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Downlink interference minimization in cooperative cognitive LTE-femtocell networks

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Abstract

Femtocell is considered to be one of the most promising solutions for future indoor wireless communication. Due to the scarcity of spectrum resources, femtocells need to share the spectrum with other networks, which will inevitably bring in severe interference. Therefore, minimizing the cross-tier and co-tier interference while maintaining high system throughput or spectrum efficiency is one of main challenges before largely deploying femtocell networks. In order to effectively mitigate the interference, cognitive radio-enabled techniques can play a key role by providing more secondary spectrum access opportunities, especially in dense femtocells deployment scenarios. Supported by cognitive radio functionality, femtocell users can access and share these licensed spectra including the frequency bands of both macrocells and other licensed systems (e.g., TV white spaces) as long as not causing harmful interference to the coexisting licensed systems. In this paper, based on cognitive sensing, we propose a joint channel assignment and power allocation scheme, aiming to minimize the aggregate interference from multiple femtocells to the licensed users while satisfying the constraints of each femtocell's capacity and power budget. It is believed that the cooperation among multiple femtocells is quite helpful in mitigating the interference considering the mobility of the licensed users. Specifically, Hungarian algorithm is involved in our scheme to address the co-tier femtocell interference issue. In order to illustrate our scheme more explicitly, we come up with the concepts of Physical Cluster and Virtual Cluster and synthetically apply the related algorithms to reduce the interference step by step. Finally, the performances of employed algorithms are evaluated and analyzed. Numerical results have validated that the proposed scheme is viable and effective in managing the femtocell interference.

Keywords: Femtocell; Cognitive radio; TV white spaces (TVWS); Interference mitigation; Hungarian algorithm; Cooperative resource allocation; Convex optimization

1 Introduction

With the advent of big data era and the emergence of new hand-held devices such as tablet PC and smart phones, data intensive applications like online video streaming and network gaming have inexorably occupied more and more users' focus. Future mobile wireless networks call for higher data rate for providing more high quality services and better user experience. Recent studies have suggested that this rapidly increasing demand for high data rate is chiefly generated from indoor environments [1], where exist more than 50% voice calls and 70% data traffic [2]. However, indoor radio coverage is generally poor due to the wall penetration losses inside buildings especially when the user is located in the cell edge. This clear discrepancy between high data rate demand and low received signal to interference and noise ratio (SINR) leads to many research discussions. The idea of femtocells, which are principally designed to extend macro cellular services into indoor environments, is one of them.

Femtocells are small-coverage, low-cost, plug-and-play networking systems, where a femtocell access point (FAP) or femtocell base station is installed at home or in an office. Afterwards, the indoor femtocell user equipment (FUE) can be connected to the FAP instead of a macrocell base station to get high-quality voice and data services with much lower power consumption, and all the network traffic will be backhauled to the macrocell network and/or the internet via either wired broadband connections such as digital subscriber line, passive optical network, or a divided wireless backhaul channel [3]. The FAP is also

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called as Home Node B in WCDMA systems and Home e Node B in long-term evolution (LTE) systems in the 3GPP femtocell standardization [4]. And the latter, namely LTE-femtocells, using orthogonal frequency-division multiple access (OFDMA) as the physical layer technology, are considered as one of the most promising solutions for future indoor wireless communication with large economic potentials.

Despite the many advantages of femtocells, however, there are a number of challenges in technical, regulatory, and economic aspects that need to be addressed systematically. The works of Zahir et al. [5] and Mhiri et al. [6] provide an overview of the main research challenges toward the deployment of femtocells, among which interference management including the cross-tier and intra-tier interference is one of the biggest technical challenges. In the coexisting macrocell-femtocell networks, macrocells and femtocells interfere with each other for spectrum sharing, and there is also mutual interference among femtocells. In fact, the interference problem can be extremely intractable in a dense deployment scenario due to the lack of spectrum resources. Given that, various interference management strategies have been proposed to address this issue including for instance, collaborative resource allocation [7], fractional frequency reuse (FFR) [8,9], directional beamforming [10], cognitive radio approach [11], and power control [12-17]. Among variety of methods, power control has been extensively researched and used as an effective interference mitigation solution for both cross-tier and co-tier interference. Specifically, distributed solutions like game theory [12] or reinforcement learning [13] could explore appropriate power level to minimize the cross-tier interference in large-scale deployments. More often than not, power control can be combined with other methods like cognitive radio (CR) to reduce the interference. For that reason, we will put more attention on the related work later.

There have been a substantial research focusing on the interference mitigation through power control. In [14], the authors have studied the downlink cross-tier interference problem in macro-femto two-tier networks with shared spectrum, and a distributed power control scheme is proposed and analyzed. In [15], the authors have studied downlink spectrum sharing co-tier interference in an overlay mode in cognitive femtocell networks. Then, they employed dual decomposition method to solve the problem and proposed a joint channel allocation and fast power control scheme. In [16], resource allocation in open access OFDMA femtocell networks has been studied, while a new resource allocation method is proposed to reduce cross-tier interference and improve performance of both neighboring macrocell users and femtocell users. In [17], a subcarrier and power allocation method has been presented to manage cross-tier interference in underlay femtocell networks. Basically, these papers only take the interference power as a constraint rather than an optimization objective. In that case, they may not be applicable when the situations vary. Moreover, [15,16], and [17] all tackled power control problem in a distributed manner due to the self-organizing feature of femtocell networks, and they all involved CR technology to mitigate the interference efficiently.

Indeed, the interference generated by femtocells will tend to be a localized phenomenon when the femtocells are heavily deployed in urban areas in the future. Since the FAP coverage is much smaller, CR technology could play a crucial role in obtaining this localized interference information including sensing, processing, and decision making. The Federal Communications Commission in USA has authorized dynamic spectrum access operation for cognitive radio in TV white spaces (TVWS) since 2008 [18], which has created new opportunities for femtocells to utilize TVWS for interference mitigation. Interference study in [19] mainly focused on cognitive LTE-femtocell in TV white spaces. The paper proposed two interference-avoiding antenna schemes as a reference for future cognitive femtocell deployment using TV white spaces, which can also be a solution to ensure successful femtocell operation.

Due to the complexity in the real implementation scenarios, regulations relative to TV white spaces may not be fully implemented, and even meeting all the regulatory requirements cannot guarantee that the primary users are not influenced completely. Moreover, the interference threshold varies a lot under different circumstances, which means that the power allocation algorithms taking the interference as a constraint may be not very effective in a more realistic setting. Additionally, most prior studies [14-17] address either cross-tier or co-tier femtocell interference in isolation under the assumption that the other kind of interference is already well resolved. In this paper, a new interference mitigation scheme is presented to address both co-tier and cross-tier interference problem for future cognitive LTE-femtocell networks. We take the interference power as the optimization objective, which is different from the ideas of the related papers mentioned above. Through cognitive spectrum sensing [20,21], joint macro-femto channel scheduling, or other spectrum utilization approaches (e.g., authorized shared access proposed by Qualcomm and its partners), femtocell users in a local area can obtain accessible channels. Then, channel and power resources can be collaboratively allocated among multiple femtocells for interference mitigation based on the physical cluster and the virtual cluster. However, the performance gain is achieved at the cost of some cooperative overheads including the exchange of information like access channel, location, link quality estimation and mobility of PUs among femtocells. Basically, our contributions can be summarized as follows:

- We come up with the new concepts of physical cluster (PC) and virtual cluster (VC) for multiple femtocells to collaboratively allocate resources.
- We propose two independent algorithms including subcarrier power allocation algorithm for interference minimization in a single femtocell and virtual cluster-based power budget adjustment algorithm to be part of solutions for the femtocell interference management.
- We employ Hungarian algorithm, which is a typical solution to the linear task allocation problem, to minimize cross-tier interference from femtocells to the users of licensed systems including macrocell networks and TV broadcast systems while avoiding co-tier femtocell interference based on the physical cluster.
- We recommend femtocells to utilize TVWS through cognitive sensing and propose an integrated joint channel assignment and power allocation scheme to deal with the interference problem for femtocells with fewer available channels in a dense deployment scenario.

The rest of the paper is organized as follows: Section 2 describes the system model as well as the concepts of PC and VC. In Section 3, the primary interference minimization problem is formulated, derived, and analyzed. Afterward, a solution algorithm for interference minimization in a single femtocell will be provided. In section 4, two secondary problems are illustrated respectively, and relevant algorithms are presented. And then, we incorporate both Sections 3 and 4 together to form our proposed integrated scheme. Numerical results are given in Section 5, while Section 6 concludes the paper.

2 System model

As shown in Figure 1, we mainly consider the coexistence scenario between cognitive femtocells and licensed (primary) systems such as macrocells and TV systems. Assume that femtocell users share the same spectrum with primary users. In the downlink signal transmission, a FAP in one femtocell transmits desired signals to its member FUEs and thus generally causes undesired harmful interference signals to the FUEs of its neighboring femtocells and also the primary users. Adjacent femtocells can be assigned different channels to avoid severe co-channel interference or the femtocells occupying the same channel must separate at least for a safety distance [22] to avoid co-tier interference. Furthermore, the aggregate interference from multiple femtocells to a certain primary user sometimes cannot be neglected due to the large number of femtocells that use the same channel in a densely deployed scenario. Therefore, it is quite a challenging job to achieve successful operation for considerable femtocells in a certain area when quite limited primary channels are available.

For channel modeling, we consider the following model:

$$H_{k,i} = X_{k,i} \cdot 10^{(-\mathrm{PL}/10)}, \tag{1}$$

where $H_{k,i}$ denotes the channel power gain of the kth subcarrier of the ith femtocell and $X_{k,i}$ is used to describe the effect of the fading and assumed to be Rayleigh distributed random variables with mean equal to one. PL is the pass loss component that can be calculated using the following model [23]:

$$\mathrm{PL}_{\mathrm{LOS}}(dB) = 18.7\log(d) + 46.8 + 20\log(f_{\mathrm{c}}/5), \tag{2}$$

$$\mathrm{PL}_{\mathrm{NLOS}}(dB) = 20\log(d)+46.4+20\log(f_{\mathrm{c}}/5)+L_{\mathrm{W}}, \tag{3}$$

where d denotes the distance (m) between the FAP and the FUE, f_c is the carrier frequency (GHz), and L_{W} represents the wall penetration loss (dB) with $L_{\mathrm{W}} = 5n_{\mathrm{w}}$ for light walls and $L_{\mathrm{W}} = 12n_{\mathrm{w}}$ for heavy walls where n_{w} is the number of walls between BS and MS.

In cognitive LTE-femtocell networks, the interference introduced by the kth subcarrier of the ith femtocell to the primary user (PU) (i.e., TV receiver) band, $I_{k,i}$, is the integration of the power spectrum density (PSD) of the kth subcarrier of the ith femtocell across the PU band, B, and can be expressed as

$$I_{k,i} = \int_{d_{k,i}-B/2}^{d_{k,i}+B/2} G_{k,i}\Phi_{k,i}(f)df = P_{k,i}\Omega_{k,i}, \tag{4}$$

where $G_{k,i}$ is the channel power gain between the kth subcarrier of the ith femtocell and the PU receiver. $d_{k,i}$ is the spectral distance between the kth subcarrier of the ith femtocell and the PU band. $\Phi_{k,i}$ is the PSD of the kth subcarrier of the ith femtocell. Besides, the expression of the PSD depends on the adopted multicarrier technique, such as OFDM. $P_{k,i}$ denotes the transmission power emitted by the kth subcarrier of the ith femtocell and $\Omega_{k,i}$ denotes the interference factor of the kth subcarrier of the ith femtocell. We can see that $\Omega_{k,i}$ is mainly associated with $G_{k,i}$ if OFDM technique is adopted.

The level of interference induced by the femtocell varies depending on the distance between the femtocell and other systems as well as the transmission power of the FAP. Thus, we may firstly assign the available channels to the femtocells based on the distance and then adjust the power budgets of different FAPs to alleviate the underlying interference. Traditional graph coloring approach is not efficient for lack of enough channels. To deal with this

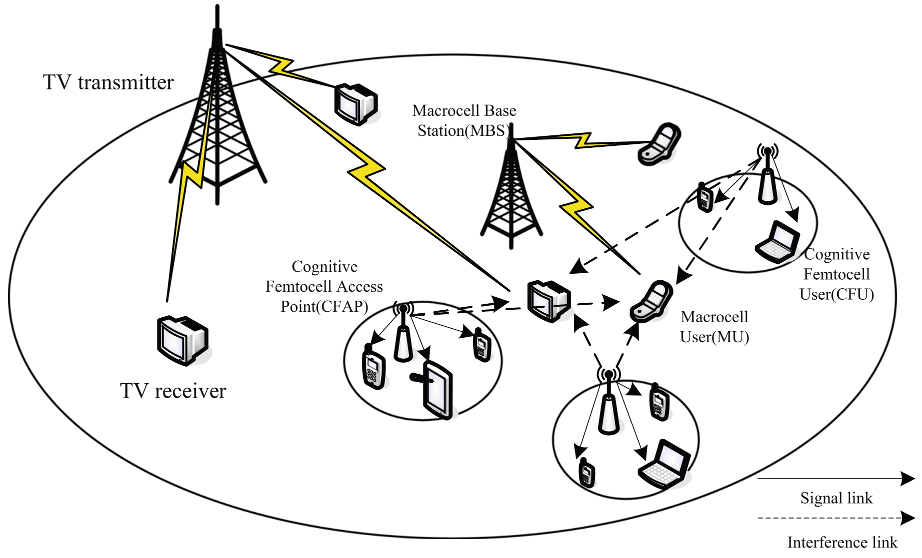

Figure 1 Coexisting LTE and cognitive femtocell networks.

problem, we come up with the new concepts of physical cluster (PC) and virtual cluster (VC), which is essentially a question of femtocell grouping.

Figure 2 is an illustration of PC and VC. We define the spatial correlation of femtocells, γ, as follows:

$$\gamma = \frac{r}{d}, \tag{5}$$

where r denotes the radius of the femtocell coverage and d denotes the distance between two femtocells. Neighboring femtocells can be grouped into a physical cluster if the spatial correlation between any two femtocells satisfies the following constraint:

$$\gamma \geq \gamma_0, \tag{6}$$

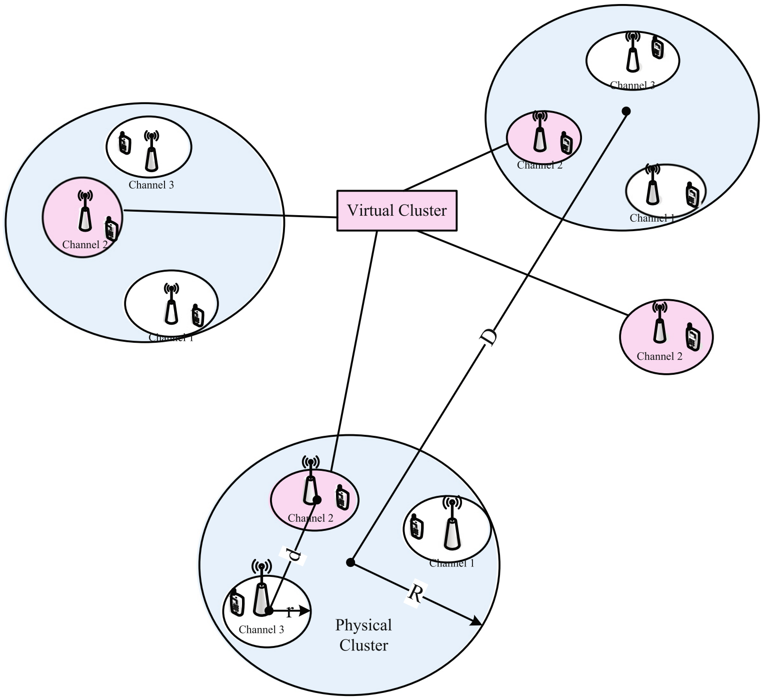

Figure 2 Illustration of physical cluster and virtual cluster.

where γ_0 is the minimum spatial correlation depending on safety distance d_0. Each physical cluster has a clustering center that could be found through some clustering algorithms. In a dense deployment scenario, there are quite finite channels, say six channels (1.4 MHz), for femtocells so that the number of femtocells grouped in a PC cannot be larger than 6. That is because femtocells in a PC need to use different channels to avoid co-tier interference.

In contrast to physical cluster that is related to the location information of the femtocells, virtual cluster is a kind of logical cluster. Instead of being physically co-located, the femtocells using the same channel but in different physical clusters can be grouped into a virtual cluster. However, if two PCs are quite close, potential harmful interference may still be inadmissible. Thus, we define the spatial correlation of the PCs, γ', as follows:

$$\gamma' = \frac{R}{D}, \tag{7}$$

where R denotes the radius of the PC which depends on the safety distance d_0. D denotes the distance between two PCs. In order to ensure the interference among the femtocells in a VC is generally tolerable, another constraint needs to be satisfied

$$\gamma' \le \gamma'_0, \tag{8}$$

where $\gamma'_0 = R/(2R + d_0)$.If R is defined as half of the d_0, then we have $\gamma'_0 = 1/4$. In other words, member femtocells operating on the same channel in a virtual cluster should be separated as far as possible to guarantee minimum interference.

3 Problem formulation and interference mitigation

Given the fact that the interference generated by femtocells tends to be a localized phenomenon due to the small coverage and large number of femtocells, centralized methods may be confronted with more challenges with limited control and instruction information from the radio network controller, which implies local and possibly distributed solutions will be more practical and efficient. Following this idea, we are interested in the feasibility of interference minimization by multiple femtocells collaboratively in a local area. In this section, the primary problem will be formulated and analyzed. And in the following section, two secondary problems will be illustrated, respectively. Finally, we will incorporate them together to produce our proposed scheme.

First of all, we will consider the downlink power allocation problem of multiple femtocells. As set forth, our objective is to minimize aggregate cross-tier interference from multiple femtocells to the co-channel primary user subject to the total capacity requirement and total transmission power constraints of these femtocells. Therefore, the optimization problem can be formulated as follows:

$$\begin{aligned}
&P1: \min_{P_{k,j,i}} \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{K} \rho_{k,j,i}P_{k,j,i}\Omega_{k,j,i}\\
&\text{Subject to}\\
&\rho_{k,j,i} \in \{0,1\}, \forall k,j,i\\
&\sum_{j=1}^{M} \rho_{k,j,i} \le 1, \forall k, \forall i \in \{1,2,\cdots,N\}\\
&\sum_{j=1}^{M}\sum_{k=1}^{K} \rho_{k,j,i}C_{k,j,i} \ge C_{T_i}, \forall i \in \{1,2,\cdots,N\}\\
&\sum_{j=1}^{M}\sum_{k=1}^{K} \rho_{k,j,i}P_{k,j,i} \le P_{T_i}, \forall i \in \{1,2,\cdots,N\}\\
&P_{k,j,i} \ge 0, \forall k \in \{1,2,\cdots,K\}, \forall j,i,
\end{aligned} \tag{9}$$

where $\rho_{k,j,i}$ denotes the subcarrier allocation index. If the kth subcarrier is allocated to the jth FUE of the ith femtocell, $\rho_{k,j,i} = 1$, otherwise $\rho_{k,j,i} = 0$. $P_{k,j,i}$ denotes the transmission power in the kth subcarrier from the ith FAP to the jth FUE, and $\Omega_{k,j,i}$ denotes the interference factor of the jth FUE of the ith femtocell in the kth subcarrier. $C_{k,j,i}$ denotes the capacity of the jth FUE of the ith femtocell in the kth subcarrier, and C_{T_i} denotes the total capacity requirement of the ith femtocell. P_{T_i} denotes the total power budget of the ith femtocell. N is the number of femtocells, M is the number of the users of each femtocell (usually 2 to 4), while K is the total number of subcarriers in each femtocell.

In order to solve this optimization problem with lower computational complexity, two steps are needed [24]. That is, in each femtocell, the subcarriers are assigned to the users in the first step followed by allocating the power for these subcarriers then. Herein, the subcarriers to the user allocation in each femtocell is carried out according to the following formula:

$$j^* = \arg\max_j \left\{H_{k,j}/\sigma^2\right\}; \rho_{k,j^*} = 1, \tag{10}$$

where $H_{k,j}$ denotes the channel power gain of the kth subcarrier from the FAP to the jth FUE. And $\sigma^2 = I_{k,j} + P_N$ where $I_{k,j}$ denotes the interference power of the jth FUE in the kth subcarrier while P_N denotes the power of noise. The assignment is mainly considering the channel power gain to interference and noise ratio. The maximum data rate in downlink can be obtained if the subcarriers are assigned to the user who has the best channel gain for that subcarrier. In this regard, other effective assignment strategy may also be applicable.

After the assignment of the subcarriers to FUEs in each femtocell, the values of the subcarrier allocation indicators $\rho_{k,j,i}$ are determined. Using the Shannon capacity formula $C_{k,i} = \log_2\left(1 + \frac{P_{k,i}H_{k,i}}{\sigma^2}\right)$, we can get

$$P_{k,i} = \frac{\sigma^2}{H_{k,i}}\left(2^{C_{k,i}} - 1\right). \tag{11}$$

Here, the bandwidth of the subcarrier is omitted as it is a constant. Substituting Eq. (11) into Eq. (9), the problem $P1$ could be reformulated as follows:

$$P2: \min_{C_{k,i}} \sum_{i=1}^{N}\sum_{k=1}^{K} \frac{\sigma^2}{H_{k,i}}\left(2^{C_{k,i}} - 1\right)\Omega_{k,i}$$

Subject to

$$\sum_{k=1}^{K} C_{k,i} \geq C_{T_i}, \forall i \in \{1, 2, \cdots, N\} \tag{12}$$

$$\sum_{k=1}^{K} \frac{\sigma^2}{H_{k,i}}\left(2^{C_{k,i}} - 1\right) \leq P_{T_i}, \forall i \in \{1, 2, \cdots, N\}$$

$$C_{k,i} \geq 0, \forall k \in \{1, 2, \cdots, K\}, \forall i \in \{1, 2, \cdots, N\}.$$

Theorem: The optimal solution to $P2$ is

$$P_{k,i}^{*} = \left[\frac{\alpha_i}{\Omega_{k,i} + \beta_i} - \frac{\sigma^2}{H_{k,i}}\right]^{+}, \forall i \in \{1, 2, \cdots, N\}, \tag{13}$$

where $[x]^{+} = \max(0, x)$.

The proof is detailed in the 'Appendix' section.

However, it is computationally complex to solve more than one Lagrangian multiplier shown in Eq. (13), these multipliers can be found numerically using ellipsoid or interior point method with a polynomial time complexity $o\left(N^3\right)$ [25]. In addition, the solution indicates that aggregate interference minimization of multiple femtocells tends to be a distributed result, which means that as long as the interference from each femtocell is minimized, the aggregate interference of multiple femtocells will reach the minimum level. Actually, this can be regarded as a non-collaborative way for resource allocation. Since the PUs at the cell coverage of the licensed systems should satisfy at least a target SINR or an outage probability, which will produce an acceptable interference threshold, the optimized aggregate interference from multiple femtocells should be controlled under this threshold by appropriately selecting capacity requirement and power budget of each femtocell as well as the number of femtocells. However, this is the case that we did not consider the co-tier interference among multiple femtocells. Moreover, the interference component from each femtocell to the co-channel PU is also different. In Section 4, we will further discuss the two secondary problems based on PC and VC.

Interference minimization in a single femtocell is very important in our analysis. Therefore, we will first formulate the subproblem and then provide the solution algorithm since it will be used for collaborative resource allocation in the following section.

3.1 Interference minimization in a single femtocell

As Eq. (13) shows, each single femtocell could minimize its interference to the co-channel primary user by optimal subcarrier power allocation. In the circumstances, the problem $P2$ could be simplified and reformulated as follows:

$$P3: \min_{C_k} \sum_{k=1}^{K} \frac{\sigma^2}{H_k}\left(2^{C_k} - 1\right)\Omega_k$$

Subject to

$$\sum_{k=1}^{K} C_k \geq C_T \tag{14}$$

$$\sum_{k=1}^{K} \frac{\sigma^2}{H_k}\left(2^{C_k} - 1\right) \leq P_T$$

$$C_k \geq 0, \forall k \in \{1, 2, \cdots, K\}.$$

For this problem, we will consider that firstly, we allocate the power to the subcarriers under only the capacity requirement, where the final solution for the single femtocell can be simplified as follows:

$$P_k' = \left[\frac{\alpha}{\Omega_k} - \frac{\sigma^2}{H_k}\right]^{+}. \tag{15}$$

By substituting Eq. (15) into $\sum_{k=1}^{K} C_k = C_T$, we can get

$$\alpha = \sqrt[K]{2^{C_T} \cdot \prod_{k=1}^{K} \frac{\sigma^2}{H_k} \cdot \Omega_k}. \tag{16}$$

Then, we summarize the power of all the subcarriers and compare it with the total power budget. If it is over the budget, the problem $P3$ has no solution. Otherwise, i.e., $\sum_{k=1}^{K} P_k{}' \leq P_T, \forall k \in \{1, 2, \cdots, K\}$, then Eqs. (15) and (16) will be the optimal solution for $P3$.

It is notable that if the summation of the allocated power under only the capacity requirement is lower than the available power budget, there exists the power margin that can still be utilized

$$P_{Left} = P_T - \sum_{k=1}^{K} P_k'. \tag{17}$$

Basically, there are two thoughts about the left power. That is, we can add it to all the subcarriers equally or we can add it to the subcarrier with the minimal interference factor Ω_k. In fact, the latter will produce less interference, which is also validated in the numerical simulations section. Therefore, we adopt this strategy, and our proposed interference minimization algorithm can be described in Algorithm 1.

Algorithm 1 Interference minimization (IM) algorithm

```
Input: $K, P_{\text{budget}}, C_{\text{limit}}$
Output: $P_k, \forall k \in F, I_{\text{total}}$
Initialization: $\text{F} = \text{N} = \{1, 2, \cdots, K\}$, $P_T = P_{\text{budget}}$, and $C_T = C_{\text{limit}}$
Start
  1. Sort $\left\{V_k = \frac{\sigma^2}{H_k}\Omega_k, k \in \text{N}\right\}$ in decreasing order with $i$ being the sorted index
  2. $V_{\text{prod}} = \prod_{k \in \text{N}} V_k$, $\alpha = \sqrt[|\text{N}|]{2^{C_T} \cdot V_{\text{prod}}}$, $n = 1$
  3. while $\alpha < V_{i(n)}$ do
         $V_{\text{prod}} = V_{\text{prod}} / V_{i(n)}$, $\text{N} = \text{N} \backslash \{i(n)\}$,
         $\alpha = \sqrt[|\text{N}|]{2^{C_T} \cdot V_{\text{prod}}}$, $n = n + 1$
  4. end while
  5. Set $P_k{}' = \left[\frac{\alpha}{\Omega_k} - \frac{\sigma^2}{H_k}\right]^+$
  6. if $\sum_{k=1}^{K} P_k{}' > P_T$ then
         there is no solution and stop the algorithm
  7. else
         $P_{\text{Left}} = P_T - \sum_{k=1}^{K} P_k{}'$,
         $k^* = \arg\min_k \{\Omega_k\}$, $P_{k^*}{}' = P_{k^*}{}' + P_{\text{Left}}$
  8. end if
  9. $P_k = P_k{}', \forall k \in \text{F}$, $I_{\text{total}} = \sum_{k=1}^{K} P_k \Omega_k$
End
```

4 Collaborative resource allocation based on PC and VC

In Section 3, we formulated the primary optimization problem and provided a solution algorithm for interference minimization in a single femtocell. In other words, Section 3 addressed the issue of cross-tier interference minimization from multiple femtocells in a non-collaborative way. In this section, we will concentrate more on dealing with the inter-femtocell interference and the cooperation among femtocells.

4.1 Physical cluster-based femtocell channel assignment

Femtocells that are sharing the same channels may interfere with each other when they are geographically adjacent located. Thus, neighboring femtocells need to be assigned different channels to avoid co-tier interference. As mentioned earlier, we could group neighboring femtocells into a physical cluster according to the spatial correlation of these femtocells. In each physical cluster, Hungarian algorithm will be employed to assign different channels to member femtocells so that the total interference caused by these femtocells to the primary users can be minimized. Hungarian algorithm was put forward by Hungarian mathematician Edmonds in 1965, and this algorithm is generally used to solve the problem of linear task allocation. In other words, limited channel resources are utilized by member femtocells in a PC collaboratively. The corresponding optimization problem can be formulated as follows:

$$
\begin{aligned}
&P4: \min_{\nu_{m,n}} \sum_{n=1}^{L} \sum_{m=1}^{M_0} c_{m,n} \nu_{m,n} \\
&\text{Subject to} \\
&\nu_{m,n} \in \{0, 1\}, \forall m, n \\
&\sum_{m=1}^{M_0} \nu_{m,n} = 1, \forall n \\
&\sum_{n=1}^{L} \nu_{m,n} = 1, \forall m,
\end{aligned}
\tag{18}
$$

where $\nu_{m,n}$ denotes the femtocell channel assignment indicator. $\nu_{m,n} = 1$ means that the nth channel is assigned to the mth femtocell, otherwise $\nu_{m,n} = 0$. L is the number of available channels in a local area, while M_0 represents the number of the femtocells in a physical cluster. Usually, we have $M_0 \leq L$. Also, $c_{m,n}$ is the link weight that is used to construct the utility matrix and can be selected as follows:

$$
c_{m,n} = I_{m,n} = \sum_{k=1}^{K} P_k \Omega_k, \tag{19}
$$

where $I_{m,n}$ denotes the minimal interference induced by the mth femtocell using the nth channel to the co-channel primary user and can be calculated by applying Algorithm 1.

It is assumed that each femtocell is assigned only one channel that consists of a group of subcarriers and the primary users using these channels are in different locations. However, when Hungarian algorithm is employed in a PC, certain femtocells cannot be assigned the best channel due to member cooperation. Nevertheless, Hungarian algorithm has got much better performance based on a minimum interference generation criterion, which can be demonstrated in the numerical results section.

It is worthwhile to note that what Hungarian algorithm minimized is the interference to the whole primary system including multiple primary users. As for each primary user, the aggregate interference is not minimized and may be still unacceptable. That is why we take further measures to deal with the problem based on the virtual cluster.

4.2 Virtual cluster-based femtocell power allocation

After the assignment of available channels, inter-femtocell interference could be avoided and the interference between femtocells and primary systems could be mitigated to some extent. However, the aggregate interference from multiple femtocells sharing the same channel might be still inadmissible to the co-channel primary user. If a distributed approach is adopted, the femtocells in a virtual cluster is non-collaborative with a fixed power budget. They could have different contributes to the interference generation because of different distances from the victim primary user. Moreover, the mobility of the primary user also leads to the variation of the interference component.

Therefore, it is necessary for femtocells in each of the virtual clusters to adjust power budgets collaboratively to reduce the harmful cross-tier interference further. As set forth, member femtocells of a virtual cluster is actually located in different physical clusters including certain scattered femtocells that cannot be grouped into any PCs due to the lower spatial correlation. We will formulate the power budget reallocation problem as follows:

$$\begin{aligned} &P5: \min_{P_i} \sum_{i=1}^{N} P_i \Psi_i \\ &\text{Subject to} \\ &\sum_{i=1}^{N} P_i = P_{\text{total}} \\ &P_{\min} \leq P_i \leq P_{\max}, \forall i \in \{1, 2, \cdots, N\}, \end{aligned} \tag{20}$$

where P_i denotes the power budget of the ith FAP and Ψ_i denotes the pass loss component from the ith FAP to the primary user. $P_{\text{total}} = NP_0$ where P_0 denotes the initially fixed power budget for all FAPs while N is the number of the femtocells in a VC. $P_{\min}$ and $P_{\max}$ are available minimum and maximum power budgets for the FAPs, respectively.

This is a simple linear optimization problem or portfolio optimization problem [25] more exactly. P_i represents the investment in asset i, and the return of each investment is fixed and given by $-\Psi_i$. It is obvious that we should invest in those assets that have larger rate of return on investment. Then, the concrete solution will be described in the summarized power budget adjustment algorithm (Algorithm 2).

Based on the analysis stated above, we can combine both Sections 3 and 4 together to form our proposed cluster-based cooperative femtocell interference mitigation scheme. Generally, the total implementation procedure is described in Algorithm 3.

Algorithm 2 Power budget adjustment algorithm

```
Input: $N, P_{\text{budget}}, P_{\min}, P_{\max}$
Output: $P_i, \forall i \in F$
Initialization: $\text{F} = \{1, 2, \cdots, N\}$, $P_0 = P_{\text{budget}}$, and $P_{\min} = P_{\min}, P_{\max} = P_{\max}$
Start
  1. In each of the virtual clusters, sort $\{\Psi_i, i \in F\}$ in increasing order with $s$ being the sorted index
  2. $Y = \left\lfloor \frac{NP_0 - NP_{\min}}{P_{\max} - P_{\min}} \right\rfloor, n = 1$
  3. while $n \leq Y$ do
         $P_{s(n)} = P_{\max}, n = n + 1$
  4. end while
  5. $P_{s(Y+1)} = P_{\min} + \text{mod}\left(\frac{NP_0 - NP_{\min}}{P_{\max} - P_{\min}}\right)$,
     $P_{s(Y+2)} = \cdots = P_{s(N)} = P_{\min}$
  6. if $\Psi_i = \cdots = \Psi_k$ then
         $P_i = \cdots = P_k = \frac{P_i + \cdots + P_k}{k - i + 1}$
  7. end if
End
```

Algorithm 3 Proposed cluster-based interference minimization (CIM) algorithm

```
Initialization: No. of femtocells: $S$, $\gamma_0$, $\gamma_0'$
Start
  1. Determine the available channels via cognitive sensing or joint scheduling and then divide physical clusters among femtocells according to the spatial correlation constraints
  2. Execute Algorithm 1 to calculate the minimum interference weight when femtocells operating on different channels
  3. Execute Hungarian algorithm in each of the physical clusters to assign channels for femtocells
  4. Divide virtual clusters among femtocells, and in each of the virtual clusters, apply Algorithm 2 to adjust power budgets of member femtocells
  5. Under adjusted power budgets of femtocells in each virtual cluster, apply Algorithm 1 again to update the power allocated to each subcarrier in each femtocell
End
```

5 Simulation results

In this section, our proposed downlink interference minimization scheme for femtocell networks will be evaluated by extensive numerical results. Simulation parameters are listed in Table 1.

It is assumed that there is a light wall between the FAP and the FUE, but a heavy wall between the FAP and the primary user. Without loss of generality, the interference introduced by the primary systems to the FUEs is assumed

Table 1 Simulation parameters

Parameter description	Value
Femtocell radius	10 m
Maximum number of FUEs per femtocell	4
Femtocell transmission power (fixed)	10 dBm
Femtocell transmission power (min)	8 dBm
Femtocell transmission power (max)	12 dBm
The noise power	$2.4 \times 10^{-13} W$
Light wall penetration loss	5 dB
Heavy wall penetration loss	12 dB
Carrier frequency	2 GHz (600 MHz)
Channel bandwidth	180 KHz
Subcarrier bandwidth	15 KHz
Number of subcarriers per channel	12

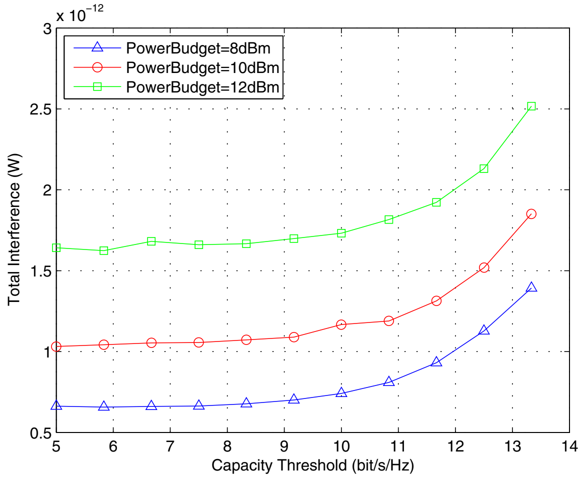

Figure 4 **Total interference vs. capacity threshold with different power budgets in a single femtocell.**

to be negligible due to the separation of a long enough safety distance. If femtocells are located at the cell margin of the primary systems, there will be no degradation in terms of the capacity of femtocell users.

5.1 Interference minimization in a single femtocell

Since femtocells have the feature of self-organizing, it is important to mitigate the interference from a single femtocell. In the simulation, we use capacity 160 bit/s for the maximum capacity threshold and power 10 dBm as the fixed power budget of the femtocell. Figures 3, 4, 5 and 6 reflect some characteristics of interference decrease.

Figure 3 illustrates the performance of the proposed IM algorithm compared with the other two power allocation schemes. To be specific, it is shown that the total interference produced by IM algorithm is approximately one third of that by average power allocation scheme with a fixed 10-dBm power budget of the FAP when the capacity threshold is 10 bit/s/Hz and that proportion becomes one half when the capacity threshold increases to 13.4 bit/s/Hz. The effect of interference mitigation is absolutely remarkable. Additionally, IM algorithm also outperforms left power fair allocation scheme mentioned in subsection 3.1. As the capacity threshold increases, the total interference stays invariable for average power allocation, decreasing for left power fair allocation and increasing for IM algorithm. That is because when capacity threshold increases, the power allocated to each subcarrier increases, which leads to the decrease of left power budget. Thus, the gap between left power fair allocation

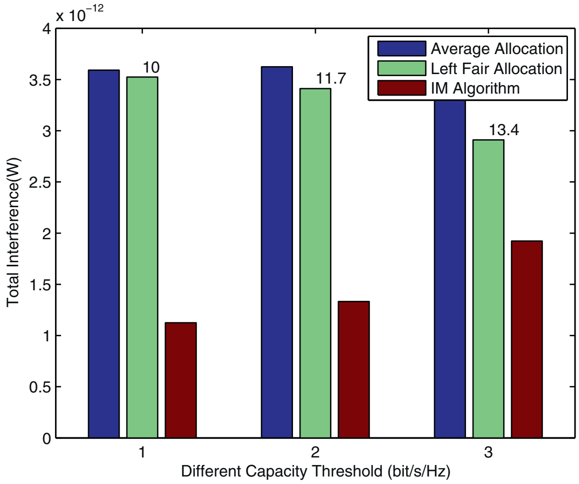

Figure 3 **Comparison of different subcarrier power allocation schemes in a single femtocell.**

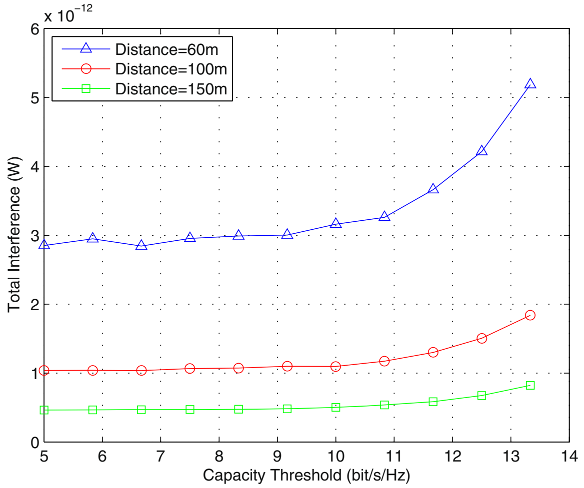

Figure 5 **Total interference vs. capacity threshold with different distances from the femtocell to the primary user.**

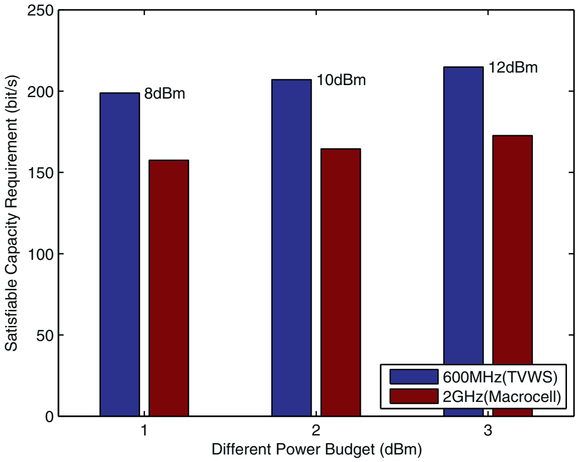

Figure 6 **Comparison of different frequencies used by the femtocell.**

and IM algorithm will be narrowed. In the extreme cases where there is no left power budget, left power fair allocation and IM algorithm will achieve the same performance.

Figure 4 plots the total interference versus the capacity constraint with different power budgets of the FAP using the proposed IM algorithm in a single femtocell. It is obvious that the total interference increases along with the increase of the capacity threshold and the power budget since it is just a function of the two input parameters. In fact, there is a tradeoff between the desirable minimum total interference and expected maximum system throughput. Thus, the capacity threshold should be appropriately selected to control the interference under a certain level.

Figure 5 describes the influence of distance from the femtocell to the victim primary user. As Figure 5 shows, a longer separation distance to the primary user will make the femtocell generate less interference, which is the most direct and effective approach for interference mitigation. In order to meet the interference threshold of the primary user, a safety distance is required. However, this is not suitable for the case that multiple femtocells use the same channel where the single femtocell safety distance is invalid because of the aggregate interference.

Figure 6 compares the performances of two different frequencies used by the femtocell. Actually, they represent two typical licensed systems, that is, 2 GHz for the macrocell networks and 600 MHz for the TV broadcast system. Figure 6 indicates that the TVWS could satisfy higher capacity requirement than the macrocell frequency bands under different power budget constraints. This result can be attributed to the good transmission character of the TV bands, which also demonstrates that the femtocell could utilize TVWS to achieve higher data rate for more high-quality services.

5.2 Physical cluster-based femtocell channel assignment

Figure 7 illustrates the optimal performance of Hungarian algorithm when it is employed to assign channels among the femtocells in a physical cluster based on a minimum interference generation criterion. As Figure 7 shows, random channel assignment will produce much more interference than Hungarian algorithm especially when the number of the accessible channels for femtocells in a physical cluster is increasing. In other words, the cross-tier interference could be effectively reduced by Hungarian algorithm while avoiding the co-tier interference in a heavily deployed femtocell network.

5.3 Virtual cluster-based femtocell power allocation

Figures 8 and 9 demonstrate the effectiveness of power budget adjustment based on the virtual cluster. As is shown in Figure 8, after the collaborative reallocation of the power budgets among member femtocells in a VC, the total aggregate interference is reduced compared to the non-collaborative way, where each FAP has equal and fixed power budget. However, the decrease of interference is quite limited.

Figure 9 extends the range of power budget adjustment but still with a minor interference decrease. This is mainly because the capacity threshold is the same among member femtocells in a VC considering the fairness of the femtocells. If we adjust both the power budget and the capacity threshold of the femtocell according to different interference factors of femtocells, the total aggregate interference will be reduced further. In addition, a large number of femtocells in a VC will definitely result in an increase of total aggregate interference. Therefore, the femtocell number in a VC cannot be excessive in order to control the interference under a certain level.

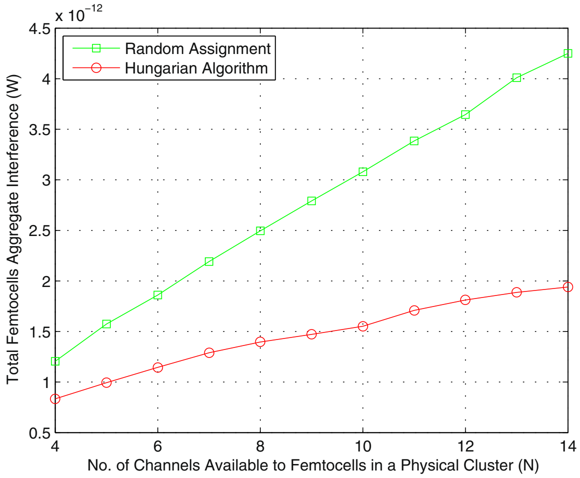

Figure 7 **Comparison of channel assignment algorithms based on the physical cluster.**

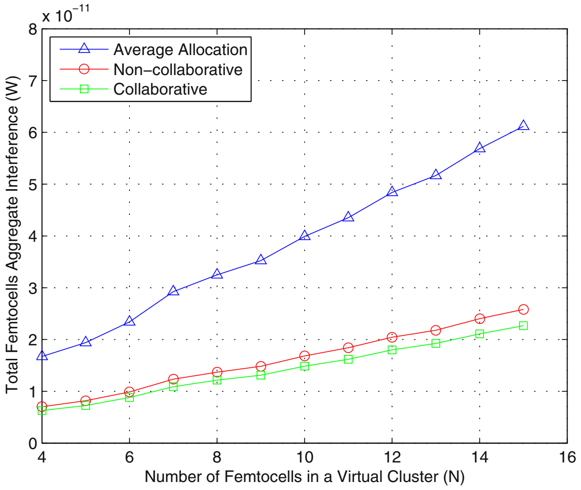

Figure 8 Comparison of power allocation algorithms based on the virtual cluster with $P_{\min} = 8$ dBm, $P_{\max} = 12$ dBm.

6 Conclusions

In this paper, an interference minimization scheme in downlink cognitive femtocell networks is proposed. The joint channel assignment and power allocation scheme aims at minimizing the interference from femtocells to the primary users while avoiding the co-tier femtocell interference. Based on the physical cluster and the virtual cluster, multiple femtocells could utilize resources cooperatively to mitigate the interference. The related interference minimization problems are formulated, and employed algorithms are combined together to reduce the interference layer by layer. Moreover, by taking advantage of cognitive radio technology as well as joint scheduling, the proposed scheme could address the severe interference issue even with fewer available channels in the heavily deployed femtocell networks. Finally, the numerical simulation results verify that the effect of interference mitigation is generally notable.

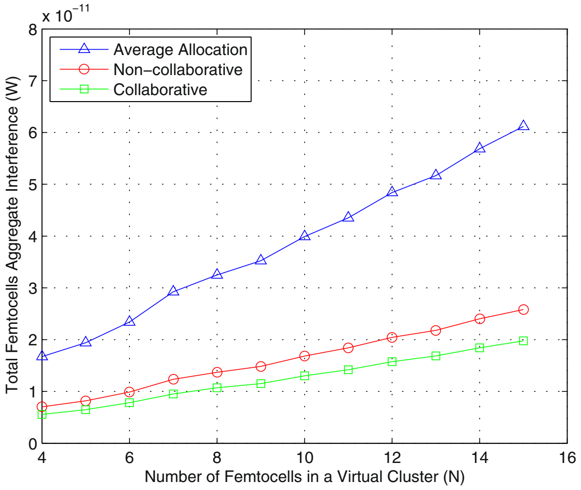

Figure 9 Comparison of power allocation algorithms based on the virtual cluster with $P_{\min} = 6$ dBm, $P_{\max} = 14$ dBm.

Appendix

The proof of Theorem 1.

Proof. The problem $P2$ is a convex optimization problem which can be solved by the Lagrangian multiplier approach. The Lagrangian of $P2$ can be written as

$$\begin{aligned}G = &\sum_{i=1}^{N}\sum_{k=1}^{K}\frac{\sigma^2}{H_{k,i}}\left(2^{C^*_{k,i}-1}\right)\Omega_{k,i} + \sum_{i=1}^{N}\alpha_i\left(C_{T_i} - \sum_{k=1}^{K}C^*_{k,i}\right)\\ &+\sum_{i=1}^{N}\beta_i\left(\sum_{k=1}^{K}\frac{\sigma^2}{H_{k,i}}\left(2^{C^*_{k,i}}-1\right) - P_{T_i}\right)\\ &-\sum_{i=1}^{N}\sum_{k=1}^{K}\frac{\sigma^2}{H_{k,i}}\left(2^{C^*_{k,i}}-1\right)\mu_{k,i}\\ =&\sum_{i=1}^{N}L_i\end{aligned} \tag{21}$$

where

$$\begin{aligned}L_i = &\sum_{k=1}^{K}\frac{\sigma^2}{H_{k,i}}\left(2^{C^*_{k,i}}-1\right)\Omega_{k,i} + \alpha_i\left(C_{T_i} - \sum_{k=1}^{K}C^*_{k,i}\right)\\ &+\beta_i\left(\sum_{k=1}^{K}\frac{\sigma^2}{H_{k,i}}\left(2^{C^*_{k,i}}-1\right) - P_{T_i}\right) - \sum_{k=1}^{K}\frac{\sigma^2}{H_{k,i}}\left(2^{C^*_{k,i}}-1\right)\mu_{k,i}\end{aligned} \tag{22}$$

where $\alpha_i, \beta_i, i \in \{1, 2, \cdots, N\}$ and $\mu_{k,i}, k \in \{1, 2, \cdots, K\}$, $i \in \{1, 2, \cdots, N\}$ are the Lagrange multipliers. The corresponding Karush-Kuhn-Tucker conditions can be written as follows:

$$\begin{aligned}&C^*_{k,i} \geq 0; \alpha_i \geq 0; \beta_i \geq 0; \mu_{k,i} \geq 0; \mu_{k,i}\frac{\sigma^2}{H_{k,i}}\left(2^{C^*_{k,i}}-1\right) = 0\\ &\alpha_i\left(C_{T_i} - \sum_{k=1}^{K}C^*_{k,i}\right) = 0; \beta_i\left(\sum_{k=1}^{K}\frac{\sigma^2}{H_{k,i}}\left(2^{C^*_{k,i}}-1\right) - P_{T_i}\right) = 0\\ &\frac{\partial L_i}{\partial C^*_{k,i}} = \frac{\sigma^2}{H_{k,i}}\left(2^{C^*_{k,i}}\Omega_{k,i}\right) - \alpha_i + \beta_i\frac{\sigma^2}{H_{k,i}}2^{C^*_{k,i}} - \mu_{k,i}\frac{\sigma^2}{H_{k,i}}2^{C^*_{k,i}} = 0\end{aligned} \tag{23}$$

Then, the final solution should satisfy the total power and capacity constraints of each femtocell. Rearranging the last condition in Eq. (23), we can obtain

$$C^*_{k,i} = \log 2\left(\frac{\alpha_i H_{k,i}}{\sigma^2\left(\Omega_{k,i} + \beta_i - \mu_{k,i}\right)}\right) \tag{24}$$

Substituting Eq. (24) into Eq. (11), we have

$$P_{k,i}^{*} = \frac{\alpha_i}{\Omega_{k,i} + \beta_i - \mu_{k,i}} - \frac{\sigma^2}{H_{k,i}} \tag{25}$$

Considering $\mu_{k,i} P_{k,i}^{*} = 0$, if $\frac{\sigma^2}{H_{k,i}} < \frac{\alpha_i}{\Omega_{k,i}+\beta_i-\mu_{k,i}}$, we have $\mu_{k,i} = 0$. Then, $P_{k,i}^{*} = \frac{\alpha_i}{\Omega_{k,i}+\beta_i} - \frac{\sigma^2}{H_{k,i}}$. Otherwise, if $\frac{\sigma^2}{H_{k,i}} \geq \frac{\alpha_i}{\Omega_{k,i}+\beta_i-\mu_{k,i}}$, owing to that $P_{k,i}^{*} = \frac{\alpha_i}{\Omega_{k,i}+\beta_i-\mu_{k,i}} - \frac{\sigma^2}{H_{k,i}} \geq 0$, we can get $P_{k,i}^{*} = 0$. Summarizing the above derivations achieves the claim. $\square$

Competing interests

The authors declare that they have no competing interests.

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