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Price-Based Power Control with Statistical Delay QoS Guarantee in Two-tier Femtocell Networks

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***Abstract*—Macrocells may suffer serious interference induced by the deployment of co-channel femtocells. To mitigate the cross-interference, we design a novel price-based power control method, with each femtocell user's delay quality-of-service (QoS) provisioning, in uplink OFDMA two-tier femtocell networks. Assuming that the macrocell base station (MBS) protects itself by pricing the interference from femtocell users (FU), a Stackelberg game is formulated with a goal to reach the joint utility maximization of the macrocell and the femtocells subject to a maximum tolerable interference power at the MBS. The Nash Equilibrium (NE) of its non-cooperative subgame is found with optimization theory firstly, and then a particle swarm optimization (PSO) aided power allocation (PSO-PA) algorithm is proposed to achieve the final Stackelberg Equilibrium (SE). Simulation results show that our proposed power allocation algorithm can converge quite fast and bring much higher effective capacity (EC) at FU side.**

I. INTRODUCTION

As indicated in [1], nearly 90% of data transmission and 60% of mobile voice are originated from indoor environments. In order to provide high data rate for indoor mobile users, the application of femtocells has been considered. It will not only enhance the indoor coverage without much additional cost, but also bring other significant benefits such as improving network capacity, belonging handset battery life and so on.

However, in spite of these advantages, femtocells will induce excessive interference, which greatly restricts the network performance. Hence, interference mitigation has been an indispensable task and a hot research topic recently. Power control is an effective mean to alleviate the cross-tier interference [2, 3]. In [2], a distributed channel assignment algorithm for mitigating interference among femtocells is given, which improves the experience of all users, but the interference from FUs to the MBS has not been considered. A power control strategy for spectrum-sharing OFDMA two-tier femtocell networks is studied in [3], which considers the interference restraint from FUs to the macrocell, however it doesn't take the delay QoS of the FUs into consideration.

In another aspect, as smart mobile terminals become popular, the wireless networks have loaded a mount of data services with diverse delay QoS requirements. For example, a mixture of delay sensitive applications (e.g., video teleconferencing) and delay tolerant ones (e.g., web browsing and file downloading) must be supported. Therefore, resource allocation with delay QoS guarantee in two-tier femtocell has become increasingly significant research area. Due to the time-varying nature of wireless channels, it is difficult and impractical to impose a deterministic delay guarantee for services over wireless networks. To address this issue, the EC has been adopted to provide the statistical QoS provisioning in [4].

In this paper, we study the power control in the uplink OFDMA two-tier femtocell networks with statistical delay QoS guarantee. We assume that the MBS protects itself by pricing the interference from femtocell users. Firstly, we formulate a price-based Stackelberg game, where the MBS acts as the leader and can communicate with FUs; FUs behave as the followers and only know the MBS's power strategy. The maximum tolerable interference power at the MBS will be seen as the resources that all followers are competing for. Our goal is to jointly maximize the utility of the MBS and the EC of each FU with different delay QoS requirement. We solve the proposed problem by finding the NE point of non-cooperative subgame with optimization theory firstly, and a PSO-PA algorithm based on the proposed Stackelberg game model has been proposed. Numerical results show that our proposed algorithm can converge quite fast and bring much higher average EC for each FU.

The rest of the paper is organized as follows. In Section II, we describe the system model and formulate the problem as a price-based Stackelberg game. In Section III, we will solve the formulated problems and proposed a PSO-PA algorithm to obtain the SE point. Simulation results are presented to analyze the performance of the proposed algorithm in Section IV. Finally, we conclude the paper in Section V.

II. SYSTEM MODEL AND GAME FORMULATION

A. System Model

The scenario considered in this paper is shown in Fig. 1, where K femtocells are overlaid in a macrocell. It is assumed that all femtocells share the same frequency with the macrocell and each femtocell provides heterogeneous delay-QoS services for FUs. Additionally, the total cross-tier interference to the MBS should be restricted to a certain threshold in every shared spectrum. To avoid intra-cell interference, for any given subchannel, we assume that there is only one scheduled active user during each time slot in each femtocell.

In this paper, all channels involved are assumed to be independently block-fading, which means that the channel

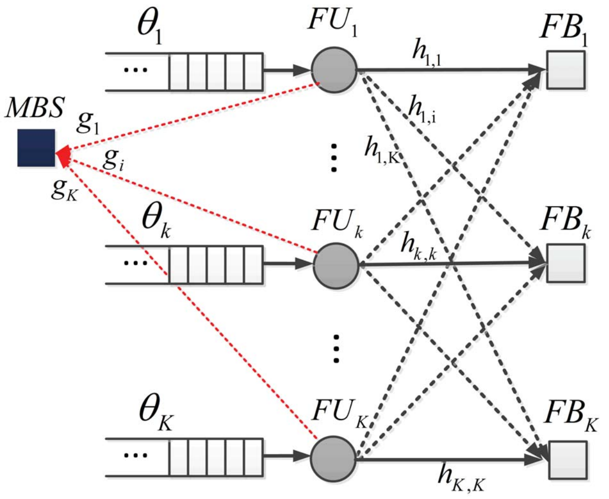

Fig. 1: The system model of the two-tier femtocell network

gains remain constant during each transmission block, but possibly change from one block to another. Let $B_k(k \in \mathcal{K})$ denote the FBS, where $\mathcal{K} = \{1, 2, ..., K\}$. FU k represents the scheduled user in FBS B_k and its transmit power is p_k. $h_{k,j}$ and g_k are instantaneous channel power gains from FU k to FBS B_j and to MBS respectively. We assume that the additional interference from the macrocell users is regarded as the background noise, which is additive white Gaussian noise (AWGN) with σ^2 as power.

The signal to interference and noise ratio (SINR) of FU k is

$$\gamma_k(p_k, \boldsymbol{p_{-k}}) = \frac{p_k h_{k,k}}{\sum\limits_{j \neq k} p_k h_{j,k} + \sigma^2}, \forall k \in \mathcal{K}, \tag{1}$$

where $\boldsymbol{p_{-k}}$ denotes other FUs' transmit power except FU k. According to the Shannon's capacity formula, the ideal achievable data rate of FU k is

$$R_k(p_k, \boldsymbol{p_{-k}}) = w log_2(1 + \gamma_k(p_k, \boldsymbol{p_{-k}})), \tag{2}$$

where w is the frequency width of each subchannel.

In practice, as the result of the variance of physical channel, $R_k(p_k, \boldsymbol{p_{-k}})$ is stochastic variable, which makes it definitely difficult and unpractical to provide an accurate delay bound guarantee for FU k. Therefore, the statistical QoS metric and delay-bound violation probability have been widely used. Denote θ_k to be the statistical delay exponent of the FU k. It characterizes the steady-state delay violation probability of FU k by

$$P(D_k \geq D_k^{\max}) \doteq e^{-\theta_k c_k D_k^{\max}}, \tag{3}$$

where D_k represents the actual delay and is a random variable, $D_k^{\max}$ is the delay bound, and c_k is a constant determined by the arrival and service processes. Apparently, a smaller θ_k implies a looser delay-QoS constraint and a larger one corresponds to a more strict delay-QoS constraint. Then, EC is defined as the maximum constant arrival rate that a given service process (channel) can support in order to guarantee the statistical delay requirement specified by θ_k [5]. Analytically, the EC of FU k is given by

$$E_c(\theta_k) = -\frac{1}{\theta_k T} \ln(\mathbb{E}[e^{-\theta_k T R_k(p_k, \boldsymbol{p_{-k}})}]), \tag{4}$$

where $\mathbb{E}$ is the expectation operator and T is the block duration.

B. Stackelberg Game Formulation

Stackelberg game is a strategic game that consists of a leader and several followers competing with each other on certain resources. The leader moves firstly and the followers move subsequently.

In this paper, we formulate the MBS as the leader, the FUs as the followers. At first, The MBS protects itself by imposing a set of prices on per unit of received interference power from each FU. Then, the FUs update their power allocation strategies to maximize their individual EC based on the assigned interference prices. The maximum interference that the MBS can tolerate is Q, then the following restraint should be satisfied at MBS side:

$$\sum_{k=1}^{K} I_k(p_k) \leq Q, \tag{5}$$

where $I_k(p_k) = g_k p_k$ denotes the power of the interference from FU k to MBS.

At the MBS's side, the MBS's target is to maximize its revenue obtained by selling the interference quota to FUs, which can be expressed as

$$U_M(\boldsymbol{\mu}, \boldsymbol{p}) = \sum_{k=1}^{K} \mu_k I_k(p_k), \tag{6}$$

where $\boldsymbol{\mu} = [\mu_1, \mu_2, ..., \mu_K]^T$ represents the interference price vector, and μ_k denotes the interference price for FU k. $\boldsymbol{p} = [p_1, p_2, ..., p_K]^T$ is power allocation matrix for all the FUs. The MBS needs to find the optimal interference prices $\boldsymbol{\mu}$ to maximize its revenue within its tolerable aggregate interference margin. The problem can be formulated as:

$$\textbf{Problem2.1}: \max U_M(\boldsymbol{\mu}, \boldsymbol{p}), \tag{7a}$$

$$\sum_{k=1}^{K} I_k(p_k) \leq Q, \tag{7b}$$

$$\boldsymbol{\mu} > 0. \tag{7c}$$

At FU's side, we assume each FU expects to have a much higher spectrum efficiency under a certain delay-QoS constraint. Since ln(x) is a monotonically increasing function, from (4), a higher $-\mathbb{E}[e^{-\theta_k T R_k(p_k, \boldsymbol{p_{-k}})}]$ results in a higher EC. Therefore, the utility for FU k ($\forall k \in \mathcal{K}$), can be formulated as

$$U_k(p_k, \boldsymbol{p_{-k}}) = -\mathbb{E}[e^{-\theta_k T R_k(p_k, \boldsymbol{p_{-k}})}] - \mu_k I_k(p_k), \tag{8}$$

where $I_k(p_k)$ is the interference quota FU that k would like to buy from the MBS under the interference price μ_k. It is observed from (8) that the utility function of each FU consists of two parts: profit and cost. If the FU k increases its transmit power, the profit increases, which implies higher effective capacity, but it will definitely cause more interference to the MBS and needs to pay for it at the cost of $\mu_k I_k(p_k)$. For each FU k, this problem can be formulated as

$$\mathbf{Problem2.2}: \max U_k(p_k, \boldsymbol{p_{-k}}), \tag{9a}$$

$$p_k \geq 0, \forall k \in \mathcal{K} \tag{9b}$$

$$p_k \leq p_{\max}, \forall k \in \mathcal{K} \tag{9c}$$

$$\theta_k > 0, \forall k \in \mathcal{K}, \tag{9d}$$

where p_{max} is the maximum transmit power of FU k.

Problem2.1 and **Problem2.2** together form a Stackelberg game. The objective of this game is to find the SE point(s), from which neither the MBS nor each FU has incentive to deviate. The SE of the proposed game is investigated in the following subsection.

C. Stackelberg Equilibrium

For the proposed Stackelberg game, the SE is defined as follows.

Definition 2.1: Let $\boldsymbol{\mu}^*$ be a solution for **Problem 2.1** and p_k^* be a solution for **Problem 2.2** of FU k. Then the point $(\boldsymbol{\mu}^*, \boldsymbol{p}^*)$ is a SE for the proposed Stackelberg game if for any $(\boldsymbol{\mu}, \boldsymbol{p})$,the following conditions are satisfied:

$$U_M(\boldsymbol{\mu}^*, \boldsymbol{p}^*) \geq U_M(\boldsymbol{\mu}, \boldsymbol{p}^*), \tag{10}$$

$$U_k(p_k^*, \boldsymbol{p}_{-k}^*, \boldsymbol{\mu}^*) \geq U_k(p_k, \boldsymbol{p}_{-k}^*, \boldsymbol{\mu}^*). \tag{11}$$

It is not difficult to see that for a given $\boldsymbol{\mu}$, FUs strictly compete in a non-cooperative manner, which can be seen as the subgame of the proposed Stackelberg game. Generally, the SE for a Stackelberg game can be obtained by finding its subgame's NE point firstly. At the MBS side, since there is only one player, the best response of the MBS can be readily obtained by solving **Problem 2.1**. Thus, the SE can be obtained as follows. For a given $\boldsymbol{\mu}$, **Problem 2.2** is solved firstly. Then, based on the obtained best response functions $\boldsymbol{p}^*$ of the FUs, which is a function of $\boldsymbol{\mu}$, we solve **Problem 2.1** for the optimal interference price $\boldsymbol{\mu}$.

III. POWER OPTIMIZATION

In this section, we provide the solutions for the formulated problems with following steps: finding the NE for the subgame firstly, and searching the SE point subsequently. For tractable simplicity, we assume that the MBS gives interference price for each FU uniformly, which is denoted as μ.

A. NE of the Non-cooperative Subgame

Firstly, we consider the sparsely deployed scenario, i.e, in rural areas. Then, interference between each femtocell can be negligible, i.e, $h_{j,k} = 0, \forall j \neq k$. As a result, the **Problem 2.2** can be translated into

$$\mathbf{Problem3.1}: \max \mathbb{E}[-e^{-\theta_k B \log(1+\frac{h_{k,k}p_k}{\sigma^2})}] - \mu g_k p_k, \tag{12a}$$

$$p_k \geq 0, \forall k \in \mathcal{K} \tag{12b}$$

$$p_k \leq p_{\max}, \forall k \in \mathcal{K} \tag{12c}$$

$$\theta_k > 0, \forall k \in \mathcal{K}. \tag{12d}$$

It's observed that the objective function is a concave function over p_k, which has a unique optimal solution. The derivate of $U_k(p_k, \boldsymbol{p_{-k}})$ is

$$\begin{aligned}&\tfrac{\partial U_k(p_k,\boldsymbol{p_{-k}})}{\partial p_k}\\ &= \mathbb{E}[\tfrac{\partial}{\partial p_k}(-e^{-\theta_k BT\log_2(1+\frac{h_{k,k}p_k}{\sigma^2})} - \mu g_k p_k)]\\ &= \textstyle\int [-\theta_k\beta(1+\frac{h_{k,k}p_k}{\sigma^2})^{-(\theta_k\beta+1)} + \mu g_k] f(h_{k,k}) dh_{k,k},\end{aligned} \tag{13}$$

where $\beta = \frac{BT}{\ln 2}$, and $f(h_{k,k})$ represents the probability density function (PDF) of $h_{k,k}$. Let $\frac{\partial U_k(p_k,p_{-k})}{\partial p_k} = 0$. According to the theory in [6], for a given interference price μ, the optimal solution for (12a) is

$$\widehat{p}_k(\mu) = \frac{\sigma^2}{h_{k,k}}\left[\left(\frac{\theta_k\beta h_{k,k}}{\mu g_k \sigma^2}\right)^{\frac{1}{1+\theta_k\beta}} - 1\right]. \tag{14}$$

Then, solution of **Problem 3.1** is accordingly

$$p_k^*(\mu) = \begin{cases} \min(\widehat{p}_k(\mu), p_{max}), \mu < \frac{\theta_k\beta h_{k,k}}{g_k\sigma^2} \\ 0 \qquad\qquad\qquad\quad , \mu \geq \frac{\theta_k\beta h_{k,k}}{g_k\sigma^2} \end{cases}. \tag{15}$$

It is observed that for a given interference μ, the NE for the subgame at FU side can be easily obtained. If the interference price is too high, i.e., $\mu \geq \frac{\theta_k\beta h_{k,k}}{g_k\sigma^2}$, FU k will not transmit. In other extreme, FU k will translate at p_{max}.

Sequently, we consider the densely deployed scenario, i.e., in the urban area. Mutual interference between each femtocell can't be neglected. Based on the conclusion above, for given $\boldsymbol{p_{-k}}$ and μ, the best response function of FU k can be obtained as

$$\widehat{p}_k(\mu) = \frac{z^2(\boldsymbol{p_{-k}})}{h_{k,k}}\left[\left(\frac{\theta_k\beta h_{k,k}}{\mu g_k z^2(\boldsymbol{p_{-k}})}\right)^{\frac{1}{1+\theta_k\beta}} - 1\right], \tag{16}$$

$$p_k^*(\mu) = \begin{cases} \min(\widehat{p}_k(\mu), p_{max}), \mu < \frac{\theta_k\beta h_{k,k}}{g_k z^2(\boldsymbol{p_{-k}})} \\ 0 \qquad\qquad\qquad\quad , \mu \geq \frac{\theta_k\beta h_{k,k}}{g_k z^2(\boldsymbol{p_{-k}})} \end{cases}, \tag{17}$$

where $z^2(\boldsymbol{p_{-k}}) = \sigma^2 + \sum\limits_{j\neq k} p_j h_{j,k}$, and $\mu_0 = \frac{\theta_k\beta h_{k,k}}{g_k z^2(\boldsymbol{p_{-k}})^2}$. For a given interference price μ, (17) represents a N-users non-cooperative game.

In general, there are multiple NEs, and there is no efficient algorithm to obtain all of them. However, since the cross-femtocell channel power gains are usually very weak due to the penetration loss, we can assume that the aggregate interference at B_k's receiver received from other femtocell co-channel FUs is bounded, i.e., $\sum\limits_{j\neq k} p_j h_{j,k} \leq \varepsilon$, where ε is the upper bound. Here, we can merely consider the worst case, i.e., $\sum\limits_{j\neq k} p_j h_{j,k} = \varepsilon, \forall k \in \mathcal{K}$. If we denote $\sigma^2 + \varepsilon$ as z^2, the problem at the FU side will be exactly the same as **Problem 3.1** with σ^2 replaced by z^2. So the NE point is unique at this case and the NE can be calculated by (15).

B. PSO aided Power Allocation Algorithm

As analyzed above, for a given μ, the NE of the subgame will be obtained under the sparsely deployed scenario and the densely deployed one with inter-cell interference seriously restricted. Substituting $p_k^*(\mu)(k \in \mathcal{K})$ into **Problem 2.1**, the optimization problem at the MBS side can be formulated as

$$\mathbf{problem3.2}: \ \max \sum_{k=1}^{K} \mu I_k(\mu) \tag{18a}$$

$$\sum_{k=1}^{K} I_k(\mu) \leq Q, \tag{18b}$$

$$\mu > 0. \tag{18c}$$

Usually, **problem3.2** is difficult to solve directly. In this paper, the best μ will be searched by utilizing the PSO algorithm, which is quite fast to converge and easy to operate. The optimization procedure of PSO is based on a population of random particles, that fly in the solution space with velocity dynamically adjusted.

In this paper, each particle has a position μ and a velocity vector v, and the performance of particle is evaluated by the $fitness$ function, $F(\mu) = \sum\limits_{k=1}^{K} \mu I_k(\mu)$. At each iteration, each particle records its personal optima, μ_p, which denotes best position it has achieved so far. At the same time, the population records the global optima, μ_g, which represents the best position searched among all the particles. The update formula of each particle is

$$v(t+1) = \omega v(t) + r_1(\mu_p(t) - \mu(t)) + r_2(\mu_g(t) - \mu(t)), \tag{19}$$

$$\mu(t+1) = \mu(t) + v(t+1), \tag{20}$$

where r_1 and r_2 are randomly and uniformly distributed in the range [0,2], and ω is a parameter in $[0,1]$. After each update, they record the best particle, and finally the particles swarm will find a optimal position in the solution space. The complete algorithm is shown in **Algorithm 1**.

IV. SIMULATION AND NUMERICAL ANALYSIS

In this section, several numerical results are provided to evaluate the performance of our proposed power allocation algorithm for two-tier femtocell networks. In the simulation, we consider sparsely deployed scenario, and the densely deployed one with inter-tier interference constraint also accords with these results. Specifically, to make a comparison, we also consider the femtocell non-cooperative resource allocation game (FNRAG) algorithm [7], in which interference price μ determined by a try-and-error method is a constant.

The mainly scalable parameters are listed in **Table I** [8]. In this evaluation, femtocells are randomly distributed within the coverage of the central MBS.

Algorithm 1: PSO aided Power Allocation Algorithm

```
Step 1: Input: $\theta = [\theta_k]_{1\times K}$,$\mathbf{h} = [h_k]_{1\times K}$,$\mathbf{g} = [g_k]_{1\times K}$,
  population size as $M$ and calculate the largest $\mu_{\max}$
  which makes at least one FU access.
Step 2: Particle population initiation
  Denote the particle population as $\mathcal{M}= \{1, 2,..., M\}$.
  Their positions and velocities are respectively initialized
  as $\mathcal{R}(0) = \{\mu_1(0), \mu_2(0), ..., \mu_M(0)\}$ and
  $\mathcal{V}(0) = \{v_1(0), v_2(0), ..., v_M(0)\}$, where $\forall m \in \mathcal{M}$,
  $\mu_m(0)$ randomly distributed in $(0, \mu_{\max})$ and satisfies
  (18b), and $v_m(0)$ is randomly distributed in $(0, v_{\max})$.
  Initialize each personal optima: $\mu_{m,p}(0) = \mu_m(0)$.
  Initialize global optima: $\mu_g(0) = arg \max_{\mu \in \mathcal{R}(0)} F(\mu)$
Step 3: Begin to search the global optima.
  while($t \leq t_{\max}$) do
    Update the population's positions and velocities to
    $\mathcal{R}(t)$ and $\mathcal{V}(t)$ with (19) and (20).
    for($m = 1 : M$)
      if($F(\mu_m(t)) > F(\mu_{m,p}(t-1))$&&$I(\mu_m(t)) < Q$)
      then$\mu_{m,p}(t) = \mu_m(t)$ else $\mu_{m,p}(t) = \mu_{m,p}(t-1)$
    end for
    $\mu^* = arg \max_{\mu \in \mathcal{R}(t)} \mu I(\mu)$
    if($F(\mu^*) > F(\mu_g(t-1))$)
    then $\mu_g(t) = \mu^*$ else $\mu_g(t) = \mu_g(t-1)$
  end while
Step 4: Output the best particle $\mu_g$ and each FU's
  allocated power $p_k^*$ with (14) or (15)
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TABLE I: Simulation Parameters

Parameter	Value
Carrier frequency	2.5GHz
The Bandwidth of Subchannel	200KHz
Number of FBS K	9
FU maximum power p_{max}	23dBm
Background noise power	-1dBm
Path loss for indoor link	$38.46 + 20\lg d$
Path loss for in-outdoor link	$38.46 + 20\lg d + L_w$

Fig. 2 shows the convergence of our proposed algorithm. In the simulation, the maximum interference the MBS can tolerate is -50dBm for every channel. The delay constraints for the FUs are set as $\theta_{1-5} = 0.001$ and $\theta_{6-9} = 0.01$. We can see from Fig. 2 that after about 7 iterations, the revenue of the MBS reach the highest, which means our proposed algorithm has a nice convergence.

Fig. 3 shows the average EC of all users versus different delay-constraints θ, where Q is -70dBm. As shown in the figure, when θ is smaller than 10^{-6}, which implies quite a loose delay-QoS constraint, the upper layer can transmit data at the Shannon capacity and the average EC of all FUs is quite high. As θ gets larger, the delay-QoS constraint becomes more stringent and the average EC decreases. In addition,

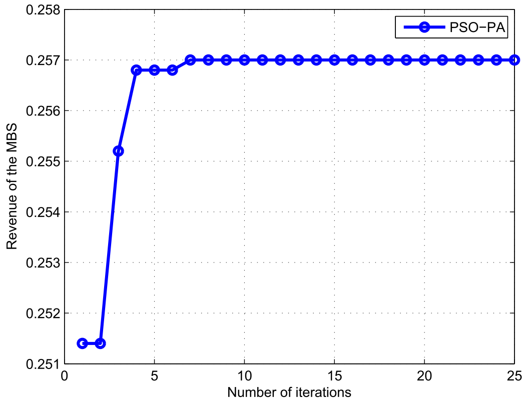

Fig. 2: Convergence of the PSO-PA

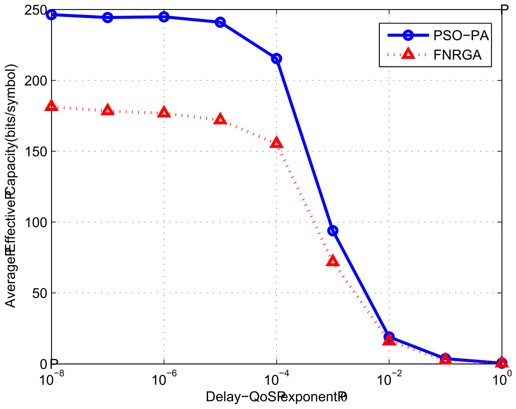

Fig. 3: Average EC vs. the Delay-QoS exponent θ

it's obviously presented in Fig. 3 that the proposed PSO-PA algorithm can bring higher average EC compared with FNRAG algorithm, since μ in FNRAG is determined by a try-and-error method and kept invariable, but μ in PSO-PA is adjusted dynamically by the MBS.

As shown in Fig. 4, we set each user's θ as 0.001 and 0.01 respectively. The average EC of all FUs increases as the Q gets larger. It's rational that as more interference can buy from the MBS, the FUs can obtain more interference permission and transmit at higher power level. However, as it reach some level, the average EC doesn't increase any more, because although the interference constraint is large enough, the FU's purchasing power is not infinite.

V. CONCLUSION

In this paper, we have studied price-based power allocation in uplink OFDMA two-tier femtocell networks, with each FU's statistical delay-QoS considered. We firstly introduce the conception of EC and formulate the problem as the Stackelberg game, in which the MBS is formulated as the leader, the FUs as the followers. We solve the proposed problem by finding the NE point of non-cooperative subgame with optimization theory firstly, and a PSO-PA algorithm based on the proposed Stackelberg game model has been proposed. Numerical results show that the proposed algorithm can converge quite fast and bring higher average EC compared with FNRGA algorithm.

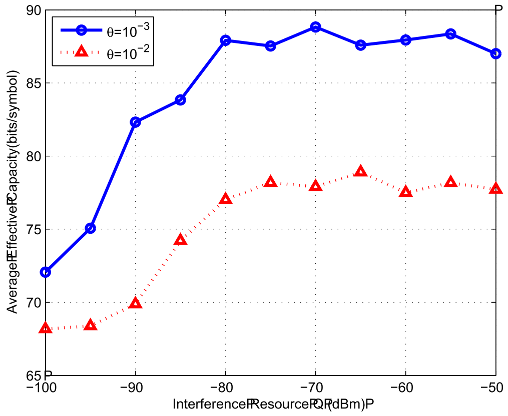

Fig. 4: Average EC vs. Q

VI. ACKNOWLEDGEMENT

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