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Power management in adjacent cognitive femtocells with distance-dependent interference in full coverage area

Guobin Zhang[*], Xin Ao, Ping Yang and Ming Li

Abstract

In cognitive heterogeneous networks, when multiple adjacent femtocells are deployed, uncontrolled transmission power can lead to severe mutual interference. In order to reduce interference while satisfying capacity requirements, we propose a power management scheme for an adjacent femtocell network. Firstly, we build an interference model for adjacent femtocells, in which distance-dependent interference to terminals within the whole femtocell coverage area is considered. Then, we calculate the total capacity of adjacent femtocells based on the mutual interference and formulate a non-convex optimization problem to maximize the capacity under the transmission power constraints. To solve the non-convex problem, we divide it into two convex subproblems and solve them with the Lagrange dual theory and linear programming method. Finally, we derive the closed-form expression of the optimal power configuration to maximize capacity while minimizing energy consumption simultaneously. The simulation results indicate that the proposed power scheme demonstrates obvious improvement in terms of capacity and power economization, compared with the maximal power configuration method.

Keywords: Adjacent femtocells, Power management, Distance-dependent interference, Capacity optimization

1 Introduction

Recently, with the development of radio access technologies and mobile internet applications, the demand for mobile data services increases explosively [1]. Latest surveys show that more than 80 % of mobile traffic is originated at home or work [2]. Therefore, traditional cellular networks are confronted with the challenge of enhancing the coverage and improving the capacity of indoor and hotspot areas. In allusion to this challenge, femtocell networks which offer better quality of experience (QoE) for indoor and hotspot users [3] are being considered as a promising technique to enhance the performance of cellular networks.

When multitudes of femtocells coexist, severe interference may arise between adjacent femtocells if the transmission power is uncontrolled. Currently, a lot of research efforts are focused on the power control and interference elimination issues in heterogeneous femtocell networks.

Most of these researches establish a heterogeneous network structure model, analyze interference between different cells, and optimize power configuration under interference and maximal transmission constraints. The authors in [4–6] construct a heterogeneous network with one macro cell and multiple small cells. The small cells utilize the licensed spectrum of the macro cell through cognitive radio with the overlay style. The authors in [7, 8] build an interference model for a hierarchical heterogeneous network and optimize the time frequency resource allocation. The proposed interference model considers the interference of the licensed network to the second- and third-level networks, as well as the interference between the second- and third-level networks. The authors in [8, 9] aim to maximize the capacity of the cognitive network, considering the interference constraint of the licensed network and transmission power constraint of the cognitive network. The authors in [3] propose a resource allocation scheme for cognitive femtocells considering sub-channel occupation fairness, co-tier and cross-tier interference mitigation, and spectrum-sensing errors.

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The main problems of the aforementioned researches are as follows: (1) Most literatures use the same approach in the analysis of the interference between femtocells, which seldom consider the distribution range and relative locations of femtocells. Therefore, few of them manage to analyze the interference and power control policy for adjacent femtocells, where severe interferences arise more frequently. (2) Few of the existing literatures discuss about the effect of user distribution and density upon network capacity, which is worthy of being considered in the process of power control for enhancing the network capacity. (3) The present interference model of a heterogeneous network is complex mainly due to the reason that all the femtocells are treated together rather than separately. As a result, the power optimization problem demands high computational complexity, and it is also hard to achieve a closed-form solution. What is worse, some researches [7–10] assume fixed channel gains from transmitters to receivers in spite of their positions. Obviously, this is against the common sense that channel gain varies with transmission distance. Therefore, building a distance-dependent interference model is a more rational option.

To reduce the interference between adjacent femtocells and enhance their sum capacity simultaneously, we propose a specialized power management scheme in this paper. In the scheme, we consider the distance-dependent variation of channel gain in the analysis of network interference and sum capacity. To maximize the sum capacity, a non-convex power optimization problem is formulated and a two-step solution is provided accordingly. The solution divides the original non-convex problem into two convex problems and solves them by the Lagrange dual theory and the linear programming theory. The main contributions of this paper are summarized as follows:

1. We propose an interference model considering a distance-dependent channel gain for adjacent femtocells.
2. When computing the sum capacity of femtocells, we take into account the user density for each femtocell and the signal to noise ratio (SNR) of users distributed in the whole coverage area of the femtocells.
3) We derive a closed-form expression of an optimal power configuration scheme for adjacent femtocells, which can maximize their sum capacity while satisfying respective capacity requirement and minimizing the total energy consumption.

The rest of this paper is organized as follows. In Section 2, we construct the system model including a two-level heterogeneous network and multiple adjacent femtocells. In Section 3, we build the distance-dependent interference model and formulate the problem of network

capacity optimization. We also provide a two-step method for solving the problem and summarize the detailed algorithm for optimal power configuration. Simulation results for performance analysis and validation are given in Section 4, followed by the conclusion in Section 5.

2 System model

Similar to [1, 6, 11–13], we consider a two-level heterogeneous cognitive network as shown in Fig. 1. The macro cell is at the first level, which occupies the licensed frequency. Multiple femtocells compose the second-level network, which adopt cognitive radio to sense the licensed frequency and find idle frequency to utilize.
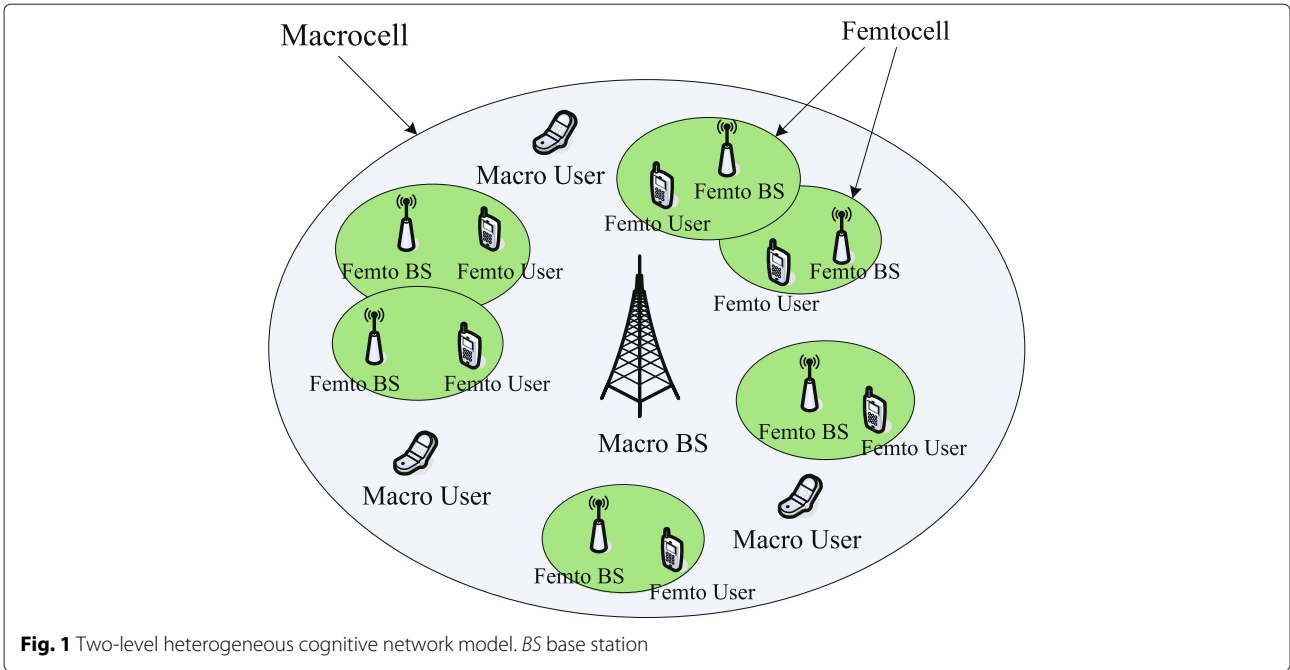
The femtocell is deployed to cover the hot spots of a licensed network so as to enhance the communication quality of service (QoS) of a hot spot area [14, 15]. In a dense femtocell-deployed network, severe interference may exist between adjacent femtocells. Therefore, we construct the network model with two adjacent femtocells to analyze their mutual interference. As shown in Fig. 2, two femtocells named Femtocell 1 and Femtocell 2 cover two circles with the radius of R_1 and R_2, respectively. Their base stations are both located in the center of the coverage area. The distance between the base stations of Femtocell 1 and Femtocell 2 is denoted by D. According to [16], the interference gain varies with the distance from the user position to the femtocell base station. Without loss of generality, we randomly choose one point to analyze its received interference. The details will be provided later in Section 3. In Fig. 2, we assume dot A_1 is the randomly chosen point, and we define L_1 to denote the distance from A_1 to the center point of Femtocell 1 and define L_2 to denote the distance from A_1 to the base station of Femtocell 2. The angle between L_1 and D is denoted by θ. In Section 3, we will discuss the power configuration strategy between the two adjacent femtocells based on the model as shown in Fig. 2.

3 Power configuration strategy

In this section, we carry out a thorough analysis of the interference and capacity of adjacent femtocells and propose a detailed power management strategy to maximize the sum capacity while minimizing the power consumption.

3.1 Interference and capacity analysis

For wireless communication, the channel gain varies with the distance between transmitter and receiver. The larger the distance, the smaller the channel gain becomes. Hence, in femtocell networks, the channel gain changes with the distance between the current user and the base station of the adjacent femtocell. Assume that the transmission power of Femtocell 1 and Femtocell 2, as shown in Fig. 2, is denoted by P_1 and P_2, respectively. Let P_{1,A_1}

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Fig. 1 Two-level heterogeneous cognitive network model. *BS* base station

and P_{2,A_1} be the received power from the base station of Femtocell 1 and Femtocell 2 in dot A_1, respectively. According to the literature [16], P_{1,A_1} and P_{2,A_1} can be expressed as the following, i.e.,

$$P_{1,A_1} = P_1 H_1 C_1 L_1^{-\alpha_1}, \tag{1}$$

$$P_{2,A_1} = P_2 H_2 C_2 L_2^{-\alpha_2}. \tag{2}$$

In Eqs. (1) and (2), H_1 and H_2 are random variables capturing the small-scale fading value of the radio link from the base station of Femtocell 1 and Femtocell 2, respectively [16]. C_1 and C_2 indicate the path loss constant of

Femtocell 1 and Femtocell 2, respectively. α_1 and α_2 indicate the distance-related path loss exponent of Femtocell 1 and Femtocell 2, respectively.

Assume that the channel Gauss white noise power is σ^2 and the total interference received in dot A_1 is I_{1,A_1}. Since the total interference includes received power from the base station of Femtocell 2 and Gauss white noise power, I_{1,A_1} can be expressed as

$$I_{1,A_1} = P_2 H_2 C_2 L_2^{-\alpha_2} + \sigma^2. \tag{3}$$

The SNR at dot A_1 is defined as the ratio of the power received from the base station of Femtocell 1 to the total interference including received power from Femtocell 2

Fig. 2 Network model with two adjacent coexisting femtocells
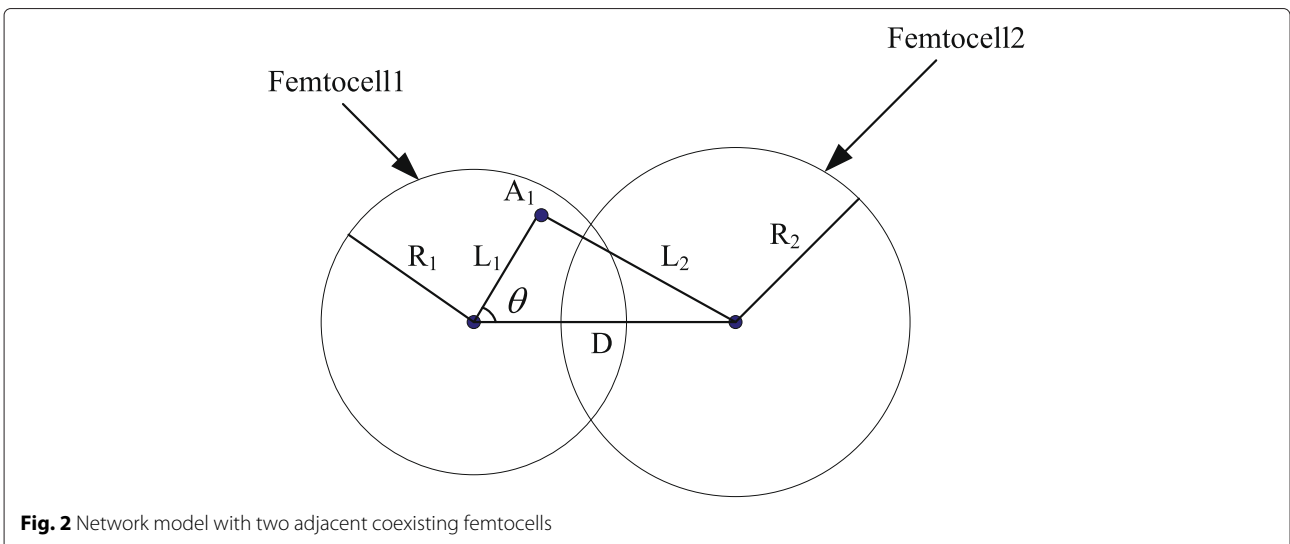
and Gauss white noise power. Therefore, expression (4) can be used to compute SNR_1 which denotes the SNR at dot A_1,

$$SNR_1 = \frac{P_{1,A_1}}{I_{1,A_1}} = \frac{P_1 H_1 C_1 L_1^{-\alpha_1}}{P_2 H_2 C_2 L_2^{-\alpha_2} + \sigma^2}. \tag{4}$$

The network capacity is defined as the summation of the communication rate of the terminals distributing within the coverage area. For simplicity, we compute the capacity of Femtocell 1 by the integral of the product of the user density and SNR in random position over the whole covering area of Femtocell 1. We define Cap_1 indicating the capacity of Femtocell 1, which is expressed by

$$Cap_1 = \int_0^{R_1} \int_0^{2\pi} \frac{\rho_1 P_1 H_1 C_1 L_1^{-\alpha_1}}{P_2 H_2 C_2 L_2^{-\alpha_2} + \sigma^2} L_1 \, d\theta \, dL_1, \tag{5}$$

where ρ_1 denotes the user distribution density of Femtocell 1.

From Fig. 2, Eq. (6) can be obtained:

$$L_2 = \sqrt{(D - L_1 \cos\theta)^2 + (L_1 \sin\theta)^2}. \tag{6}$$

Next, Eq. (7) can be deduced from Eqs. (5) and (6).

Similarly, we define Cap_2 to indicate the capacity of Femtocell 2 and ρ_2 to denote the user distribution density of Femtocell 2. And the same deduction method can be applied for the expression of Cap_2, as shown in Eq. (8).

$Cap_1 =$

$$\int_0^{R_1} \int_0^{2\pi} \frac{\rho_1 P_1 H_1 C_1 L_1^{-\alpha_1}}{P_2 H_2 C_2 \left((D - L_1 \cos\theta)^2 + (L_1 \sin\theta)^2\right)^{-\frac{\alpha_2}{2}} + \sigma^2} L_1 \, d\theta \, dL_1$$

$$\tag{7}$$

$Cap_2 =$

$$\int_0^{R_2} \int_0^{2\pi} \frac{\rho_2 P_2 H_2 C_2 L_2^{-\alpha_2}}{P_1 H_1 C_1 \left((D - L_2 \cos\theta)^2 + (L_2 \sin\theta)^2\right)^{-\frac{\alpha_1}{2}} + \sigma^2} L_2 \, d\theta \, dL_2$$

$$\tag{8}$$

Finally, the sum capacity of Femtocell 1 and Femtocell 2 can be expressed by

$$C_{tot} = Cap_1 + Cap_2, \tag{9}$$

where C_{tot} refers to the sum capacity.

3.2 Network capacity optimization

In a cell centered with the base station, the transmission power is always expected to be as large as possible so as to obtain high capacity. However, in femtocell networks, large transmission power can bring severe interference to adjacent femtocells and reduce their capacity consequently. Therefore, we need to obtain the trade-off between the femtocell capacity and the interference to its adjacent femtocell, so as to maximize the sum net-

work capacity. According to Eq. (9), femtocell capacity as follows:

$$\max_{P_1, P_2} \left(Cap_1 + Cap_2\right) \tag{10}$$

subject to

$$Cap_1 \geq Th_1 \tag{11}$$

$$Cap_2 \geq Th_2 \tag{12}$$

$$P_1 \leq P_{LT1} \tag{13}$$

$$P_2 \leq P_{LT2} \tag{14}$$

$$P_1 h_{1p} + P_2 h_{2p} \leq I_p. \tag{15}$$

In Eqs. (11) and (12), Th_1 and Th_2 denote the minimal capacity requirements of Femtocell 1 and Femtocell 2, respectively. In Eqs. (13) and (14), P_{LT1} and P_{LT2} denote the maximal permitted transmission power of Femtocell 1 and Femtocell 2, respectively. In Eq. (15), h_{1p} and h_{2p} denote the interference gain to licensed network from Femtocell 1 and Femtocell 2, respectively, and I_p denotes the maximal interference power constraint to licensed network.

3.3 Solution to optimization problem

The formulated optimization problem contains a complex integral expression in the objective and constraint conditions. Therefore, it is difficult to solve it with the normal method for convex optimization problems. Herein, we adopt a two-step method to solve it. First, we transform Eq. (10) to a convex problem by changing the optimized variable and ignoring some constraints and solve it by the Lagrange dual method. Second, we re-consider the constraints ignored in the first step and formulate a linear programming problem to obtain the final solution for P_1 and P_2 based on the results in the first step.

Step 1:

Since Femtocell 1 and Femtocell 2 are adjacent, the interference from the adjacent femtocell is much more severe than the Gauss white noise power. Therefore, the Gauss white noise power can be ignored in the interference computation. Thus, Eqs. (7) and (8) are changed to Eqs. (16) and (17):

$Cap_1 =$

$$\int_0^{R_1} \int_0^{2\pi} \frac{\rho_1 P_1 H_1 C_1 L_1^{-\alpha_1}}{P_2 H_2 C_2 \left((D - L_1 \cos\theta)^2 + (L_1 \sin\theta)^2\right)^{-\frac{\alpha_2}{2}}} L_1 \, d\theta \, dL_1,$$

$$\tag{16}$$

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$$\text{Cap}_2 =$$

$$\int_0^{R_2} \int_0^{2\pi} \frac{\rho_2 P_2 H_2 C_2 L_2^{-\alpha_2}}{P_1 H_1 C_1 \left((D - L_2 \cos\theta)^2 + (L_2 \sin\theta)^2\right)^{-\frac{\alpha_1}{2}}} L_2 \, d\theta \, dL_2. \tag{17}$$

For simplicity, we define Co_1 and Co_2 as Eqs. (18) and (19) to substitute the corresponding parts in Eqs. (16) and (17):

$$\text{Co}_1 = \int_0^{R_1} \int_0^{2\pi} \frac{\rho_1 H_1 C_1 L_1^{-\alpha_1}}{H_2 C_2 \left((D - L_1 \cos\theta)^2 + (L_1 \sin\theta)^2\right)^{-\frac{\alpha_2}{2}}} L_1 \, d\theta \, dL_1, \tag{18}$$

$$\text{Co}_2 = \int_0^{R_2} \int_0^{2\pi} \frac{\rho_2 H_2 C_2 L_2^{-\alpha_2}}{H_1 C_1 \left((D - L_2 \cos\theta)^2 + (L_2 \sin\theta)^2\right)^{-\frac{\alpha_1}{2}}} L_2 \, d\theta \, dL_2. \tag{19}$$

Then, Eqs. (16) and (17) are simplified to Eqs. (20) and (21):

$$\text{Cap}_1 = \text{Co}_1 \frac{P_1}{P_2}, \tag{20}$$

$$\text{Cap}_2 = \text{Co}_2 \frac{P_2}{P_1}. \tag{21}$$

Then, Eqs. (10), (11), and (12) are changed to Eqs. (24) to (24):

$$\max_{P_1, P_2} \left(\text{Co}_1 \frac{P_1}{P_2} + \text{Co}_2 \frac{P_2}{P_1} \right) \tag{22}$$

subject to

$$\text{Co}_1 \frac{P_1}{P_2} \geq \text{Th}_1 \tag{23}$$

$$\text{Co}_2 \frac{P_2}{P_1} \geq \text{Th}_2 \tag{24}$$

At this stage, we do not consider the constraints (13) to (15) temporarily. We substitute $\frac{P_1}{P_2}$ by the new optimized variable Pr in the optimization objective (22) and its constraints (23) and (24), and consequently, a new optimization expression is obtained as follows:

$$\max_{\text{Pr}} \left(\text{Co}_1 \text{Pr} + \text{Co}_2 \frac{1}{\text{Pr}} \right) \tag{25}$$

subject to

$$\text{Co}_1 \text{Pr} \geq \text{Th}_1 \tag{26}$$

$$\text{Co}_2 \frac{1}{\text{Pr}} \geq \text{Th}_2 \tag{27}$$

The problem (25) is a convex optimization problem with linear constraints. Therefore, we can adopt the Lagrange dual method to solve it. The solving process is shown in Appendix 1, where the optimal solution Pr_o for Pr variable is achieved.

Step 2:

At this stage, we will obtain the final optimal value for P_1 and P_2 based on the value of Pr_o achieved in step 1. From the point of energy saving, we aim to minimize the power consumption summation in the final solution of P_1 and P_2. Then, the problem required to be solved at this stage can be formulated as Eq. (28) with constraints (29) to (34).

$$\min_{P_1, P_2} (P_1 + P_2) \tag{28}$$

subject to

$$\frac{P_1}{P_2} = \text{Pr}_o \tag{29}$$

$$\int_0^{R_1} \int_0^{2\pi} \frac{\rho_1 P_1 H_1 C_1 L_1^{-\alpha_1}}{P_2 H_2 C_2 \left((D - L_1 \cos\theta)^2 + (L_1 \sin\theta)^2\right)^{-\frac{\alpha_2}{2}} + \sigma^2} L_1 \, d\theta \, dL_1 \geq \text{Th}_1 \tag{30}$$

$$\int_0^{R_2} \int_0^{2\pi} \frac{\rho_2 P_2 H_2 C_2 L_2^{-\alpha_1}}{P_1 H_1 C_1 \left((D - L_2 \cos\theta)^2 + (L_2 \sin\theta)^2\right)^{-\frac{\alpha_2}{2}} + \sigma^2} L_2 \, d\theta \, dL_2 \geq \text{Th}_2 \tag{31}$$

$$P_1 \leq P_{\text{LT1}} \tag{32}$$

$$P_2 \leq P_{\text{LT2}} \tag{33}$$

$$P_1 h_{1p} + P_2 h_{2p} \leq I_p \tag{34}$$

Constraints (30) and (31) mean that with both consideration of the adjacent femtocell interference and Gauss white noise, the capacity of Femtocell 1 and Femtocell 2 needs to exceed to the respective minimal capacity requirements. Constraints (32) to (34) limit the maximal permitted value for P_1 and P_2. But we cannot obtain the lower limitation of P_1 and P_2 directly from Eqs. (32) to (34). However, the transmit power of the base station must be large enough to meet the capacity requirements of the cell. Hence, we analyze the variation relation between P_1 and P_2 according to Eqs. (30) and (31) so as to obtain lower limits of P_1 and P_2, which leads to Theorem 1.

Theorem 1. By adhering to the solution of problem (25), i.e., the ratio of P_1 and P_2 keeps at a specific value of Pr_o, we can conclude that the following two constraints are equivalent to constraints (30) and (31), respectively.

$$P_2 \geq \frac{M_0 \sigma^2}{H_2 C_2 (D + R_1)^{-\alpha_2}}, \tag{35}$$

$$P_1 \geq \frac{M_0 \sigma^2}{H_1 C_1 (D + R_2)^{-\alpha_1}}, \tag{36}$$

where M_0 is a relatively large value which makes the noise part in the denominator of Eqs. (30) and (31) ignorable.

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Proof. Before going to the detailed proof, we would like to introduce a common skill in mathematics. Define two real variables X and Y and a relatively large value of M. If $X \geq MY$ is satisfied, we say that Y is small enough to be ignored in the expression of $X + Y$. Then, it is sufficient to prove that we can find a value of M_0 which makes the noise part in the denominator of Eqs. (30) and (31) ignorable.

Let us take the deduction of the lower limit of P_2 as example and analyze the relative variation process of P_1 and P_2 in detail. Firstly, we assume that the transmission power P_2 is equal to zero. Then, constraint (30) is changed to Eq. (37), which indicates that the transmission power of Femtocell 1 only needs to resist the interference of Gauss white noise power to meet the capacity requirement of Th_1, i.e.,

$$\int_0^{R_1} \int_0^{2\pi} \frac{\rho_1 P_1 H_1 C_1 L_1^{-\alpha_1}}{\sigma^2} L_1 \, d\theta \, dL_1 \geq \text{Th}_1 \qquad (37)$$

We define P'_{LT1} to indicate the minimal P_1 value, which makes the capacity requirement Th_1 satisfied when the transmission power of Femtocell 2 is zero. Then, Eq. (38) is obtained, and it can be concluded that $P_1 \geq P'_{\text{LT1}}$ is always satisfied.

$$\int_0^{R_1} \int_0^{2\pi} \frac{\rho_1 P'_{\text{LT1}} H_1 C_1 L_1^{-\alpha_1}}{\sigma^2} L_1 \, d\theta \, dL_1 = \text{Th}_1 \qquad (38)$$

Secondly, we consider the scenario that P_2 increases from zero. When P_2 starts to be larger than zero, P_1 needs to be larger than P'_{LT1} and changes to $\text{Pr}_o P_2$ in order to satisfy constraint (29). Then, since Eq. (29) is the solution of problem (22) according to step 1, it can be concluded that Eq. (29) can make Eq. (23) satisfied, which means that Th_1 is attained. But in problem (22), Gauss white noise power is ignored, whereas in Eq. (30) the interference of Gauss white noise power is considered; therefore, P_1 must be larger than $\text{Pr}_o P_2$ to make Eq. (30) satisfied. Then, we define P'_1 indicating the new value of P_1 which is larger than $\text{Pr}_o P_2$ to make Eq. (30) satisfied. Consequently, as Eq. (31) must be satisfied for the solution of Eq. (28), P_2 will increase with P'_1 to P'_2, which make $P'_1 = \text{Pr}_o P'_2$ exist. Repeatedly, P_1 will increase again because of the consideration of Gauss white noise power and P_2 will increase accordingly by the constraint (29). The process will be repeated until P_2 is large enough to make σ^2 insignificant. Then, constraint (30) becomes in accordance with Eq. (23), and Eq. (29) can make Eq. (30) satisfied.

From Eq. (2) and Fig. 2, it can be seen that when L_2 equals to $D + R_1$, the P_2 interference to Femtocell 1 arrives at the smallest value of the Femtocell 1 coverage area. If the smallest P_2 interference to Femtocell 1 is large enough to make σ^2 insignificant, we can ignore σ^2 in all the coverage areas of Femtocell 1. Well then, according to Eqs. (3)

and (4), it can be concluded that when Eq. (39) is satisfied we can ignore the interference of σ^2 for all coverage of Femtocell 1.

$$P_2 H_2 C_2 (D + R_1)^{-\alpha_2} \geq M_0 \sigma^2 \qquad (39)$$

Since, when σ^2 is ignored, constraint (29) can make Eq. (30) satisfied and constraint (30) can be transformed to Eq. (39) equivalently. From Eq. (39), Eq. (35) is proved, which gives the lower limit of P_2. The process described above is shown in Fig. 3.

A similar process can be applied to obtain the P_1 lower limit, and Eq. (36) can be proved.

By Theorem 1 usage, the optimization problem (28) is transformed into a convex linear programming problem. The solution process is shown in Appendix 2, in which we obtain the final solution for P_1 and P_2. □

3.4 Detailed procedure of algorithm
The whole process of obtaining the final value of P_1 and P_2 is illustrated in Algorithm 1. Firstly, we obtain the Pr_o value of the problem (25) solution according to step 1 in Section 3.3. Then, for step 2, according to the proof of Theorem 1, we perform two iterative processes to obtain
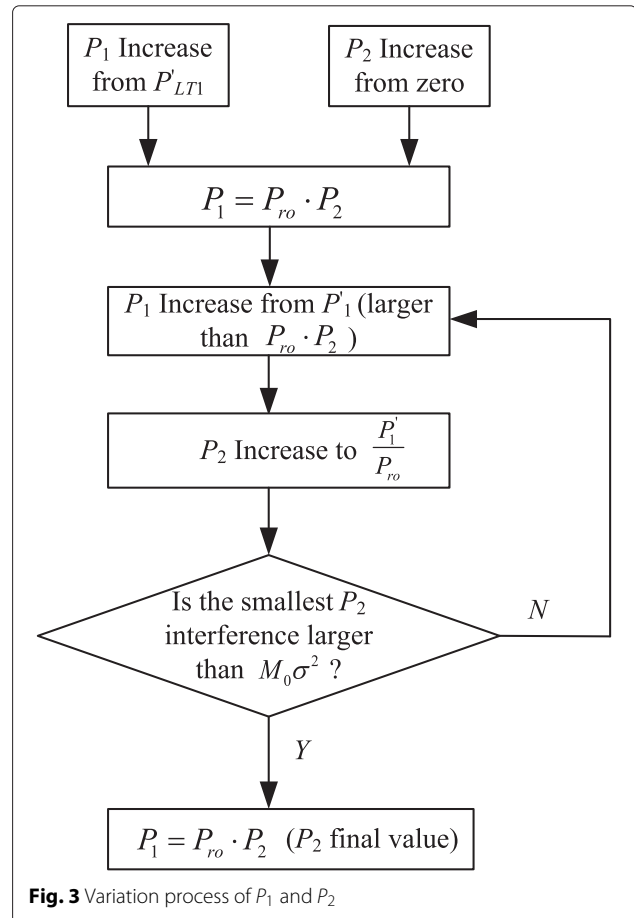

Fig. 3 Variation process of P_1 and P_2

Algorithm 1 Detailed Procedure of P_1 and P_2 Obtaining

Require:

    1) Let $\mathrm{Pr}_o = 0$, $P_1 = 0$, $P_2 = 0$;

    2) Initialize $P_{1,t1}$ by

$$\int_0^{R_1} \int_0^{2\pi} \frac{\rho_1 P_{1,t1} H_1 C_1 L_1^{-\alpha_1}}{\sigma^2} L_1 \, d\theta \, dL_1 = \mathrm{Th}_1;$$

    3) Let $P_{2,t1} = 0$;

    4) Initialize $P_{2,t2}$ by

$$\int_0^{R_2} \int_0^{2\pi} \frac{\rho_2 P_{2,t2} H_2 C_2 L_2^{-\alpha_2}}{\sigma^2} L_2 \, d\theta \, dL_2 = \mathrm{Th}_2;$$

    5) Let $P_{1,t2} = 0$.

1: **if** $\mathrm{Th}_1 + \frac{C_{o1} C_{o2}}{\mathrm{Th}_1} \geq \mathrm{Th}_2 + \frac{C_{o1} C_{o2}}{\mathrm{Th}_2}$ **then**

2:     $\mathrm{Pr}_o \leftarrow \frac{\mathrm{Th}_1}{C_{o1}}$

3: **else**

4:     $\mathrm{Pr}_o \leftarrow \frac{\mathrm{Th}_2}{C_{o2}}$

5: **end if**

6: $P_{2,t1} \leftarrow \frac{P_{1,t1}}{\mathrm{Pr}_o}$

7: **while** $P_{2,t1} \leq \frac{M_0 \sigma^2}{H_2 C_2 (D+R_1)^{-\alpha_2}}$ **do**

8:     Update $P_{1,t1}$ by $\mathrm{Cap}_1 = \mathrm{Th}_1$

9:     Update $P_{2,t1}$ by $P_{2,t1} = \frac{P_{1,t1}}{Pr_o}$

10: **end while**

11: $P_{1,t2} \leftarrow P_{2,t2} \mathrm{Pr}_o$

12: **while** $P_{1,t2} \leq \frac{M_0 \sigma^2}{H_1 C_1 (D+R_2)^{-\alpha_1}}$ **do**

13:     Update $P_{2,t2}$ by $\mathrm{Cap}_2 = \mathrm{Th}_2$

14:     Update $P_{1,t2}$ by $P_{1,t2} = P_{2,t2} \mathrm{Pr}_o$

15: **end while**

16: $P_1 \leftarrow max(P_{1,t1}, P_{1,t2})$

17: $P_2 \leftarrow max(P_{2,t1}, P_{2,t2})$

Table 1 Numerical values of simulation parameters

Parameters	Values
Gauss white noise power σ^2	-80 dbW
Fading value H_1	Rayleigh fading ($\sim$Exp (1))
Fading value H_2	Rayleigh fading ($\sim$Exp (1))
800 MHz path loss constant C_1	$\left(\frac{0.375}{4\pi}\right)^2$
800 MHz path loss constant C_2	$\left(\frac{0.375}{4\pi}\right)^2$
800 MHz path loss exp. α_1	3
800 MHz path loss exp. α_2	3
2.5 GHz path loss constant C_1	$\left(\frac{0.12}{4\pi}\right)^2$
2.5 GHz path loss constant C_2	$\left(\frac{0.12}{4\pi}\right)^2$
2.5 GHz path loss exp. α_1	4
2.5 GHz path loss exp. α_2	4
Variable comparison parameter M_0	10
Femtocell 1 capacity requirements Th_1	200 Mbit/s
Femtocell 2 capacity requirements Th_2	500 Mbit/s
Femtocell 1 user distribution density ρ_1	100/km^2
Femtocell 2 user distribution density ρ_2	100/km^2, 200/km^2
Femtocell 1 maximal power P_{LT1}	1 W
Femtocell 2 maximal power P_{LT2}	2 W
Femtocell 1 interference gain h_{1p}	Rayleigh fading ($\sim$Exp (1))
Femtocell 2 interference gain h_{2p}	Rayleigh fading ($\sim$Exp (1))
Licensed network interference constraint I_p	10 W
Femtocell 1 and Femtocell 2 distance D	1 km

two groups of P_1 and P_2 values, which satisfy the lowest constraints of P_1 and P_2, respectively. The two group values are denoted by $P_{1,t1}$ and $P_{2,t1}$ and $P_{1,t2}$ and $P_{2,t2}$, respectively. Lastly, since the lowest constraints of P_1 and P_2 need to be satisfied simultaneously, we choose the maximal values of the two groups as the final result for P_1 and P_2.

4 Simulation results

In this section, we validate the performance of the proposed power management scheme for adjacent femtocells by Monte Carlo simulations. We build a two-layer heterogeneous network with one macro cell and two adjacent femtocells as shown in Figs. 1 and 2. We consider two-band usage (800 MHz and 2.5 GHz) as in [15]. The simulation parameters and their numerical values are summarized in Table 1.
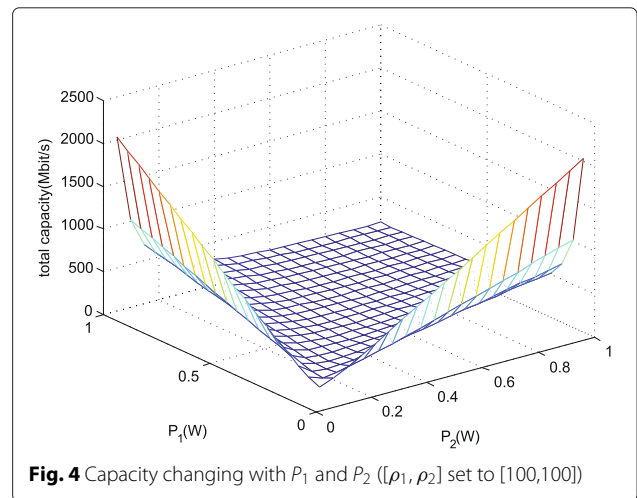
4.1 Analysis of influence of P_1 and P_2 variation upon capacity

We validate the influence of P_1 and P_2 variation upon the sum capacity computed by (9). We choose two groups of setting for $[\rho_1, \rho_2]$ for comparison, which are [100,100] and [100,200]. The value of $[R_1, R_2]$ is set to [0.6,0.6] for
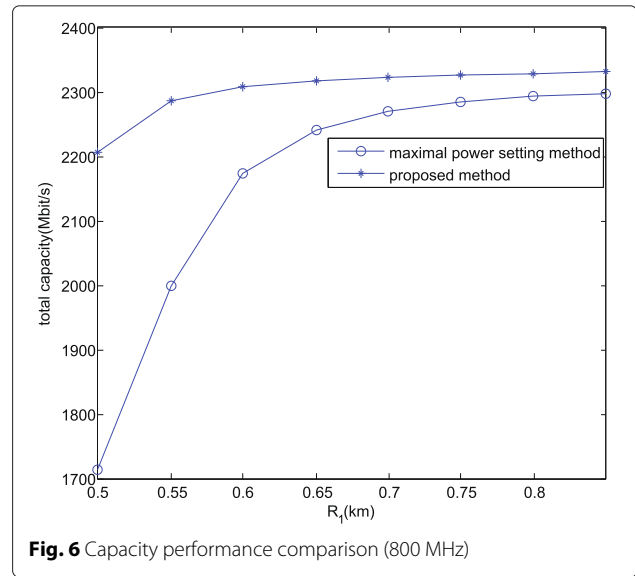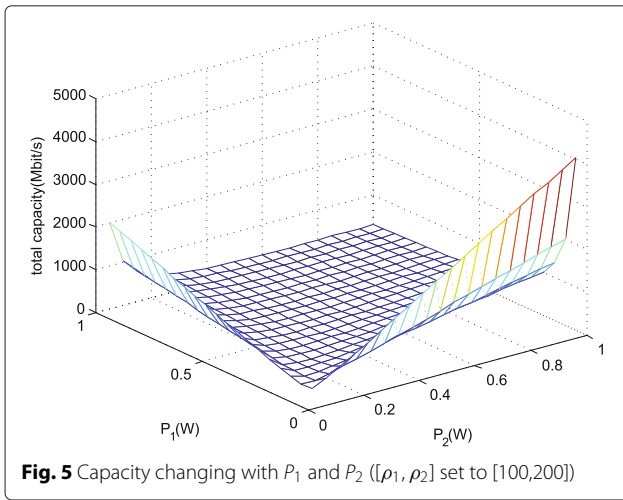
both groups of setting. Figures 4 and 5 shows the capacity changes with P_1 and P_2 variation corresponding to the two groups of setting. From the two figures it can be seen that in the middle part the capacity value is lower and in the edge part the capacity value is higher. In other words the variation trend can be summarized as the sum capacity increases with the difference value of P_1 and P_2 enlarging.

Fig. 4 Capacity changing with P_1 and P_2 ($[\rho_1, \rho_2]$ set to [100,100])

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Fig. 5 Capacity changing with P_1 and P_2 ([ρ_1, ρ_2] set to [100,200])

**Fig. 6** Capacity performance comparison (800 MHz)

This can be explained by (22), in which the value of $\frac{P_1}{P_2}$ decides the value of the sum capacity. When $\frac{P_1}{P_2}$ reaches some value, the sum capacity curve will attain the lowest position. Then from the lowest position, with the $\frac{P_1}{P_2}$ value variation the capacity value will increase. In Fig. 4 since the configuration of Femtocell 1 and Femtocell 2 are identical, the capacity variation presents a symmetrical trend with P_1 and P_2 variation. For Fig. 5 since the user density ρ_2 is larger than ρ_1, the P_2 influence to capacity is greater than P_1. Therefore the sum capacity increases with P_2 increasing more obviously.

### 4.2 Capacity performance analysis of proposed method

We validate the capacity performance of the proposed power management strategy by comparing with other methods. We set R_2 as 0.5 km and [ρ_1, ρ_2] as [100,100]. We compare the proposed power configuration with the maximal power setting method, in which for Femtocell 1 and Femtocell 2 the transmission power are both set to the maximal limitation. In other words, in maximal power setting method, P_1 and P_2 are set to P_{LT1} and P_{LT2}, respectively. Figures 6 and 7 compare the sum capacity of the proposed method with maximal power setting method in 800-MHz usage and 2.5-GHz usage, respectively. From the two figures, it can be seen that the sum capacity increases with the R_1 value. This is for the reason that when P_{LT1} and P_{LT2} are fixed, the network capacity will increase with the coverage area. Moreover, from the two figures, we can see that the proposed method has obvious enhancement in capacity performance compared to the maximal power setting method. This is because we choose the reasonable power configuration to maximize the sum capacity, whereas the compared method simply sets each power to the maximal limitation.

4.3 Energy performance analysis of proposed method

The energy consumption has been one of the main concerns in the current researches of wireless communication system. In the proposed power management method, besides the network capacity maximization, we look into energy consumption minimization in problem (26). Therefore, we validate the power consumption performance of the proposed method by comparing it with the maximal power setting method as shown in Fig. 8. For Fig. 8, we set R_2 as 0.5 km and [ρ_1, ρ_2] as [100,100]. In Fig. 8, we take into account 800-MHz and 2-GHz usage. It is shown that in the proposed method the power consumption increases with the R_1 value. This is because, for power consumption minimization, P_1 and P_2 will be set to the lower limit as far as possible, and we obtain the lower limit by Eqs. (35) and (36), which increase as R_1 and

Fig. 7 Capacity performance comparison (2.5 GHz)

Fig. 8 Energy consumption performance comparison
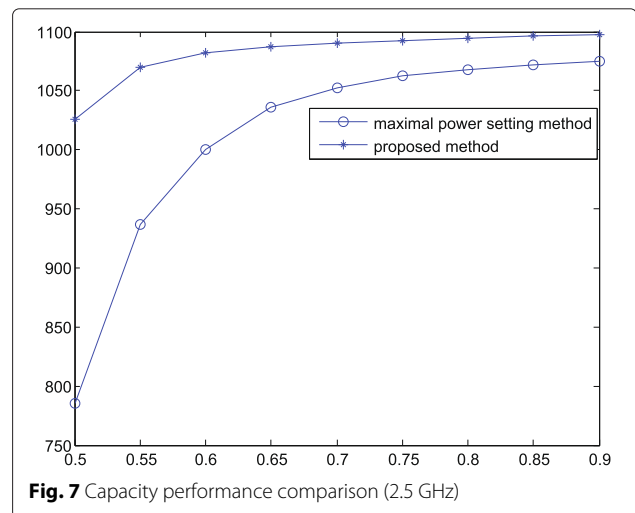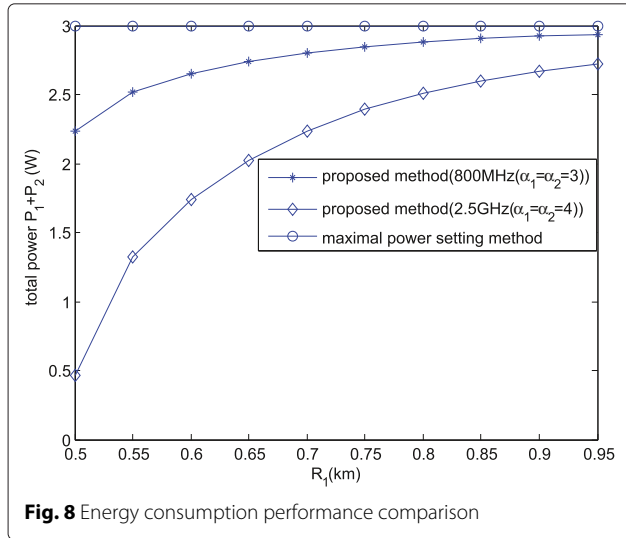
R_2 increase. Therefore, when R_2 is fixed, the sum power increases with R_1 variation until it becomes infinitely close to the upper limit.

5 Conclusions

We propose a two-stage power configuration scheme for adjacent femtocells in cognitive heterogeneous network in this paper. In the first stage, by jointly considering the distance-dependent interference, user distribution, and user performance in terms of SNR, we manage to derive an expression for sum capacity of femtocells. Subsequently, we formulate the problem of maximizing sum capacity while satisfying the minimum capacity requirements for each femtocell. The solution for this problem indicates that maximum sum capacity can be achieved as long as the ratio between the transmission power of two adjacent femtocells keeps at some specific value. Then, in the second stage, we further formulate a new problem of minimizing power consumption while adhering to the solution in the first stage. Optimal power setting for each femtocell is derived in this stage. Extensive simulations show that the proposed scheme brings significant enhancement in terms of network capacity and energy conservation. In the future, we plan to extend our research to the scenario of multiple adjacent femtocells.

Appendix 1

Proof. For problem (25), we define the Lagrange dual function as Eq. (40):

$$
\begin{aligned}
L(x, \lambda) = \\
-\left(Co_1 Pr + Co_2 \frac{1}{Pr} \right) + \lambda_1 \left(Th_1 - Co_1 Pr \right) \\
+ \lambda_2 \left(Th_2 - Co_2 \frac{1}{Pr} \right),
\end{aligned} \tag{40}
$$

in which, $\lambda_i (i = 1, 2)$ is the Lagrange multiplier corresponding to constraints (26) and (27). Then, the KKT (Karush-Kuhn-Tucker) conditions of the problem (25) can be expressed as following from Eqs. (41) to (46):

$$
Co_1 Pr \geq Th_1 \tag{41}
$$

$$
Co_2 \frac{1}{Pr} \geq Th_2 \tag{42}
$$

$$
\lambda_i \geq 0 (i = 1, 2) \tag{43}
$$

$$
\lambda_1 \left(Th_1 - Co_1 Pr \right) = 0 \tag{44}
$$

$$
\lambda_2 \left(Th_2 - Co_2 \frac{1}{Pr} \right) = 0 \tag{45}
$$

$$
-\left(Co_1 + Co_2 \frac{1}{Pr^2} \right) - \lambda_1 Co_1 + \lambda_2 Co_2 \frac{1}{Pr^2} = 0 \tag{46}
$$

From KKT conditions, we can obtain the possible solution as Eq. (47):

$$
\begin{cases}
Pr_1 = \frac{Th_1}{Co_1} \\
Pr_2 = \frac{Co_2}{Th_2}
\end{cases} \tag{47}
$$

Bring Pr_1 and Pr_2 to Eq. (25), then we can obtain the final solution of Pr as Eq. (48):

$$
Pr = \begin{cases}
\frac{Th_1}{Co_1} & Th_1 + \frac{Co_1 Co_2}{Th_1} \geq Th_2 + \frac{Co_1 Co_2}{Th_2} \\
\frac{Co_2}{Th_2} & Th_1 + \frac{Co_1 Co_2}{Th_1} \leq Th_2 + \frac{Co_1 Co_2}{Th_2}
\end{cases} \tag{48}
$$

□

Appendix 2

Proof. We substitute Eqs. (30) and (31) with Eqs. (35) and (36), respectively, and problem (28) becomes a linear programming program. Afterwards, we eliminate one variable, P_1, and the problem (28) is transformed to Eq. (49):

$$
\min_{P_2} ((1 + Pr_o) P_2) \tag{49}
$$

subject to

$$
P_2 \geq \frac{M_0 \sigma^2}{H_2 C_2 (D + R_1)^{-\alpha_2}} \tag{50}
$$

$$
P_2 \geq \frac{M_0 \sigma^2}{H_1 C_1 (D + R_2)^{-\alpha_1} Pr_o} \tag{51}
$$

$$
P_2 \leq \frac{P_{LT1}}{Pr_o} \tag{52}
$$

$$
P_2 \leq P_{LT2} \tag{53}
$$

$$
P_2 \leq \frac{I_p}{Pr_o h_{1p} + h_{2p}} \tag{54}
$$

Equations (50) to (51) give the permitted range of P_2, and Eqs. (52) to (54) indicate the lower limit of P_2. The optimal solution for P_2 can be obtained as Eq. (55):

$$P_2 = \max \left(\frac{M_0 \sigma^2}{H_2 C_2 (D + R_1)^{-\alpha_2}}, \frac{M_0 \sigma^2}{H_1 C_1 (D + R_2)^{-\alpha_1} \Pr_o} \right) \tag{55}$$

The corresponding solution for P_1 is obtained as Eq. (56):

$$P_1 = \Pr_o \max \left(\frac{M_0 \sigma^2}{H_2 C_2 (D + R_1)^{-\alpha_2}}, \frac{M_0 \sigma^2}{H_1 C_1 (D + R_2)^{-\alpha_1} \Pr_o} \right) \tag{56}$$

$\square$

References
1. H Zhang, C Jiang, N Beaulieu, X Chu, X Wang, T Quek, Resource allocation for cognitive small cell networks: a cooperative bargaining game theoretic approach. IEEE Trans. Wirel. Commun. **14**, 3481–3493 (2015)
2. JMR Avil, M Toril, S L-Ramirez, A femtocell location strategy for improving adaptive traffic sharing in heterogeneous LTE networks. EURASIP J. Wirel. Commun. Netw. **12**, 1–13 (2015)
3. H Zhang, C Jiang, X Mao, H Chen, Interference-limited resource optimization in cognitive femtocells with fairness and imperfect spectrum sensing. IEEE Trans. Veh. Technol. **10**, 1–11 (2015)
4. F Song, X Wen, N Li, Power allocation for OFDM-based cognitive heterogeneous networks. SCIENCE CHINA. **58**, 1–12 (2013)
5. F Chen, W Xu, Y Guo, J Lin, M Chen, in *Proceedings of the 8th International Conference on Communications and Networking in China: August 2013; Guilin*. Resource allocation in OFDM-based heterogeneous cognitive radio networks with imperfect spectrum (IEEE, 2013), pp. 46–51
6. S Cheng, S Lien, F Chu, K Chen, On exploiting cognitive radio to mitigate interference in macro/femto heterogeneous networks. IEEE Wirel. Commun. **18**, 40–47 (2011)
7. G Jagadish, R Catherine, Resource allocation, transmission coordination and user association in heterogeneous networks a flow-based unified approach. IEEE Trans. Wirel. Commun. **12**, 1340–1351 (2013)
8. M Adian, H Aghaeinia, Optimal resource allocation in heterogeneous MIMO cognitive radio networks. IEEE Wireless Personal Commun. **76**, 23–39 (2014)
9. S Wang, Z Zhou, M Ge, C Wang, Power allocation for OFDM-based cognitive heterogeneous networks. IEEE J. Sel. Areas Commun. **31**, 464–475 (2013)
10. R Xie, F Yu, H Ji, Y Li, Energy-efficient resource allocation for heterogeneous cognitive radio networks with femtocells. IEEE Trans. Wirel. Commun. **11**, 3910–3920 (2011)
11. S Bu, F Yu, Y Qian, in *Proceedings of the 31st International Conference on Computer Communications: December 2012; Anaheim*. Energy-efficient cognitive heterogeneous networks powered by the smart grid (IEEE, New York, NY, USA, 2012), pp. 23–39
12. X Peng, G Peng, J Hyun-Park, D Park, D Ky-Kim, in *Proceedings of the 9th International Symposium on Communications and Information Technology: September 2009; Icheon*. Max-min fairness based radio resource management in fourth generation heterogeneous networks (IEEE, New York, NY, USA, 2009), pp. 208–213
13. H Zhang, C Jiang, N Beaulieu, X Chu, X Wen, M Tao, Resource allocation in spectrum-sharing OFDMA femtocells with heterogeneous services. IEEE Trans. on Commun. **7**, 2366–2377 (2014)
14. H Zhang, X Chu, W Guo, S Wang, Coexistence of wi-fi and heterogeneous small cell networks sharing unlicensed spectrum. IEEE Commun. Mag. **53**, 158–164 (2015)
15. H Zhang, H Liu, C Jiang, X Chu, A Nallanathan, X Wen, A practical semi-dynamic clustering scheme using affinity propagation in cooperative picocells. IEEE Trans. Veh. Technol. **99**, 1–11 (2014)
16. X Lin, J Andrews, A Ghosh, Analysis and design for carrier aggregation in heterogeneous cellular networks. IEEE Trans. Commun. **61**, 4002–4015 (2013)