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Optimized Iterative Algorithm for Energy-Efficient Power Allocation in Two-tier Heterogeneous Networks

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Abstract

In heterogeneous networks, the issue of interference between femtocells and macrocells should be carefully considered. Resource allocation schemes with cognitive technologies have been a key challenge to manage interference. In this paper, we investigate price-based power allocation strategies with the energy efficiency criterion for a spectrum-sharing heterogeneous cognitive network from the aspect of energy efficiency, and provide the utility function of macrocell and femtocells based on a non-cooperative Stackleberg game model. We build a combination of price vector and power allocation values by standard Lagrangian method and propose an improved iteration algorithm based on price updating to obtain the Stackleberg equilibrium solution. The simulation results verify the proposed method can improve energy efficiency and achieve better utility.

***Keywords**: heterogeneous networks；Resource allocation；energy efficiency criterion；Iterative Algorithm*

1. Introduction

The incremental require of wireless data activity has been promoting the innovation of communication network technologies that can meet the demands in an energy efficient manner. Heterogeneous network, evolving from traditional cellular networks, deploys femtocells in hot spots and indoor circumstance to improve the overall network coverage and capacity. In a two-tier heterogeneous network, macro base station (MBS) and femtocells share radio spectrum resources in diverse multiple access schemes to improve the total spectrum efficiency. However, the introduction of femtocells alters the cellular topology by creating an underlay of small cells, which increases co-tier and cross-tier interferences and greatly restricts the network performance [1]. Therefore, the interference mitigation in two-tier heterogeneous networks has become an active area of research.

Cognitive radio is viewed as an effective approach for improving the utilization of the radio spectrum. The cognitive transceivers have flexible spectrum sensing ability, and can adjust transmission parameters adaptively according to the ambient environment [2]. If MBS has the cognitive capability to be aware of the access of femtocells and the femtocells have the cognitive capability to monitor the surrounding channel environment and are able to randomly obtain sub-channels. The spare spectrum of MBS (primary user) can be accessed by the femtocell (secondary user) dynamically without causing harmful interference.

As the behaviors of the primary users and secondary users interact with each other, game theory, as an effective tool for the analysis of interactive decision making, has been

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applied in the spectrum sharing problem. A great deal of Scholarly work has been done for interference management and resource allocation based on game theory. To alleviate cross-tier interference at the macrocell from cochannel femtocells, authors of [3] proposed a distributed utility-based SINR adaptation at femtocells, however, which lacked a mathematical model for calculating the power allocation value with high accuracy. Literature [4] modeled the downlink power allocation problem in femtocell-based cellular networks as a stackelberg game and showed the existence of Nash equilibrium. And on this basis, Literature [5] introduced quality-of-service constraint and further discussed the mathematical program with equilibrium constraints, derived the best response for a one leader-multiple follower game. Literature [6] and [7] applied the interference power constraint to guarantee the quality-of-service (QoS) of MBS in the uplink and considered the utility maximization of the macrocell and the femtocells based price-based Srackelberg game. The above exiting methods have better performance in resource allocation; however, they ignored the problem of energy efficiency, the base station consumed large power resources with small increase in utility function profit. In order to find a relatively balance over power consumption and information rate, a joint iterative two-step resource allocation algorithm is derived in [8] to mitigate co-channel interferences and improve average power energy efficiency. Literature [9] built an energy-efficiency utility function proposed an iteration algorithm based on the interference price updating to obtain the stackelberg equilibrium solution, but the algorithm ignored the relationship between interference price and power allocation, a mass of variables make the algorithm sophisticated.

In this paper, we mainly focus on the issues of spectrum sharing and resource allocation for energy efficient transmissions. To mitigate the interference effect, the power allocation problem is formulated as a co-channel non-cooperative dynamic Stackelberg game based the price of interference. Different from previous work which only considerd the price of interference from different femtocells to MBS, we establish the utility function of MBS by setting prices vector for each femtocell to determine the optimum interference ratio, and propose an interation algorithm based on interference price derivation and price matrix updating to obtain the Stackleberg equilibrium solution.

The rest of this paper is organized as follows. Section II describes the system model of spectrum sharing in two-tier cognitive heterogeneous networks. In section III, the problem of power allocation with the energy efficiency criterion based on non-competitive Stackleberg game is analyzed. Section Ⅳ presents the algorithm to compute the Stachelberg equilibrium and price matrix. Section V presents the simulation results, and section Ⅵ states the conclusion.

2. System Model

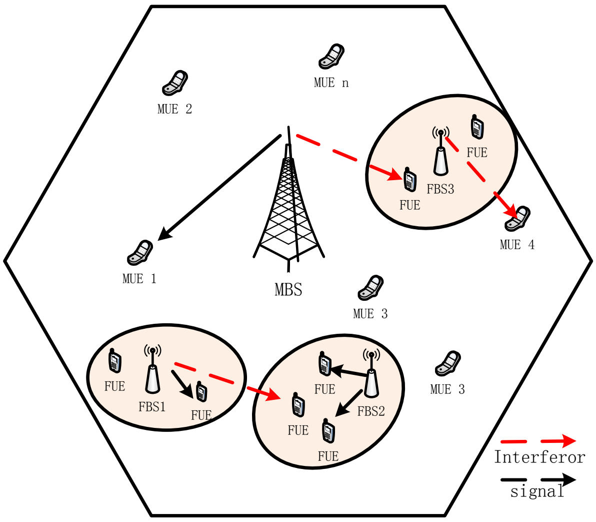

Figure 1. The Model of Two-Tier Heterogeneous Networks

Consider a downlink two-tier heterogeneous cognitive radio network consisting of one central MBS and N cochannel femtocells, illustrated in Figure 1, each femtocell base station (FBS) provides service for several FUEs. We suppose that all femtocells viewed as secondary users can access the same frequency band as the MBS. For simplicity, we assume that each sub-channel is allocated to one MUE, and around the MUE there are N FBSs utilizing the same sub-channel with MUE. In the practical network, there is a potential interference to MUE from all N femtocells. To reduce the interference effect and achieve energy efficient transmissions, the MBS needs to perform power allocation and charge an interference price to femtocells, while the femtocells should adaptively adjust the transmission power or change the access of sub-bands.

Let p_i (where $i = 1, 2...N$) denote the transmit power of FBS_i and p_m be the transmit power of the MBS. g_i is the channel power gain from FBS_i to MUE over the given sub-band, h_i is the channel power gain from FBS_i to the FUEs located in FBS_i and h_m is channel power gain from MBS to its serving MUE. We further assume that all the channel power gains are independent and identically distributed random variables and the channels are block-fading and remain constant during each transmission slot. Based on the analysis above, the calculation of signal-to-interference-plus-noise ratio (SINR) is given. In femtocell i, the received SINR at the scheduled FUE from its serving base station can be expressed as:

$$SINR_i(p_i, \mathbf{p}_{-i}) = \frac{p_i h_i}{\sum_{j=1, j\neq i}^{N} g_{ji} p_j + \sigma^2} \tag{1}$$

where g_{ji} is the channel power gain from other collocated femtocell j to fenmtocell i and $\mathbf{p}_{-i}$ is the power allocation vector of all FBSs except FBS_i. σ^2 represents the variance of the additive white Gaussian noise at FUE.

According to the Shannon formula, the achievable data rate of FBS_i for a given sub-channel can be written as

$$R_i(p_i, \mathbf{p}_{-i}) = W \log_2\left(1 + SINR_i(p_i, \mathbf{p}_{-i})\right) \tag{2}$$

where W is the transmission bandwidth of sub-channel.

Based on the consideration of data rate, energy efficiency performance criterion takes the power consumption cost into account. And the utility function without interference price can be written as [10].

$$\eta_i\left(p_i,\mathbf{p}_{-i}\right)=W\log_2\left(1+SINR_i\left(p_i,\mathbf{p}_{-i}\right)\right)-\mu p_i \quad (3)$$

where μ is a constant price parameter with the unit of $bit/s/W$.

To guarantee the communication quality of MUE, the aggregate interference from all the femtocell should be bounded, *i.e*.

$$\sum_{i=1}^{N} p_i g_i \le I_{\max} \quad (4)$$

where $I_{\max}$ is the maximum interference tolerance of MUE.

In this paper, we assume the above interference power constrain is imposed at MBS , which protects itself through pricing the interference from FBSs. Stackelberg game model is applied in this scenario, and (3) is used as the criterion of energy efficiency to formulate utility function of MBS and FBSs.

3. Problem Formulation

In this section, we formulate the problem of power allocation with the energy efficiency criterion as a non-cooperative Stackleberg game. In the scenario, the MBS is the leader who moves first, and the FBSs are the followers who move after the leader. The MBS protects its users by pricing the interference from femtocells and maximizes its utility function revenue by selling its interference tolerance. The utility function of MBS and FBSs are written as (5) and (6) respectively

$$\psi_m\left(p_m,\mathbf{p},\lambda_i\right)=W\log_2\left(1+\frac{p_m h_m}{\sum_{i=1}^{N} g_i p_i+\sigma_m^{\,2}}\right)-\mu_m p_m+\sum_{i=1}^{N}\lambda_i g_i p_i, i=1,2...N \quad (5)$$

$$\psi_i\left(p_i,\mathbf{p}_{-i},\lambda_i\right)=W\log_2\left(1+\frac{p_i h_i}{\sum_{i=1}^{N} g_{ij} p_j+\sigma_i^{\,2}}\right)-\mu_i p_i-\lambda_i g_i p_i, i=1,2...N \quad (6)$$

where $\boldsymbol{\lambda}=\left[\lambda_1,\lambda_2,......\lambda_N\right]$ and $\mathbf{p}=\left[p_1,p_2,......p_N\right]$ is the price and power allocation vector respectively. σ_m and σ_i represent the variances of additive Gaussian white noise（AWGN） at MBS and FBSs. In (6), the third term represents the interference cost. Because the results in (6) have a direct impact on utility revenue in (5) and p_m is independent of $\mathbf{p}$, the maximum of (5) has a hidden condition as follows:

$$\max \sum_i \lambda_i g_i p_i \quad (7)$$

$$\text{Subject to} \quad \sum_{i=1}^{N} p_i g_i \le I_{\max} \quad (8)$$

4. Iterative Algorithm Based On Game Theory

4.1. Energy Efficient Power Allocation and Determination of Price Interference

As the Stakelberg game is kind of non-cooperative games, the solution can be acquired through the Nash Equilibrium, where neither MBS nor FBSs have incentive to deviate from its strategy unilaterally. To find the Nash Equilibrium solution of above Stackelberg game, the best response of FBSs must be calculated firstly. Once the MBS acquaints the best strategies of the FBSs, and then derives its best values of power transmission.

Let $\boldsymbol{\lambda}^*$ and $\mathbf{p}^*$ as the optimal price and power vectors respectively, then the following condition must be satisfied.

$$\psi_m\left(p_m^*, p_i^*, \lambda_i^*\right) \ge \psi_m\left(p_m^*, p_i^*, \lambda_i\right), \forall i \tag{9}$$

$$\psi_i\left(p_i^*, \mathbf{p}_{-i}^*, \lambda_i^*\right) \ge \psi_i\left(p_i, \mathbf{p}_{-i}^*, \lambda_i^*\right), \forall i \tag{10}$$

Partial differentiating (6) with respect to p_i and putting the resulting expression equal to zero gives the value of p_i for which the strategy response is optimal for given the other femtocells' strategy of power allocation ,

$$\frac{\partial \psi_i\left(p_i, \mathbf{p}_{-i}, \lambda_i\right)}{\partial p_i} = 0 \tag{11}$$

$$p_i^* = \left[\frac{W}{\left(\mu_i + \lambda_i g_i\right)\ln 2} - \frac{\sigma_i^2 + I_F}{h_i}\right]^+ \tag{12}$$

where $I_F = \sum_{j=1, j\neq i}^{N} g_{ij} p_j$ represents the total interference from other FBSs, $(.)^+$ denotes that max(.,0). Equation (12) is the optimal response strategy for collocated femtocells with the knowledge of other femtocells' strategy, the proof process is detailed described in [10].

In (12), λ_i is still unknown. To build the connection between λ_i and p_i , substituting the solution of p_i into formula (7) - (8)then these two equations are transformed into

$$\max \sum_i \lambda_i g_i p_i = \sum_i \left[\frac{\lambda_i g_i W}{\left(\mu_i + \lambda_i g_i\right)\ln 2} - \frac{\lambda_i g_i (\sigma_i^2 + I_F)}{h_i}\right]^+ \tag{13}$$

$$\text{subject to } \sum_i \left[\frac{W g_i}{\left(\mu_i + \lambda_i g_i\right)\ln 2} - \frac{g_i (\sigma_i^2 + I_F)}{h_i}\right]^+ \le I_{\max} \tag{14}$$

Due to the issues of convex objective function, equation (13) is difficult to be solved. To find the optimal solution, we convert the function to the minimization problem as

$$\min_{\lambda \ge 0} \sum_i \frac{\lambda_i g_i (\sigma_i^2 + I_F)}{h_i} \tag{15}$$

$$\text{subject to } \sum_i \frac{W g_i}{\left(\mu_i + \lambda_i g_i\right)\ln 2} \le I_{\max} + \sum_i \frac{g_i (\sigma_i^2 + I_F)}{h_i} \tag{16}$$

The above objective function can be solved by standard Lagrangian method. According to the objective function and constrain condition, we establish the following expression

$$L\left(\boldsymbol{\lambda}, \beta, \theta\right) = \sum_i \frac{\lambda_i g_i (\sigma_i^2 + I_F)}{h_i} + \beta\left(\sum_i \frac{W g_i}{\left(\mu_i + \lambda_i g_i\right)\ln 2} - I_{\max} - \sum_i \frac{g_i (\sigma_i^2 + I_F)}{h_i}\right) - \sum_i \lambda_i \theta_i \tag{17}$$

where β and θ are Lagrangian multipliers associated with maximum interference constraint and $\lambda_i \ge 0$ respectively.

To solve the optimization problems, the KKT condition is used in the case of unequal constraint. Here, the Karsh-Kuhn-Tucker (KKT) conditions and derivation of (17) can be written as

$$\beta\left(\sum_i \frac{W g_i}{\left(\mu_i + \lambda_i g_i\right)\ln 2} - I_{\max} - \sum_i \frac{g_i (\sigma_i^2 + I_F)}{h_i}\right) = 0 \tag{18}$$

$$\frac{\partial L\left(\lambda, \beta, \theta\right)}{\partial \lambda_i} = \frac{g_i \lambda (\sigma_i^2 + I_F)}{h_i} - \beta \frac{W g_i^2}{\left(\mu_i + \lambda_i g_i\right)^2 \ln 2} - \theta_i \tag{19}$$

Assume that $I_{\max}$ is large enough that all the FBSs can communicate. Because $\lambda_i > 0$ and $\lambda_i \theta_i = 0$, we can put $\theta_i = 0$ and obtain the expression of price as

$$\lambda_i = \sqrt{\frac{\beta W}{g_i \ln 2} \cdot \frac{h_i}{I_F + \sigma_i^2}} - \frac{\mu_i}{g_i} \tag{20}$$

With the assumption that $\lambda_i > 0$, it's easy to find $\beta \neq 0$.Substitute (20) into get the expression of $\sqrt{\beta}$

$$\sqrt{\beta} = \sqrt{\left(\frac{\ln 2}{W}\right)^3} \cdot \frac{\sum_i \sqrt{\frac{g_i\left(I_F + \sigma^2\right)}{h_i}}}{I_{\max} + \sum_i \frac{g_i\left(I_F + \sigma^2\right)}{h_i}} \tag{21}$$

Putting the value of $\sqrt{\beta}$ back into (20) we can write

$$\lambda_i^* = \frac{\ln 2}{W} \cdot \frac{\sum_i \sqrt{\frac{g_i\left(I_F + \sigma^2\right)}{h_i}}}{I_{\max} + \sum_i \frac{g_i\left(I_F + \sigma^2\right)}{h_i}} \cdot \sqrt{\frac{h_i}{g_i(I_F + \sigma_i^2)}} - \frac{\mu_i}{g_i} \tag{22}$$

The aim of the MBS is to maximize its utility function by doing power allocation based on the given allocation of femtocells and price of interference. To solve the optimal price determination, we also take partial derivatives with respect to p_m and get solutions as follows.

$$\frac{\partial \psi_m\left(p_m, \mathbf{p}, \lambda_i\right)}{\partial p_m} = 0 \tag{23}$$

$$p_m^* = \left[\frac{W}{\mu_m \ln 2} - \frac{I_M}{h_m}\right]^+ \tag{24}$$

where $I_M = \sigma_m^2 + \sum_{i=1}^{N} g_i \left[\frac{W}{\left(\mu_i + \lambda_i g_i\right)\ln 2} - \frac{\sigma_i^2 + I_F}{h_i}\right]^+$.

4.2. Optimized Power Allocation Iteration Algorithm

Based on the optimized derivation for price interference, the power iteration algorithm as follows is used to get the Nash equilibrium for the power competition game.

Algorithm: The Optimized Iterative Algorithm

Initialize $\mathbf{p} = \left[p_1, p_2 ......p_N\right]$, $\boldsymbol{\lambda} = \left[\lambda_1, \lambda_2 ......\lambda_N\right]$ and p_m , l
repeat
    for $i = 1$ to N
        compute price of interference and updates $\lambda_i^{(l)}$ according to (22)
        compute and updates $p_i^{(l)}$ according to (12)
        calculate p_m according to (24)
        $l = l + 1$
    end
until $\left\|p_i^{(l)} - p_i^{(l-1)}\right\| / \left\|p_i^{(l-1)}\right\| \leq \varepsilon$ or iterative times exceed

The above algorithm stop operation until the convergence is satisfied or the iterative timesis exceed. Hence, we can get the optimal solutions of maximize the utility function for femtocells and macrocells with reasonable complexity.

5. Numerical Results and Discussions

In this section, the numerical results to evaluate performance are presented. In the simulations, three FBSs with co-channel mode is adopted. Considering the path loss and for simplicity, the channels from all FBSs to their scheduled users are set as $h_1 = 0.8, h_2 = 0.7, h_3 = 0.6$. Similarly, the channel gains from FBSs to MUE are considered as $g_1 = 0.3, g_2 = 0.2, g_3 = 0.1$. The unit bandwidth is used and the price parameters are set as $\mu_m = \mu_i = 0.15$ for macrocell and femtocells. Furthermore, background noise variance σ_m^2 and σ_i^2 is taken as 1.

Figure 2 illustrates the performance of Stackelberg game equilibrium between the MBS and the femtocells in term of the number of iteration. It can be seen that as the number of iteration increases, the transmit power in the network gradually converge to stable values. Under the given parameters, $p_m^* = 3.0983$ and $\mathbf{p}^* = [0.9325\ 1.5097\ 1.1355]$ .Because of MBS has a priority towards communication demand, the transmit power of MBS is relatively large in numeric values.

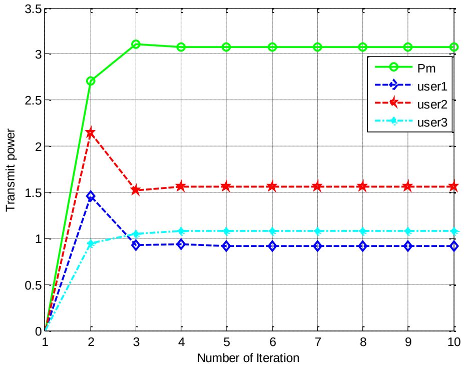

Figure 2. Convergence of Stackleberg Game Equilibrium

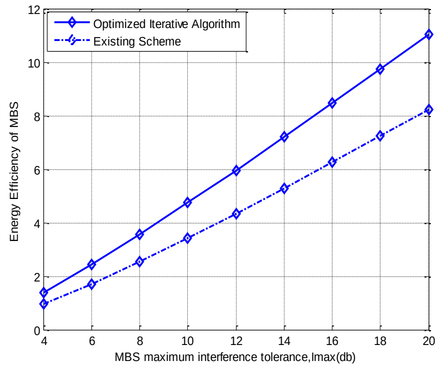

Figure 3. The Performance of Energy Efficiency versus Maximum Interference Tolerance ($I_{\max}$)

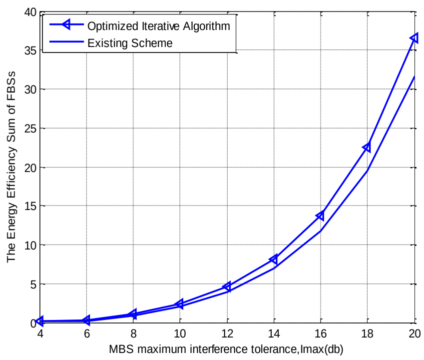

Figure 4. The Performance of Energy Efficiency of Femtocells versus $I_{\max}$

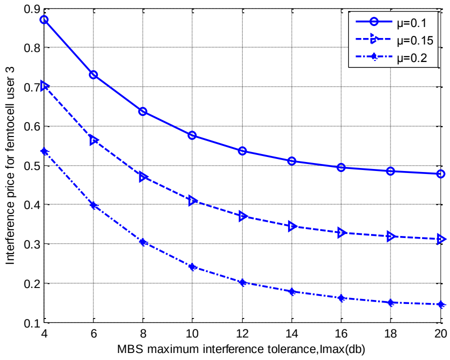

Figure 5. The Interference Price of FUE versus $I_{\max}$ Under Diverse Pricing Parameters

In Figure 3, we investigate the energy efficiency function value of macrocell versus diverse maximum interference tolerance $I_{\max}$ and compare the proposed optimized iterative algorithm with the existing scheme which set the price of interference as a value.

Figure 4 shows the comparison of two schemes in the aspects of energy efficiency sum of FBSs versus $I_{\max}$. With interference tolerance increasing, there is an apparently growth in the sum function. And the proposed algorithm has a slightly improvement in the performance of communication.

From formula (22), the expression of λ_i^* is got. In order to explore and verify the changing relationship between λ_i^* and μ_i, the λ_i^* of femtocell user 3 with two variables is simulated. Through Figure5 we can find that λ_3^* is inversely proportional to $I_{\max}$ and μ_i respectively, which is exactly consistent with the formula.

6. Conclusions

In this paper, we study the power allocation problem as a Stackelberg game for two-tier spectrum-sharing heterogeneous networks with femtocells and cognitive radio. From the view of energy-efficiency, we introduce interference price vector to formulate the utility function, in which communication rates and power consumption are both considered. Based on the principle of maximizing the utility function, we solve the price vector by standard Lagrangian method to eliminate a variable in calculation. An optimized iterative algorithm based on interference price updating has been proposed to get the Stackleberg power allocation solution. Simulation results confirm the superior performance of the proposed solution.

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Conflict of Interests

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

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