**SCIENCE CHINA**
Information Sciences

• RESEARCH PAPER •

August 2015, Vol. 58 082305:1–082305:11
doi: 10.1007/s11432-014-5213-6

# Coordinated resource allocation to maximize the number of guaranteed users in OFDMA femtocell networks

WANG Kan*, LI HongYan, ZHANG Hao & PAN Hao

*State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an* 710071*, China*

Received November 8, 2014; accepted February 2, 2015; published online March 17, 2015

**Abstract** In this paper, we optimize the downlink resource allocation in orthogonal frequency division multiple access (OFDMA) involved femtocell networks. In dense environments, femtocell users are typically exposed to severe interference and thus not all of them can be guaranteed data rate requirements. Therefore, we aim to develop a novel and efficient scheme for maximum users with guaranteed performance, with relatively scarce resources available in femtocell networks. First, we analyze the relationship between the optimization objective, the location of users and their data rate requirements, finding that the former one is inverse proportional to the latter two. Then, based on the relationship, we propose a subchannel reuse criterion among femtocells. Finally, we formulate this subchannel reuse criterion and develop a corresponding simple resource allocation scheme, performed both at the central node-level and the coordinated femtocell base stations (FBSs)-level. Simulation results show that our proposed scheme outperforms the conventional ones in terms of the success rate and spectrum spatial reuse (SSR).

**Keywords** OFDMA, femtocell, resource allocation, subchannel reuse, improvement threshold

**Citation** Wang K, Li H Y, Zhang H, et al. Coordinated resource allocation to maximize the number of guaranteed users in OFDMA femtocell networks. Sci China Inf Sci, 2015, 58: 082305(11), doi: 10.1007/s11432-014-5213-6

## 1 Introduction

Femtocells, deployed by users and connected to the backbone networks via broadband connections, will play a significant role in the next generation network. Due to the limited coverage, multiple femtocells can transmit data simultaneously within a small-sized area, thereby significantly improving the spectral efficiency in the underlaying macrocell networks. In addition, femtocells can use existing broadband connections as backhauls, thus facilitating the access to cellular networks for indoor users [1–3]. Femtocells can also save energy and cost since they only need to cover a relatively small area and serve a small number of users.

However, the mutual interference between femtocells has become a serious issue. This is because femtocells are irregularly deployed by subscribers and thus operators cannot manage femtocell interference by using traditional frequency planning approaches. Furthermore, a dynamic interference management is also very difficult, since operators may not master the femtocell backhauls and thus larger transmission

* Corresponding author (email: kanwangkw@outlook.com)

© Science China Press and Springer-Verlag Berlin Heidelberg 2015 

delays may exist in information exchange. Therefore, it is necessary to propose a new and efficient resource allocation scheme to mitigate the femtocell interference.

A large number of resource allocation schemes have been proposed in the literature. In [4–6], the authors propose the centralized approaches to maximize the sum-rate in heterogeneous macro-femto networks. In [7–9], the authors utilize dynamic and distributed methods to maximize the sum-rate and the sum-utility in femtocell networks, by employing a joint optimization of power and subchannel allocation. In [10–12], the authors analyse the effect of an imperfect channel estimation on the cooperative communications systems, considering partial relay selection to reduce the CSI feedback burden or power consumption. However, all of these schemes do not consider diverse Quality of Service (QoS), e.g., data rate requirements for various users. In [13,14], the authors allocate subchannels and Modulation and Coding Schemes (MCSs) to satisfy all users data rate requirements while minimizing the transmit power in femtocell networks. Yet, this power minimization is feasible only when there are sufficient resources in femtocell networks, i.e., it is assumed that networks can meet all users data rate requirements simultaneously. However, in the case where some users data rate demands are very large or excessive users are connected to the networks simultaneously, this power minimization problem is infeasible. Therefore, how to maximize the number of guaranteed users whose required data rates are fully satisfied, will be the key issue in some networks with relatively scarce resources.

The optimization problem based on the user number maximization is very difficult to solve and cannot be handled efficiently even by using the centralized approaches. In [15], to cope with all infeasible constraints, the authors use an elastic programming method for the optimization problem in order to maximize the number of guaranteed users within one single femtocell. In [16], considering the multi-cell femtocell scenario, the authors propose a cluster-based approach to completely eliminate the interference between femtocells within each cluster. Both two studies adopt the protocol model in modeling the interference [17]. In [18], the authors develop and implement one resource management system, referred to as FERMI, to rationally distinguish users who require just link adaptation from those that require resource exclusively, and then categorize them as class 1 (who can share subchannels with neighboring femtocells) or class 2 (who require subchannels isolation). This categorization is similar to the subchannel reuse criteria delivered in this paper; it however, only incorporates the distance between users and their associated femtocells, without involving users's data rate requirements.

In this paper, we will attempt to satisfy as many users (with diverse data rate requirements) as possible in femtocell networks with scarce resources. First, we analyse the relationship between the optimization objective and the location of users as well as their data rate requirements. Then, we propose a subchannel reuse criterion among femtocells and also illustrate the same with an example. Finally, based on the proposed criterion, we develop a novel and low-complexity resource allocation scheme, performed both at the central node-level and the coordinated femtocell base stations (FBSs)-level. Our contributions are as follows.

(1) Proposing a low-complexity yet effective solution to the resource allocation for dense femtocell networks.

(2) Incorporating the practical interference model into the formulation of the optimization problem.

(3) Exploiting the coordinated FBSs-level subchannel allocation algorithm in order to further improve the network performance.

## 2 Network model

We consider femtocell networks based on orthogonal frequency division multiple access (OFDMA) technology. As shown in Figure 1, femtocells are classified into clusters geographically. For each cluster, there exists one central node that manages all the femtocells within it. Let $\mathcal{M} = \{1, 2, \ldots, M\}$ and $\mathcal{U} = \{1, 2, \ldots, U\}$ be the set of femtocells and users, respectively. Each femtocell is in charge of one or multiple users. Let $\mathcal{U}_m$ and $\mathcal{U}_n$ be the set of users associated with femtocell $m$ and $n$, respectively. It is evident that $\bigcup_{m\in\mathcal{M}} \mathcal{U}_m = \mathcal{U}$ and $\mathcal{U}_m \bigcap \mathcal{U}_n = \emptyset$, for any $m \neq n$. Assume that both FBSs and users are configured with one transmit and one receive antenna, respectively. Furthermore, let $\mathcal{K}$ be the set

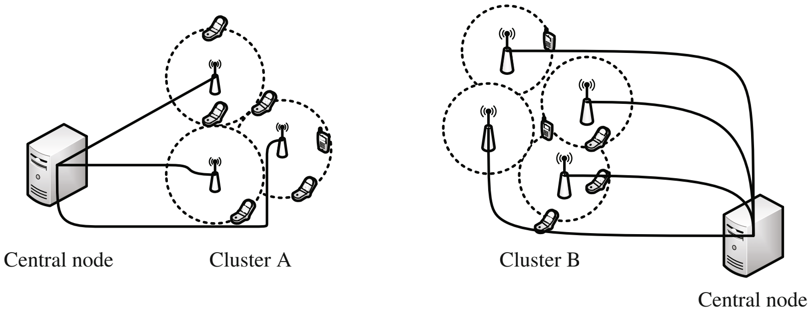



**Figure 1** Network model.

of subchannels for allocation with each subchannel $k \in \mathcal{K}$ having a bandwidth of $B$. There exists no access restriction on any subchannel $k$ for each femtocell $m$. Therefore, inter-cell interference occurs when neighboring femtocells use the same subchannels.

The wireless propagation model adopted in this work is the Finite Difference Time-Domain (FDTD)-based model [19]. Let $g_{mu}^{k}$ be the channel gain between femtocell $m$ and user $u$ on subchannel $k$. Each user can observe different channel gains over $\mathcal{K}$, i.e., $g_{mu}^{k}$ for all $k \in \mathcal{K}$ are independent Rayleigh random variables [8]. Meanwhile, slow fading is assumed so that channel gains remains unchanged during the channel coherence time.

We consider the subchannel allocation in the downlink transmission. Let $\rho_{mu}^{k}$ be the binary variable, which is equal to 1 if subchannel $k$ is allocated to user $u$ by femtocell $m$, or is 0 otherwise. Furthermore, let $\gamma_{mu}^{k}$ and $r_{mu}^{k}$ be the achievable signal-to-interference-plus-noise ratio (SINR) and rate for user $u$ from its associated femtocell $m$ on subchannel $k$, respectively. Given the constant and equal power level $p_c$ on each subchannel, $\gamma_{mu}^{k}$ and $r_{mu}^{k}$ can be expressed as follows:

$$\gamma_{mu}^{k} = \frac{p_c g_{mu}^{k}}{\sum_{m' \neq m} p_c x_{m'}^{k} g_{m'u}^{k} + \sigma^2}, \tag{1}$$

$$r_{mu}^{k} = B \log_2 \left(1 + \frac{1}{\Gamma} \gamma_{mu}^{k}\right), \tag{2}$$

where $\sigma^2$ is the thermal noise power imposed on subchannel $k$, and $\Gamma$ is the SINR gap to capacity [8]. $x_{m'}^{k}$ represents an indicative variable, which is equal to 1 if subchannel $k$ is allocated to femtocell $m' \in \mathcal{M}$ or is 0 otherwise. In the following, for simplicity, $\Gamma$ is assumed to be 1 and $B$ is ignored.

Considering several subchannel allocation constraints and the users's data rate requirements, the resulting resource allocation problem can be formulated as follows:

$$\max_{\rho_{mu}^{k}, x_{m}^{k}, z_u} \sum_{u \in \mathcal{U}} z_u, \tag{3a}$$

$$\text{s.t.} \quad \rho_{mu}^{k} \in \{0, 1\}, \sum_{u \in \mathcal{U}_m} \rho_{mu}^{k} \leqslant 1, \tag{3b}$$

$$\varphi_u = \sum_{k \in \mathcal{K}} \rho_{mu}^{k} r_{mu}^{k}, \tag{3c}$$

$$z_u = \begin{cases} 1, & \varphi_u \geqslant d_u, \\ 0, & \varphi_u < d_u, \end{cases} \tag{3d}$$

where $z_u$ denotes a unit step function, indicating whether or not user $u$ can be fully satisfied with respect to its required data rate $d_u$. $\varphi_u$ denotes the actual rate for user $u$ obtained over all subchannels. Constraint (3b) guarantees that the number of users that can access subchannel $k$ within a femtocell is limited to 1. We further assume that the channel gain $g_{mu}^{k}$ remains constant during the resource coordination cycle; since femtocells are typically deployed in apartments or enterprises, this assumption is reasonable in such low mobility environments [20]. Note that, problem (3) is a nonlinear integer programming problem due to the existence of inter-cell interference in the denominator of (1). Typically, this class of problems are computationally prohibitive and thus very difficult to solve even by the centralized approach [21,22]. Therefore, an efficient and low-complexity resource allocation scheme is necessary and needs to be developed for femtocell networks.

## 3 Proposed frequency reuse rule

Before proposing the corresponding resource allocation scheme for femtocell networks, this section first introduces a simplified network model and then discusses two different frequency (subchannel) reuse patterns across femtocells. Based on these discussions, a simple and efficient frequency reuse criterion is presented.

### 3.1 Example

We now consider a network which consists of two femtocells with $\mathcal{M} = \{m, n\}$, two users with $\{a \in \mathcal{U}_m, b \in \mathcal{U}_n\}$, and two subchannels with $\mathcal{K} = \{1, 2\}$. The data rate requirements for user $a$ and user $b$ are 2.5 and 3.5 Mbps, respectively. And the normalized channel gain matrices are given by $\begin{pmatrix} 1.5 & 1.0 \\ 0.6 & 0.8 \end{pmatrix}$ and $\begin{pmatrix} 0.2 & 0.1 \\ 0.6 & 0.8 \end{pmatrix}$, respectively for femtocell $m$ and $n$. For example, $g_{ma}^1 = 1.5$ and $g_{ma}^2 = 1.0$ represent the channel gain between femtocell $m$ and user $a$ on subchannel 1 and 2. Meanwhile, $g_{mb}^1 = 0.6$ and $g_{mb}^2 = 0.8$ denote the the channel gains between femtocell $m$ and user $b$. Obviously, user $b$ is a cell-edge user whereas user $a$ is a cell-center user. An on-off power control scheme is adopted, where the maximum transmit power on each subchannel is set to 1 W. In addition, the thermal noise power imposed on each subchannel is assumed to be 0.1 W. The transmitter of one femtocell interferes with the receivers of the others when they are allocated the same subchannels. In the following, we consider two strategies, one with universal frequency reuse and the other with subchannel allocation using inter-cell interference coordination (ICIC) [23].

(1) Universal frequency reuse. In this case, femtocells can occupy and allocate both two subchannels to their associated users, i.e., the data rates achieved by user $a$ and $b$ are summed over subchannels $\mathcal{K} = \{1, 2\}$. Following Shannon's capacity formula (2), the achievable data rates for user $a$ and $b$ are $r_a^1 = \log_2(1 + \frac{1.5\times1}{0.2\times1+0.1}) + \log_2(1 + \frac{1.0\times1}{0.1\times1+0.1}) = 2.58 + 2.58 = 5.16$ and $r_b^1 = \log_2(1 + \frac{0.6\times1}{0.6\times1+0.1}) + \log_2(1 + \frac{0.8\times1}{0.8\times1+0.1}) = 1.81$, respectively. Therefore, user $a$ can obtain surplus data rate whereas user $b$ cannot.

(2) Subchannel allocation using ICIC. In this strategy, whether or not subchannels can be used by femtocells depends largely on the practical network deployment as well as the users's data rate requirements. We first allocate only one subchannel to each femtocell, i.e., subchannel 1 to $m$ and subchannel 2 to $n$. In this case, $r_a^2 = \log_2(1 + \frac{1.5\times1}{0.1}) + 0 = 4$ and $r_b^2 = 0 + \log_2(1 + \frac{0.8\times1}{0.1}) = 3.17$ can be obtained by user $a$ and $b$, respectively. This allocation still results in unsatisfactory data rate for user $b$. However, user $a$ can still obtain much more than its demand, which motivates us to further allocate subchannel 1 to femtocell $n$. As a result, $r_a^3 = \log_2(1 + \frac{1.5\times1}{0.2\times1+0.1}) + 0 = 2.58$ and $r_b^3 = \log_2(1 + \frac{0.6\times1}{0.6\times1+0.1}) + \log_2(1 + \frac{0.8\times1}{0.1}) = 0.89 + 3.17 = 4.06$ are obtained and both two users are guaranteed adequate supply with respect to their demands.

### 3.2 Frequency reuse criteria

From the description above, we can make the following observations: (1) cell-center users (i.e., with high channel gains) with low data rate requirements can tolerate inter-cell interference to some extent, since high data rates are always available to them; (2) cell-edge users with high data rate requirements tend to occupy subchannels exclusively. However, they can also share some subchannels with neighboring femtocells in order to obtain higher requirements, even though these subchannels can only offer lower data rates. Furthermore, assume that there exists another cell-edge user $c$, in the same position as user $b$, associated with femtocell $n$ and with data rate demand 0.5. If user $b$ lowers its requirement slightly and transfers subchannel 1 to user $c$, user $c$ can also be satisfied simultaneously, with actual rate 0.89 higher than 0.5. Therefore, it is reasonable to propose that (3) cell-edge users with low data rate requirements can share subchannels with neighboring femtocells. Symmetrically and similar to (3), it is reasonable

**Table 1** Improvement thresholds in data rates

| Case | QoS | Channel state | Improvement threshold |
|---|---|---|---|
| 1 | $d_u \downarrow$ | $h_u \downarrow$ | $\Delta_{u,\text{th}} \uparrow$ |
| 2 | $d_u \downarrow$ | $h_u \uparrow$ | $\Delta_{u,\text{th}}$ higher than case 1 |
| 3 | $d_u \uparrow$ | $h_u \downarrow$ | $\Delta_{u,\text{th}}$ higher than case 1 |
| 4 | $d_u \uparrow$ | $h_u \uparrow$ | $\Delta_{u,\text{th}} \downarrow$ |

to suppose that (4) cell-center users with high data rate requirements can also share subchannels with neighboring femtocells.

## 4 Resource allocation algorithm for the central node

In this section, we first attempt to formulate the frequency reuse criteria, and then propose the resulting subchannel allocation algorithm for the central node.

As illustrated in Figure 1, the central node is charge of all femtocells within its cluster. In such dense environments, the intra-cluster interference is very large while that of the inter-cluster is negligible.

Let $\mathcal{I}_{mu}^{k}$ be the set of interfering femtocells for user $u$ on subchannel $k$, i.e., $m' \in \mathcal{I}_{mu}^{k}$ avoids using subchannel $k$ when user $u$ is active on it. Instead of taking into account all neighboring femtocells, in most cases, as in [8], we only need to consider the femtocell $I_1$ with the largest channel gain on subchannel $k$ for user $u$. For accuracy, we further define and consider $I_2$ as the one with the second largest channel gain for user $u$ [24]. Our studies can be extended to the cases of more neighboring femtocells. However, in this study, we only consider two interfering femtocells, i.e., $\mathcal{I}_{mu}^{k} \subseteq \{I_1, I_2\}$.

Let $\gamma_{mu}^{k0}$, $\gamma_{mu}^{k1}$ and $\gamma_{mu}^{k2}$ be the SINRs achieved by user $u$ on subchannel $k$, when none, one ($I_1$) and two ($I_1$ and $I_2$) interfering femtocells are incorporated in $\mathcal{I}_{mu}^{k}$. After obtaining $\gamma_{mu}^{ki}$, $i = 0, 1, 2$, the corresponding data rate $r_{mu}^{ki}$ can also be calculated. It is obvious that $r_{mu}^{k0} < r_{mu}^{k1} < r_{mu}^{k2}$. Furthermore, let $\Delta_{mu}^{k(i-1)} = r_{mu}^{ki} - r_{mu}^{k(i-1)}$, $i = 1, 2$ be the improvement in data rates. Now we address the problem; when the forbidden for $I_i$, $i = 1, 2$ to access subchannel $k$ is justified, what should be the smallest improvements $\Delta_{mu}^{k(i-1)}$, $i = 1, 2$ in data rates (i.e., the improvement thresholds)?

In low mobility environments, the channel gain is majorly dependent on the distance between femtocell $m$ and user $u$, which can be defined as $h_u$. For simplicity, we use $h_u$ to represent the channel state for user $u$ over all subchannels. Based on the analysis in Subsection 3.1, we can summarize the resource reuse criteria in Table 1. Here, $\downarrow$ indicates a high level in values while $\uparrow$ a low level.

As shown in Table 1, we can find that the improvement threshold for user $u$ is proportional to both its data rate requirement and the distance to its associated FBS. For simplicity, let $\overline{h}_u = h_u/R_d$ ($R_d$ is the radius of the femtocell coverage) and $\overline{d}_u = \frac{d_u}{\max_{u \in \mathcal{U}} d_u}$ be the normalized relative distance and required data rate for user $u$, respectively. Therefore, the value of the improvement threshold can be given as follows:

$$\Delta_{u,\text{th}}^{i-1} = \frac{c_i}{\overline{d}_u \times \overline{h}_u}, \quad i = 1, 2, \tag{4}$$

and

$$c_1 > c_2. \tag{5}$$

Eqs. (4) and (5) together define the improvement threshold in terms of the product of the normalized data rate requirement and the relative distance to FBS for each user $u$. Constant $c_i$ is the weighting coefficient that can be adjusted by the network operator to control the value of $\Delta_{u,\text{th}}^{i-1}$. Note that, if $\Delta_{mu}^{k0} > \Delta_{u,\text{th}}^{0}$, then femtocell $I_1 \in \mathcal{I}_{mu}^{k}$ and if $\Delta_{mu}^{k1} > \Delta_{u,\text{th}}^{1}$, and both femtocells $I_1$ and $I_2$ are incorporated into $\mathcal{I}_{mu}^{k}$. In addition, as in [24], $c_1 > c_2$ implies that it needs smaller improvement for data rates when forbidding the second interfering femtocell.

After obtaining the set $\mathcal{I}_{mu}^{k}$ for each user $u$ on each subchannel $k$, the achievable rate $r_{mu}^{k}$ can be derived that is available to each central node. Therefore, problem (3) can be decomposed into $M$ independent subproblems, each of which is related to a certain femtocell. In other words, the central node needs to solve $M$ independent subproblems one by one. By transforming the constraint (3d) into two equivalent constraints:

$$d_u - \varphi_u \leqslant C(1 - z_u), \tag{6}$$

$$\varphi_u - d_u < C z_u, \tag{7}$$

the corresponding resource allocation problem for femtocell $m$ can be formulated as

$$\max_{\rho_{mu}^k, z_u} \sum_{u \in \mathcal{U}_m} z_u, \tag{8a}$$

$$\text{s.t.} \quad \rho_{mu}^k \in \{0, 1\}, \sum_{u \in \mathcal{U}_m} \rho_{mu}^k \leqslant 1, \tag{8b}$$

$$\varphi_u = \sum_{k \in \mathcal{K}_m} \rho_{mu}^k r_{mu}^k, \tag{8c}$$

$$d_u - \varphi_u \leqslant C(1 - z_u), \quad \varphi_u - d_u < C z_u, \tag{8d}$$

where $C$ represents a constant that is considerably larger than $d_u$ and $\varphi_u$. As a result, the problem (8) formulated for femtocell $m$ is an integer linear programming (ILP) problem with 0-1 variables $\rho_{mu}^k, z_u$. Branch-and-bound and cutting-plane algorithms have been proposed to solve this problem. The authors in [22] state that these two methods may not be efficient in calculating the optimal point for the large-sized networks. However, these two methods are applicable in our scheme, since they are typically performed for each femtocell with a small number of associated users. Furthermore, the resource allocation algorithm for the central node only needs to be performed on large time scales. Therefore, the scheme adopting the cutting-plane (or branch-and-bound) algorithm will not result in large computational overhead.

Upon obtaining the optimal $\rho_{mu}^{k*}$, the proposed scheme can obtain the index of user $u^{k*}$ that is allocated to subchannel $k$ for each femtocell $m$. Among all $|\mathcal{U}_m|$ candidate interfering sets on each subchannel $k$ for femtocell $m$, only the set $\mathcal{I}_{mu^{k*}}^k$ is selected by the central node. Then, knowing the interfering set for each femtocell, the central node should resolve the interfering set conflicts among femtocells, since two femtocells may exist in each other's interfering set. In this case, the femtocell $m*$ that has the higher value of $r_{mu}^k/d_u$ is allowed to transmit on subchannel $k$, whereas the other one has to be silent. The overall process for the subchannel assignment among femtocells is presented in Algorithm 1.

**Algorithm 1** Algorithm for the central node

```
for u = 1 : |U| do
    Calculate the improvement threshold Δ^i_{u,th}, i = 0, 1
    for k = 1 : |K| do
        Calculate r^{kj}_{mu}, j = 0, 1, 2
        Initialize I^k_{mu} = ∅
        if Δ^{k0}_{mu} > Δ^0_{th} then
            Femtocell I_1 is incorporated in I^k_{mu}
        end if
        if Δ^{k1}_{mu} > Δ^1_{th} then
            Femtocell I_2 is also incorporated in I^k_{mu}
        end if
        Obtain the preferred data rate r^k_{mu}
    end for
end for
Prepare the achievable data rate matrix R_m = [r^k_{mu}]
for m = 1 : |M| do
    Apply the cutting-plane algorithm to R_m
    u^{k*} and I^k_{mu^{k*}} are selected by the central node
end for
The central node solve the interfering set conflicts among femtocells
```

## 5 Resource allocation algorithm for FBSs

After Algorithm 1 is performed in the central node, each femtocell $m$ will be assigned a set of subchannels, $\mathcal{K}_m$. Then, femtocell $m$ is responsible for allocating these $|\mathcal{K}_m|$ subchannels to its users $\mathcal{U}_m$. If the wireless environments and traffic conditions vary very slowly during the resource allocation cycle, the subchannels allocated to user $u$, i.e., $\mathcal{K}_u$ should be kept constant and hence the set $\mathcal{K}_m$ exists. As described above, we assume that channel gains are stable during the resource allocation cycle. However, traffic dynamic variations typically exist in the femtocell users such that users can undergo transition from the active to inactive state and vice versa. Therefore, wastage of budget resources will occur when there are no packets to transmit for some inactive users [22]. As a result, static subchannel allocation among does not adapt to traffic variations, for which we develop a dynamic self-adapting scheme in the next subsection.

When user $u$ transits from the active to inactive state, its allocated subchannels $\mathcal{K}_u$ should be released. Then, femtocell $m$ will face two options (a) allocate $\mathcal{K}_u$ to other active users within its coverage; or (b) transfer $\mathcal{K}_u$ to neighboring femtocells. Let $\mathcal{U}_m^{\mathrm{res}}$ be the set of residual active users for femtocell $m$, i.e.,

$$\mathcal{U}_m^{\mathrm{res}} = \mathcal{U}_m^{\mathrm{act}} \backslash \mathcal{U}_m^{\mathrm{grt}}, \tag{9}$$

where $\mathcal{U}_m^{\mathrm{act}}$ and $\mathcal{U}_m^{\mathrm{grt}}$ denote the set of active users and guaranteed users (i.e., their data rate requirements are fully met), respectively. By replacing $\mathcal{U}_m$ and $\mathcal{K}_m$ with $\mathcal{U}_m^{\mathrm{res}}$ and $\mathcal{K}_u$ respectively and allocating subchannels $\mathcal{K}_u$ to $\mathcal{U}_m^{\mathrm{res}}$, problem (8) is solved. As a result, some residual users are further satisfied for femtocell $m$ and we denote the set of these users as $\mathcal{U}_m^{\mathrm{res}*}$, where $\mathcal{U}_m^{\mathrm{res}*} \subseteq \mathcal{U}_m^{\mathrm{res}}$.

Meanwhile, when $\mathcal{K}_u$ becomes available at slot $t$, where femtocell $m$ would exchange this information to its neighboring femtocells $\mathcal{N}_m$. In this way, any neighboring femtocell $m' \in \mathcal{N}_m$ can be aware of these idle subchannels. Similar to $m$, $m'$ would solve the problem (8) and hence the set $\mathcal{U}_{m'}^{\mathrm{res}*}$ is obtained.

As for which femtocell should be assigned the idle subchannels $\mathcal{K}_u$, it is evident that the one with the maximum benefit would be selected. After receiving the information $\mathcal{U}_{m'}^{\mathrm{res}*}$ from all neighboring femtocells, the selection problem for femtocell $m$ can be formulated as follows:

$$\max_{x_m, x_{m'}} \quad x_m|\mathcal{U}_m^{\mathrm{res}*}| + \sum_{m' \in \mathcal{N}_m} x_{m'}|\mathcal{U}_{m'}^{\mathrm{res}*}|, \tag{10a}$$

$$\text{s.t.} \quad x_m + \sum_{m' \in \mathcal{N}_m} x_{m'} = 1, \tag{10b}$$

$$x_m, x_{m'} \in \{0, 1\}, \tag{10c}$$

where $x_m$ indicates whether or not $\mathcal{K}_u$ is assigned to femtocell $m$.

Note that, the coordinated resource allocation for FBSs dose not need the assistance of the central node. In reality, this scheme can be performed in each FBS through the information exchange between femtocells. In our proposed scheme, FBSs could exchange messages about the idle subchannels, newly satisfied residual users and so on. Since there exist no dedicated backhauls between femtocells, these messages can be sent by broadcasting or using users to relay [3].

A pseudo code of the coordinated resource allocation algorithm for FBSs is presented in Algorithm 2 (taking FBS $m$ as an example).

**Algorithm 2** Algorithm for FBSs

```
Prepare the achievable data rate matrix R_m = [r^k_{mu}], u ∈ U_m^res, k ∈ K_u
Solve the problem (8) and obtain the the set U_m^res*
for m' = 1 : |N_m| do
    Prepare the achievable data rate matrix R_m' = [r^k_{m'u}], u ∈ U_m'^res, k ∈ K_u
    Solve the problem (8) and obtain the the set U_m'^res*
end for
Solve the problem (10) and allocate K_u
```

## 6 Relaxed problem and the corresponding optimal solution

After the suboptimal subchannel allocation scheme is proposed, as in [25], we present a relaxed problem of (3) and take its optimal solution as the benchmark to which our proposed scheme is compared.

The objective is the same but we relax the integer constraint (3b) and allow multiple users to access one subchannel in a time-sharing manner within a femtocell. Furthermore, in order to make the interference limitation tractable, we introduce a new parameter $I$ as the maximum interference temperature [26], and hence can obtain the achievable rate for any user $u$ on subchannel $k$ as follows:

$$r_{mu}^{k'} = \log_2\left(1 + \frac{p_c \cdot g_{mu}^k}{I + \sigma^2}\right). \tag{11}$$

Note that, $r_{mu}^{k'}$ can be interpreted as the lower bound of $r_{mu}^k$, and $I$ can be varied by the network operator for the purpose of interference control [26]. Thus, the relaxed problem for (3) can be formulated as

$$\max_{\rho_{mu}^k, z_u} \sum_{u\in\mathcal{U}} z_u, \tag{12a}$$

$$\text{s.t.}\ \ 0 \leqslant \rho_{mu}^k \leqslant 1, \sum_{u\in\mathcal{U}_m} \rho_{mu}^k \leqslant 1, \tag{12b}$$

$$\varphi_u = \sum_{k\in\mathcal{K}} \rho_{mu}^k r_{mu}^{k'}, \tag{12c}$$

$$d_u - \varphi_u \leqslant C(1 - z_u), \quad \varphi_u - d_u < C z_u, \tag{12d}$$

which is a standard mixed integer linear programming (MILP) problem, and can be solved either by the cutting plane or branch-and-bound algorithm. In reality, YALMIP and LPSOLVE [24] have been used along with MATLAB to resolve this class of problem. In this paper, as in [24], YALMIP is utilized.

## 7 Simulation and results

The scenario for simulation is a region hosting two femtocell clusters, each of which consists 5 femtocells and has a covering area of 20 m × 20 m. In addition, these two clusters are more than 30 m apart. Therefore, two dense and independent clusters are considered.

The radius of each femtocell is 5 m and 5 users are uniformly located within each femtocell coverage. Heavy traffic load is considered in our simulations. All users are considered to be with Poisson traffic models, and can undergo transition between the active to inactive state. Therefore, the service time of each state is dictated by an exponential distribution (mean 20 slots). Furthermore, the average data rate demand for each user can range from 0.2 to 3.2 Mbps, and are evenly spaced by 0.2 Mbps.

The cycle of resource allocation for the central node is assumed to be 100 slots while the resource allocation for FBSs is performed slot by slot. All the metrics and numerical results are averaged over 1000 slots. Due to the orthogonality of the spectrum between macrocells and femtocells, we only consider 8 and fewer subchannels (each of which has a 180 kHz bandwidth) in the simulated networks. Other detailed simulation parameters are presented in Table 2.

### 7.1 Approaches for comparison

Proposed scheme is compared with the optimal strategy presented in Section 6 through extensive simulations. Two other schemes are also evaluated for their performances. In all schemes, we adopt the equal power distribution among subchannels.

(1) Universal frequency reuse (reuse 1): Users in each femtocell can access the entire bandwidth. Therefore, there exists no intra-cluster interference coordination.

(2) Orthogonal assignment: Subchannels in each femtocell are orthogonal to that in other femtocells in the same cluster. In other words, the central node implements the static resource allocation among femtocells in advance and thus the intra-cluster interference is completely eliminated.

**Table 2** Simulation parameters

| Parameter | Value |
|---|---|
| FBS TX power | 20 dBm |
| Shadowing | Log-normal, 8 dB standard deviation |
| Path loss | $37 + 32\log(d(m))$ |
| Penetration loss | 10 dB |
| Thermal noise density | $-174.0$ dBm/Hz |
| Noise figure | 9 dB |
| Interference temperature ($I$)-to-noise ratio | 30 dB |
| FBS antenna pattern | Omni |
| User antenna pattern | Omni |

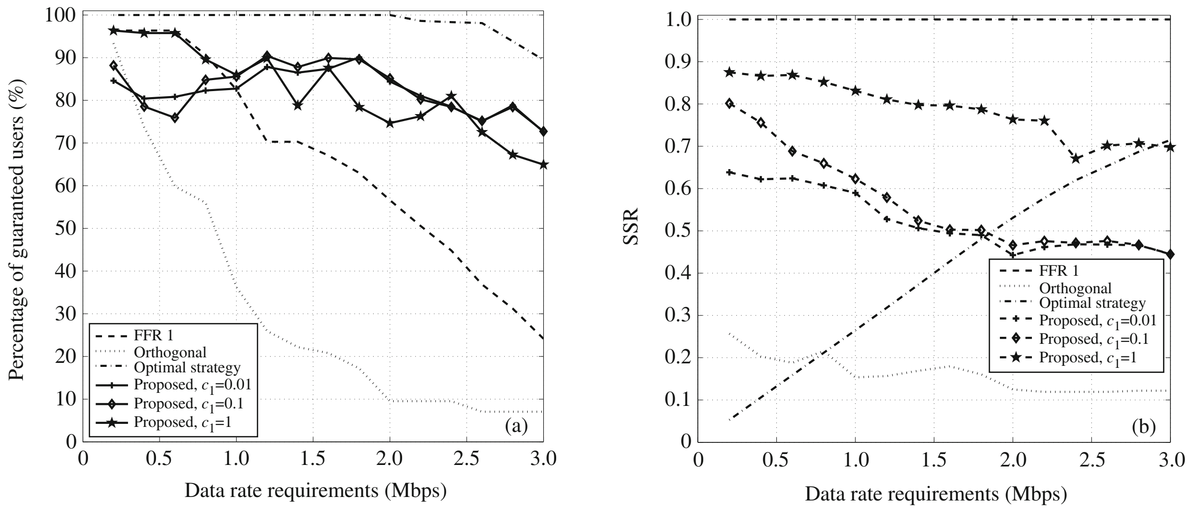



**Figure 2** Metrics vs. average data rate requirement. (a) Success rate; (b) SSR.

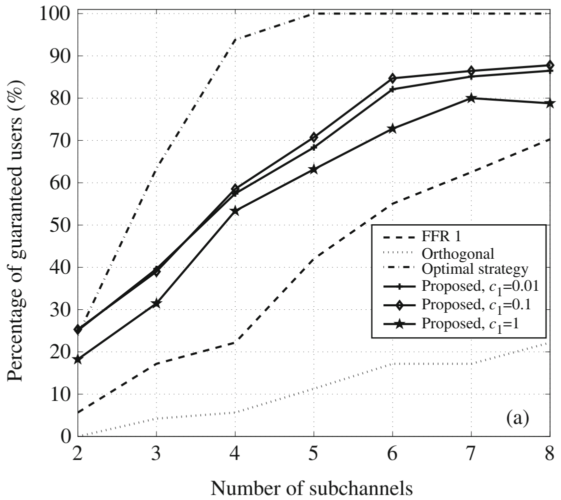
### 7.2 Simulation results

In our simulations, different resource allocation schemes are evaluated in terms of the success rate [16] and spectrum spatial reuse (SSR), respectively. Success rate is presented as the percentage of guaranteed users whose data rate demands are fully satisfied while SSR is defined as $\frac{\sum_{m\in\mathcal{M}}\sum_{k\in\mathcal{K}} x_{mk}}{|\mathcal{M}|\times|\mathcal{K}|}$.

Figure 2(a) shows the success rate versus average data rate demand under various schemes, given that the femtocell networks have a bandwidth of 8 subchannels. Compared to other schemes, our proposed ones are relatively stable for all 3 different parameters: $c_1 = 0.01, 0.1, 1$ (and $c_2 = c_1/2$), i.e., the success rate does not change much with increase in the value of demand. $c_1 = 1$ performs better in small required data rates while $c_1 = 0.01, 0.1$, almost overlapped, have higher value in large ones. The optimal strategy provides an upper-bound, which is approximately 11% and 25% higher than the proposed scheme with $c_1 = 0.01(0.1)$ and $c_1 = 1$, respectively. Reuse 1 performs badly due to the strong interference while the orthogonal assignment due to the small number of available subchannels.

Figure 2(b) compares the subchannel allocation schemes in terms of SSR. The proposed scheme with $c_1 = 1$ has higher SSR compared to those with $c_1 = 0.01$ and 0.1, which allows more subchannels to be reused among femtocells. Except for the optimal strategy, SSRs of schemes decline as the the required data rate increase. This is because that femtocells tend to occupy subchannels exclusively in order to obtain higher data rates. As for the optimal strategy, its values increase since the more flexible allocation scheme with time-sharing on subchannels is permitted within each femtocells.

The proposed schemes with $c_1 = 0.01$ and $c_1 = 0.1$ still perform similarly ($c_1 = 0.1$ has a slightly higher performance improvement), as shown in Figure 3(a), in terms of the success rate given the required data rate 1.2 Mbps. As we can see, the gap between the proposed schemes and optimal strategy becomes narrow as the number of available subchannels increases, which implies that our method especially applies to the



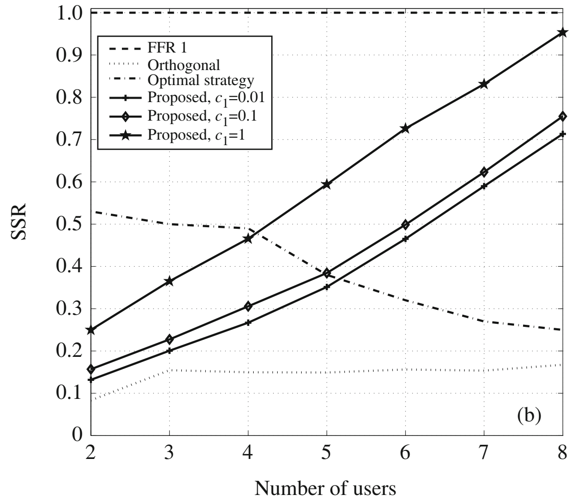




**Figure 3** Metrics vs. subchannel number. (a) Success rate; (b) SSR.

networks with more resources. Reuse 1 and orthogonal still perform badly.

Figure 3(b) shows SSR vs. subchannel number under various schemes given the average data rate requirement 1.2 Mbps. The results are consistent with our assumptions: in the lower required data rate, as the number of subchannels increases, SSR also rises because femtocells need not to occupy subchannels exclusively. $c_1 = 1$ allows more subchannels to be reused among femtocells compared to the other two values. As for the optimal strategy, as a result of more flexible approaches with time-sharing on subchannels, it only needs a small portion of available subchannels to satisfy its users, thus decreasing its SSR.

## 8 Conclusion

We developed a low-complexity and efficient resource allocation scheme for femtocell networks, capable of performing both at the central node-level and the coordinated femtocell base stations (FBSs)-level, respectively. This scheme is based on the maximization of the number of guaranteed users. First, we analysed the relationship between the optimization objective and the location of users as well as their data rate requirements, giving an example for illustration. Then, based on the example, we proposed a novel subchannel reuse criteria among femtocells. Finally, based on the proposed criteria, we presented a low-complexity resource allocation scheme. The simulation results showed that the proposed scheme improved the system performance in terms of the success rate and SSR. This improvement implies that more users can access the femtocell networks simultaneously. Therefore, our proposed scheme is particularly applicable to the femtocell networks with relatively scarce resources.

The proposed coordinated resource allocation is centralized in essence. In fact, in femtocell networks, due to the unplanned deployment and Internet-based backhauls, the implementation of centralized resource allocation is nontrival. Considering this we seek a more reliable and practical approach, which is distributed optimization. The authors in [27,28] solved distributed channel selection problem in canonical networks using game-theoretic learning, which may contribute to our work and help us to develop a more efficient and reliable algorithm for femtocell networks.

**Acknowledgements**

This work was supported by National Natural Science Foundation of China (Grant Nos. 91338115, 61231008), National S&T Major Project (Grant Nos. 2011ZX03005-004, 2011ZX03004-003, 2013ZX03004007-003), Shaanxi 13115 Project (Grant No. 2010ZDKG-26), National Basic Research Program of China (973 Program) (Grant No. 2009CB320404), Program for Changjiang Scholars and Innovative Research Team in University (Grant No. IRT0852), 111 Project (Grant No. B08038), and State Key Laboratory Foundation (Grant Nos. ISN1002005, ISN090305).

## References

1 Chandrasekhar V, Andrews J, Gatherer A. Femtocell networks: a survey. IEEE Commun Mag, 2008, 46: 59–67
2 Andrews J, Claussen H, Dohler M, et al. Femtocells: past, present, and future. IEEE J Sel Areas Commun, 2012, 30: 497–508
3 Lopez-Perez D, Valcarce A, de La Roche G, et al. OFDMA femtocells: a roadmap on interference avoidance. IEEE Commun Mag, 2009, 47: 41–48
4 Kim J, Dong-Ho C. A joint power and subchannel allocation scheme maximizing system capacity in indoor dense mobile communication systems. IEEE Trans Veh Technol, 2010, 59: 4340–4353
5 Lan T, Sinkar K, Kant L, et al. Resource allocation and performance study for LTE networks integrated with femtocells. In: Proceedings of IEEE Global Communications Conference, Miami, 2010. 1–6
6 Fei Z S, Xing C W, Li N, et al. Power allocation for OFDM-based cognitive heterogeneous networks. Sci China Inf Sci, 2013, 56: 042310
7 Madan R, Borran J, Sampath A, et al. Cell association and interference coordination in heterogeneous LTE-A cellular networks. IEEE J Sel Areas Commun, 2010, 28: 1479–1489
8 Son K, Lee S, Yi Y, et al. REFIM: a practical interference management in heterogeneous wireless access networks. IEEE J Sel Areas Commun, 2011, 29: 1260–1272
9 Xing C W, Fei Z S, Li N, et al. Statistically robust resource allocation for distributed multi-carrier cooperative networks. Sci China Inf Sci, 2013, 56: 022315
10 Zhong B, Zhang Z S, Zhang X, et al. Partial relay selection with fixed-gain relays and outdated CSI in underlay cognitive networks. IEEE Trans Veh Technol, 2013, 62: 4696–4701
11 Zhong B, Zhang Z S, Zhang X, et al. Impact of partial relay selection on the capacity of communications systems with outdated CSI and adaptive transmission techniques. EURASIP J Wirel Commun Netw, 2013, 2013: 24
12 Zhou Y Q, Liu H, Pan Z G, et al. Two-stage cooperative multicast transmission with optimized power consumption and guaranteed coverage. IEEE J Sel Area Commun, 2014, 32: 274–284
13 Lopez-Perez D, Ladanyi A, Juttner A, et al. Optimization method for the joint allocation of modulation schemes, coding rates, resource blocks and power in self-organizing LTE networks. In: Proceedings of IEEE International Conference on Computer Communications, Shanghai, 2011. 111–115
14 Lopez-Perez D, Chu X, Vasilakos A, et al. Power minimization based resource allocation for interference mitigation in OFDMA femtocell networks. IEEE J Sel Areas Commun, 2014, 32: 333–344
15 Al Bashar M S, Ding Z, Li Y. Qos aware resource allocation for heterogeneous multiuser OFDM wireless networks. In: Proceedings of IEEE Signal Processing Advances in Wireless Communications, Recife, 2008. 535–539
16 Hatoum A, Langar R, Aitsaadi N, et al. Q-FCRA: Qos-based OFDMA femtocell resource allocation algorithm. In: Proceedings of IEEE International Conference on Communications, Ottawa, 2012. 5151–5156
17 Iyer A, Rosenberg C, Karnik A. What is the right model for wireless channel interference? IEEE Trans Wirel Commun, 2009, 8: 2662–2671
18 Arslan M Y, Yoon J, Sundaresan K, et al. FERMI: a femtocell resource management system for interference mitigation in OFDMA networks. In: Proceedings of ACM 17th Annual International Conference on Mobile computing and networking, Las Vegas, 2011. 1–12
19 Valcarce A, de La Roche G, Juttner A, et al. Applying FDTD to the coverage prediction of WiMax femtocells. EURASIP J Wirel Commun Netw, 2009, 2009: 3
20 Tachwali Y, Lo B F, Akyildiz I F, et al. Multiuser resource allocation optimization using bandwidth-power product in cognitive radio networks. IEEE J Sel Areas Commun, 2013, 31: 451–463
21 Schrijver A. Theory of linear and integer programming. Chichester: John Wiley & Sons, 1998
22 Li G, Liu H. Downlink radio resource allocation for multi-cell OFDMA system. IEEE Trans Wirel Commun, 2006, 5: 3451–3459
23 Barbieri A, Damnjanovic A, Ji T, et al. LTE femtocells: system design and performance analysis. IEEE J Sel Areas Commun, 2012, 30: 586–594
24 Rahman M, Yanikomeroglu H. Enhancing cell-edge performance: a downlink dynamic interference avoidance scheme with inter-cell coordination. IEEE Trans Wirel Commun, 2010, 9: 1414–1425
25 Xue P, Gong P, Park J Y, et al. Radio resource management with proportional rate constraint in the heterogeneous networks. IEEE Trans Wirel Commun, 2012, 11: 1066–1075
26 Ng D W K, Lo E S, Schober R. Energy-efficient resource allocation in OFDMA systems with large numbers of base station antennas. IEEE Trans Wirel Commun, 2012, 11: 3292–3304
27 Xu Y H, Wang J L, Wu Q H, et al. Opportunistic spectrum access in cognitive radio networks: global optimization using local interaction games. IEEE J Sel Top Signal Process, 2012, 6: 180–194
28 Xu Y H, Wang J L, Wu Q H, et al. Opportunistic spectrum access in unknown dynamic environment: a game-theoretic stochastic learning solution. IEEE Trans Wirel Commun, 2012, 11: 1380–1391