a convex pricing to protect macrocell users and femtocell users.

Assuming that the power allocation of all users in all femtocells is given, the subchannel allocation problem can be redefined as

$$
i^* = \arg \max_i \tilde{u}_{i,n}^k (i^* | P_n).
$$

(12)

Using (1), (2), and (6), (12) can be written as

$$i^* = \arg \max_i \frac{w_i}{(1 + e^{p_i(k) - y_{i,n}^k})} - c_i e^{p_i(k)}.
$$

(13)

Let $y_i$ denote the SINR of user $i$ which maximizes its own utility. Substituting the transmission power $p_{i,n}^k = y_{i,n}^k/\kappa_n$ and SINR $y$ into (13), we obtain

$$i^* = \arg \max_i \frac{w_i}{(1 + e^{p_i(k) - y})} - c_i e^{p_i(k)}.
$$

(14)

We find that (13) is equivalent to

$$
i^* = \arg \min_i f_{i,n}^k,
$$

(15)

here, $d_{i,n}^k$ represents that the subchannel $n$ is assigned to user $i$ in femtocell $k$, and $d_{i,n}^k = 1, d_{i,n}^k = 0$ for $i \neq i^*$. Thus, subchannel $n$ will be assigned to user $i$ whose $i^*$ value is the minimum.

#### 3.3. Energy Efficient Power Allocation Strategy

Given the allocation of subchannels, power control problem can be modeled as $G_{n,p} = [\kappa_n, \{p_{i,n}^k\}, [a_{i,n}^k]]$. Let $S_{i,n}^k(p_{i,n}^k)$ denote the set of power allocation of user $i$, given the other user's strategy $p_{-i,n}^k$, which denotes the set of power allocation policy of other users.

**Definition 2.** A power allocation strategy $\bar{p}_{i,n}^k$ in the noncooperative game, if the following inequality is satisfied, for all $i, n, k$

$$
\tilde{u}_{i,n}^k (\bar{p}_{i,n}^k, \bar{p}_{-i,n}^k) \geq \tilde{u}_{i,n}^k (p_{i,n}^k, \bar{p}_{-i,n}^k).
$$

(16)

At the point of Nash equilibrium, there is no way for any player to increase its utility by changing its strategy unilaterally.

As $f_{i,n}^k$ is not a quasiconcave function of $p_{i,n}^k$, we will deal with the power control problem based on supermodular game that fulfills a pure strategy equilibrium without the quasiconcave requirement of $f_{i,n}^k$ [13]. Supermodular game was first proposed by Topkis in 1998 [14] and is defined as follows.

**Definition 3.** The unpricing game $G_{n,p} = [\kappa_n, \{p_{i,n}^k\}, [a_{i,n}^k]]$ is supermodular if, for each $i, u_{i,n}^k$ has nondecreasing differences in $(p_{i,n}^k, p_{-i,n}^k)$. For continuous and twice differentiable utilities, $u_{i,n}^k$ has nondecreasing differences in $(p_{i,n}^k, p_{-i,n}^k)$ if and only if $\partial^2 u_{i,n}^k/\partial p_{i,n}^k \partial p_{j,n}^k \geq 0$, for all $j \neq i$.

**Theorem 4.** The unpricing game $G_{n,p} = [\kappa_n, \{p_{i,n}^k\}, [u_{i,n}^k]]$ is supermodular if $\gamma_{i,n}^k \geq \beta_{i,n}$, for all $i, k, n$.

**Proof.** Let

$$
\frac{\partial u_{i,n}^k}{\partial p_{i,n}^k} = \frac{1}{(p_{i,n}^k)^2} \left[ \frac{\partial f_{i,n}^k(y_{i,n}^k)}{\partial y_{i,n}^k} \cdot \frac{\partial y_{i,n}^k}{\partial p_{i,n}^k} - f_{i,n}^k(y_{i,n}^k) \right],
$$

$$
\frac{\partial u_{i,n}^k}{\partial p_{j,n}^k} = \frac{1}{(p_{j,n}^k)^2} \left[ \frac{\partial f_{i,n}^k(y_{i,n}^k)}{\partial y_{i,n}^k} \cdot \frac{\partial y_{i,n}^k}{\partial p_{j,n}^k} - f_{i,n}^k(y_{i,n}^k) \right].
$$

$$
\frac{\partial^2 u_{i,n}^k}{\partial p_{i,n}^k \partial p_{j,n}^k} = \frac{1}{(p_{i,n}^k)^2} \times \left( \frac{\partial^2 f_{i,n}^k(y_{i,n}^k)}{\partial y_{i,n}^k \partial y_{i,n}^k} \cdot \frac{\partial y_{i,n}^k}{\partial p_{i,n}^k} + \frac{\partial f_{i,n}^k(y_{i,n}^k)}{\partial y_{i,n}^k} \cdot \frac{\partial y_{i,n}^k}{\partial p_{i,n}^k} + \frac{\partial f_{i,n}^k(y_{i,n}^k)}{\partial y_{i,n}^k} \cdot \frac{\partial y_{i,n}^k}{\partial p_{j,n}^k} \right).
$$

(17)
\[ \begin{align*}
- \frac{\partial f^k_{i,n}(y^k_{i,n})}{\partial y^k_{i,n}} \frac{\partial y^k_{i,n}}{\partial p^k_{j,n}} & = \frac{1}{(p^k_{i,n})^2} \left( \frac{\partial^2 f^k_{i,n}(y^k_{i,n})}{\partial^2 y^k_{i,n}} \cdot \frac{\partial y^k_{i,n}}{\partial p^k_{j,n}} \cdot y^k_{i,n} \right) \\
& \cdot \frac{\partial y^k_{i,n}}{\partial p^k_{j,n}} - \frac{1}{(p^k_{i,n})^2} \left[ \frac{\partial f^k_{i,n}(y^k_{i,n})}{\partial y^k_{i,n}} \cdot \frac{\partial y^k_{i,n}}{\partial p^k_{j,n}} \cdot y^k_{i,n} \right] \\
& = \frac{1}{(p^k_{i,n})^2} \left( \frac{\partial^2 f^k_{i,n}(y^k_{i,n})}{\partial^2 y^k_{i,n}} \cdot \frac{\partial y^k_{i,n}}{\partial p^k_{j,n}} \cdot y^k_{i,n} \right) \\
& - c_i h^k_{i,n} e^{\alpha \cdot (\gamma^k_{i,n} - \gamma^k_{i,n})} \\
\therefore \ y^k_{i,n} & \geq \beta_i \\
\frac{\partial^2 f^k_{i,n}(y^k_{i,n})}{\partial^2 y^k_{i,n}} & = \frac{\alpha^2 \cdot e^{\alpha(\beta_i - \gamma^k_{i,n} - \gamma^k_{i,n})} \cdot (e^{\alpha(\beta_i - \gamma^k_{i,n})} - 1)}{(1 + e^{\alpha(\beta_i - \gamma^k_{i,n})})^3} \leq 0,
\end{align*} \]

One nice property of supermodular game is that the best response has a fixed point and implies at least a Nash equilibrium.

If the utilities of the game under the condition that there is a parameter without the control of any user, we call that parameter an exogenous parameter. Here, we extend the former game \( G_{n,p} \) into a parameterized game \( G^e_{n,p} \) with \( \tilde{u}_{i,n}(p^k_{i,n}, p^k_{-i,n}, \epsilon) \) by introducing an exogenous parameter \( \epsilon \) [15]. \( G_{n,p} \) can be regarded as a special case of \( G^e_{n,p} \) with \( \epsilon = 0 \).

**Definition 5.** A parameterized game \( G^e_{n,p} = \{\kappa^e_{n,i}, \{p^k_{i,n}\}, \{\tilde{u}_{i,n}\}\} \) is supermodular if \( \tilde{u}_{i,n} \) has nondecreasing differences in \( (p^k_{i,n}, p^k_{-i,n}) \) and in \( (p^k_{i,n}, \epsilon) \), for all \( i \).

**Theorem 6.** The pricing game \( G_{n,p} = \{\kappa^k_{ni}, \{p^k_{i,n}\}, \{u_{i,n}\}\} \) with exogenous parameter \( c_i \) is a supermodular game if \( y^k_{i,n} \geq \beta_i \), for all \( i, k, n \).

**Proof.** Firstly, we change the variable of \( c_i \) to \( \epsilon \), where \( \epsilon = -c_i \).
The proof of \( \tilde{G}_{n,p} = \{\kappa^e_{n,i}, \{p^k_{i,n}\}, \{\tilde{u}_{i,n}\}\} \) as a supermodular game is \( \frac{\partial^2 \tilde{u}_{i,n}}{\partial p^k_{j,n} \partial p^k_{j,n}} \geq 0 \), for all \( j \neq i \) and \( \frac{\partial^2 \tilde{u}_{i,n}}{\partial p^k_{j,n} \partial \epsilon} \geq 0 \), for all \( i \).

\[ \begin{align*}
\frac{\partial \tilde{u}_{i,n}}{\partial p^k_{j,n}} & = \frac{1}{(p^k_{i,n})^2} \left[ \frac{\partial f^k_{i,n}(y^k_{i,n})}{\partial y^k_{i,n}} \cdot \frac{\partial y^k_{i,n}}{\partial p^k_{j,n}} \cdot y^k_{i,n} \right] \\
& - c_i h^k_{i,n} e^{\alpha \cdot \epsilon} \\
\therefore \ \frac{\partial f^k_{i,n}(y^k_{i,n})}{\partial p^k_{j,n}} & = \frac{1}{(p^k_{i,n})^2} \left[ \frac{\partial f^k_{i,n}(y^k_{i,n})}{\partial y^k_{i,n}} \cdot \frac{\partial y^k_{i,n}}{\partial p^k_{j,n}} \cdot y^k_{i,n} \right] \\
& - c_i h^k_{i,n} e^{\alpha \cdot \epsilon}
\end{align*} \]

The partial derivative of \( \tilde{u}_{i,n} \) with respect to both \( p^k_{i,n} \) and \( \epsilon \) is \( \frac{\partial^2 \tilde{u}_{i,n}}{\partial p^k_{j,n} \partial \epsilon} = h^k_{i,n} e^{\alpha \cdot \epsilon} \geq 0 \), for all \( i \); therefore, \( G_{n,p} \) is a supermodular game.

The set of Nash equilibrium in super modular game is not empty [13]. Let \( P \) denote the set of smallest elements of Nash equilibrium \( E \).

**Corollary 7.** In modified game \( G^e_{n,p} \) with \( y^k_{i,n} \geq \beta_i \) for all \( i, k, n, P \in E \) is the Pareto optimal equilibrium; that is, \( \tilde{u}_{i,n}(P) \geq \tilde{u}_{i,n}(P) \) for all \( i, P \in E \).

**Proof.** Note that, for fixed \( c_i \) and \( p^k_{-i,n} \), \( y^k_{i,n} \) decreases with the increase of \( p^k_{i,n} \), and we observe that \( f^k_{i,n}(y^k_{i,n}) \) is a monotonically increasing function of \( y^k_{i,n} \) according to (5); therefore, \( \tilde{u}_{i,n} \) is the monotonically decreasing function of \( p^k_{i,n} \). Since \( p^k_{i,n} \leq p^k_{-i,n} \), we can get

\[ \begin{align*}
\tilde{u}_{i,n}(p^k_{i,n}, p^k_{-i,n}) \leq \tilde{u}_{i,n}(p^k_{i,n}, p^k_{-i,n}).
\end{align*} \]
(1) FBS set: \( \mathcal{K} = \{1, 2, \ldots, K\} \);
(2) Energy-efficient sub-channel allocation
(3) Perform uniform power allocation among all the channels;
(4) Measure \( h_{kn}^i \) and \( I_{kn}^i \) of user \( i \) in femtocell \( k \), for all \( k, i, n \);
(5) Let \( a_{kn}^i = 0 \), for all \( k, i, n \);
(6) for each FBS do
   (7) The set of subchannel: \( \mathcal{N} = \{1, 2, \ldots, N\} \)
   (8) for \( u = 1 \) to \( F \) do
      (9) (a) find \( n^* = \arg \min_n I_{kn}^i \);
      (10) (b) \( a_{kn}^i = 1 \);
      (11) (c) \( \mathcal{N} = \mathcal{N} - \{n^*\} \);
   (12) end for
   (13) while \( \mathcal{N} \neq \emptyset \) do
      (14) (a) find \((i^*, n^*)\) based on \((i^*, n^*) = \arg \min_i I_{kn}^i \);
      (15) (b) \( a_{kn}^i = 1 \);
      (16) (c) \( \mathcal{N} = \mathcal{N} - \{n^*\} \);
   (17) end while
(18) end for
(19) Energy-efficient power allocation
(20) for each FBS do
(21) for \( n = 1 \) to \( N \) do
(22) calculate \( \cdot \);
(23) end for
(24) end for

Algorithm 1: Distributed algorithm to solve NCRAGP.

According to the definition of Nash equilibrium, and \( p_{kn}^k \) is one of the Nash equilibrium points, we have
\[
\tilde{u}_{kn}^k (p_{kn}^k, p_{-kn}^k) \leq \tilde{u}_{kn}^k (p_{kn}^i, p_{-kn}^k).
\]

From (20) and (21), we have
\[
\tilde{u}_{kn}^k (P) \geq \tilde{u}_{kn}^k (P).
\]

It can be seen from (22) that \( \tilde{G}_{n,P} \) can achieve its maximal utilities by using the Nash equilibrium point with minimum total transmit powers; that is,
\[
\tilde{P}_{kn} = \min \left[ \arg \max_{p_{kn}^k} (u_{kn}^k), P_{\text{max}} \right].
\]

3.4. A Distributed Resource Allocation Algorithm. As mentioned above, in order to reduce the complexity, we have decomposed subchannel allocation and power allocation into two subproblems. We first propose a subchannel allocation algorithm on the premise of uniform power allocation among all the subchannels. We then perform iteration beginning with the smallest possible power value until the smallest Nash equilibrium. The detailed algorithm process is shown in Algorithm 1.

4. Simulation Results and Discussion

In the simulation, macrocell radius is 500 m and femtocell radius is 10 m. The simulations consider a system of the total bandwidth \( B = 10 \text{ MHz} \), divided into \( N = 50 \) subchannels with 2 GHz carrier frequency. The AWGN variance is \( \sigma^2 = (B/N) N_0 \), where \( N_0 = -174 \text{ dBm/Hz} \). The Rayleigh fading channel is modeled as i.i.d. unit mean exponentially distributed random variables. We model the average channel gain as \( \lambda d^{-4} \) and \( \lambda = 2 \times 10^{-4} \), respectively, including path loss and antenna gain of indoor femtocell users and outdoor macrocell users [12]. In addition, the simulation considers \( c_i \) as 18 based on try-and-error method. The maximal transmit
power of users in femtocell and macrocell is 30 dBm. The number of macrousers is 50.

Figure 3 shows the topology of the simulation, where the red star represents the macrobase station (MBS), blue star denotes the femtobase station (FBS), and the red rhombus and green star represent the macrouser and femtouser, respectively.

Figure 4 shows the average energy efficiency per subchannel of the proposed Algorithm 1 compared with the existing unpricing algorithm in two-tier femtocell networks. Here, energy efficiency is defined as the ratio of capacity to transmit power on each subchannel [16]. The existing unpricing algorithm is composed of energy efficient power allocation in [16] and unpricing subchannel allocation in [17]. The proposed Algorithm 1 shows better performance than existing scheme in terms of energy efficiency. As the figure shows, with the increase of number of femtocells, the average energy efficiency per subchannel decreases because of the increase of aggregated cochannel interference. Moreover, the bigger $F$ results in higher energy efficiency because of the multiuser diversity.

Figure 5 shows the average power per subchannel of the proposed Algorithm 1 compared with the existing algorithm. As can be seen from Figure 5, the average power per subchannel increases with the increase of the number of femtocells; that is, as the number of femtocells increases, the cochannel interference is more serious; thus, the average power per subchannel needs to increase to maintain the utility of the femtouser.

Figure 6 shows the capacity of macrocells of the proposed Algorithm 1 compared with the existing algorithm. As can be seen from Figure 6, the capacity of macrocell increases with the increase of the number of femtousers per femtocell because of the multiuser diversity. Note that a large number of femtocells results in a lower energy efficiency because of the cochannel interference.

5. Conclusion

In this paper, we have investigated the energy efficient uplink power control and subchannel allocation in two-tier femtocell networks. Taking transmit power and circuit
power into account, we modeled the power control and subchannel allocation problem as a noncooperative game to maximize energy efficiency of femtocell users. To mitigate the cochannel interference, we introduced a convex pricing scheme. We decomposed the resource allocation problem into two subproblems, that is, a distributed subchannel allocation scheme and a distributed power control scheme to reduce costs and complexity. Simulation results show that the proposed algorithm can improve user utilities significantly, compared with existing resource allocation algorithms.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research is supported by the National Natural Science Foundation of China (nos. 61271179 and 61101109), the fundamental research funds for the central universities (2013RC0110), and the Cobuilding Project of Beijing Municipal Commission of Science and Technology.

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