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Co-tier Uplink Interference Management by Stackelberg Game with Pricing in Co-channel Femtocell Networks

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Abstract Due to the development of the femtocell technologies, the indoor signal quality of the mobile communications is greatly improved. However, as the femtocells are widely deployed, the uplink interference from different femtocells, i.e. the co-tier uplink interference, turns out to be a critical problem to jeopardize the performance of the femtocell networks. To tackle this problem, the concept of Stackelberg game with pricing mechanism is employed. In this game, given a maximum co-tier uplink interference that the leader can tolerate, the optimum price to maximize the utility of the leader and the optimum transmission power to maximize the utility of the followers are determined by a distributed bargaining procedure. Based on the numerical results, we first show that the distributed bargaining procedure is effective and efficient in determining the optimum price and the optimum transmission power. In addition, we also conclude that the total network capacity can be improved on condition that leader can tolerate larger amount of co-tier uplink interference from the followers.

Keywords Femtocell networks · Co-tier uplink interference · Pricing · Distributed bargaining procedure · Stackelberg game

1 Introduction

Owing to the never-ending evolution of the mobile communication technologies, a recent white paper provided by Cisco [1] reported that the number of global mobile devices and connections is expected to be 1.5 per capita by 2021. This results in the global mobile data traffic to be increased to 49 exabytes per month by 2021. Besides, around 60% of the total mobile data traffic is video in 2016. To not overwhelm the evolved Node B (eNB) or macro base station (MBS) in the mobile cellular network and violate the QoS of video services,

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60% of the total mobile data is offloaded from the eNB in 2016. Furthermore, it is also expected that video traffic will continuously increase to 78% of the total mobile data traffic by 2021. This means lots of mobile data traffic should to be offloaded from the eNB or MBS. But, the question is how to do that efficiently. Analysis of the origination and termination of the mobile traffic indicated that more than 70% of the mobile data communication and 50% of the mobile voice communication are originated from the indoor environment (e.g., office or underground market) [2]. Similarly, according to the ABI research report [3, 4], more than 80% of the mobile traffic is either originated or terminated indoor. Hence, the overall traffic load of the eNB can be greatly reduced if there exist alternative solutions for the indoor users to connect with.

Among the possible solutions, small cell is considered as one of the feasible solutions for the mobile operators to accommodate the ever-increasing indoor mobile traffic volume and provide better indoor wireless signal quality. The definition for small cells made by the small cell forum [5] is as follows: *'Small cells' is an umbrella term for operator-controlled, low-powered radio access nodes, including those that operate in licensed spectrum and unlicensed carrier-grade Wi-Fi. Types of small cells include femtocells, picocells and, microcells. Any or all of these small cells can be based on 'femtocell technology'—i.e. the collection of standards, software, open interfaces, chips and know-how that have powered the growth of femtocells.* In general, a femtocell consists of a femtocell base station (FBS) and the connected user equipments (UEs) which are called Femto UEs (FUEs). With the inclusion of the femtocells, the entire network is regarded as a macrocell-femtocell coexisted heterogeneous network. If macrocell and femtocells share the same spectrum, the interference in such heterogeneous network can be divided into two categories: cross-tier interference and co-tier interference. The cross-tier interference refers to the interference between macrocell and femtocells. The co-tier interference refers to the interference between femtocells. As illustrated in Fig. 1, the blue and red dashed lines represent the co-tier downlink interference from FBS-F_2 to the FUE-1 and the co-tier uplink interference from FUE-1 to FBS-F_2, respectively. The cyan and brown dashed lines are the cross-tier uplink interference from FUE-1 to MBS and from Macro UE (MUE) to FBS-F_2,

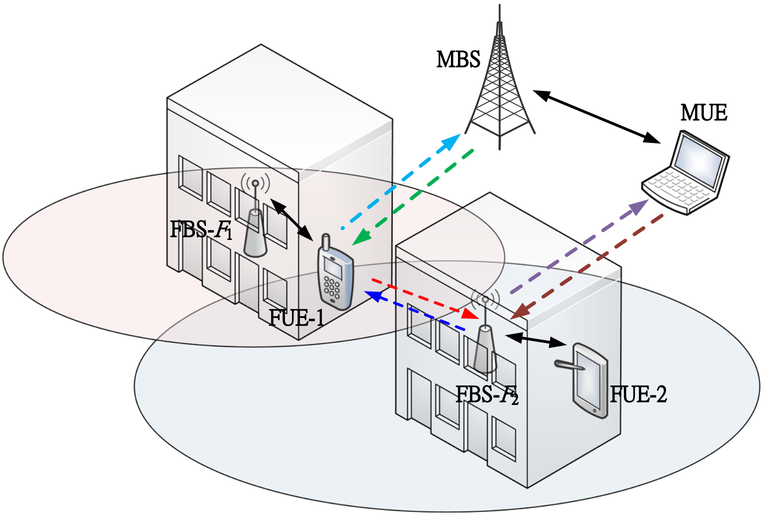


Fig. 1 Illustration of co-tier and cross-tier interference

respectively. The green and purple dashed lines represent the cross-tier downlink interference from MBS to FUE-1 and from FBS-F_2 to MUE, respectively. Among all the possible interference, this paper explores how to manage the co-tier uplink interference by playing the Stackelberg game with pricing mechanism to control the transmission power of FUEs so that the overall network capacity is maximized.

The Stackelberg game is originated from the game theory. In the beginning, game theory was mainly applied to economics, politics, psychology, and biology. Literature reviews, e.g. [6–9], have shown that game theory can also be applied to communication and network engineering. For example, it has been successfully applied to LTE-U [10] and cyber-security [11]. Furthermore, game theory is also used to find solutions for handoff mechanism [12] and radio resource allocation [13] in the macro-femto coexisted heterogeneous networks.

Interference management is an important issue in the macro-femto coexisted heterogeneous networks. However, most of the existing literature mainly focuses on mitigating the cross-tier interference. For example, the authors in [14] proposed a decentralized utility-based algorithm to reduce SINR targets of femtocells that contribute strong cross-tier interference whenever SINR of MUE cannot be met. In [15], when the cross-tier interference from all femtocells greater than a maximum allowable cross-tier interference power, the authors proposed open-loop and closed-loop cross-tier interference mitigation strategies to reduce the transmission power of the FUE that is regarded as the maximum interference source of an MBS. Different from that only the FUE that interferes an MBS most is required to reduce the transmission power in [15], whenever the cross-tier interference to an MBS exceeds the maximum allowable cross-tier interference power γ_{th}, the authors in [16] proposed to proportionally allocate γ_{th} to all the FUEs that interfere with the MBS based on their interference strength to the MBS. Then, based on the newly allocated interference strength, the MBS calculates the corresponding maximum allowable transmission power of each FUE. After being notified by the MBS, each FUE updates the transmission power accordingly. In [17], the Stackelberg game was used to study the resource allocation problem by managing the cross-tier interference from FUEs to MBS in a macro-femto coexisted heterogeneous network. Specifically, the leader and the followers in [17] are the MBS and FUEs, respectively. For each FUE to maximize its utility, it needs to increase the transmission power. When the FUEs do so, the MBS gets profits by pricing the interference they introduced. Under the premise that the maximum acceptable cross-tier interference of the MBS cannot be violated, MBS achieves the maximum utility by changing the price. On the contrary, each follower FUE tries to achieve the maximum utility by updating its transmission power. Different from most of the existing works that focus on investigating the cross-tier interference, this paper studies how to optimally manage the co-tier uplink interference by employing the Stackelberg game with pricing mechanism so that the total femtocell network capacity is maximized.

This paper is organized as follows. First, the system model used to model the co-tier uplink interference for the Stackelberg game with pricing mechanism and the utilities for the leader and the follower are described in Sect. 2. In Sect. 3, the formula to determine the optimum transmission power of the follower and the distributed bargaining procedure to find the optimum price of the leader are presented. In Sect. 4, the numerical results under different parameter values are demonstrated and discussed. Finally, Sect. 5 concludes this paper.

2 System Model

2.1 The System Model

This paper considers the scenario where there are multiple femtocells deployed within the coverage area of an MBS sharing the uplink spectrum of MBS. A femtocell is assumed to consist of one FBS and one authorized FUE. The FBS is configured to operate in the closed subscriber group (CSG) [8], which means only the authorized FUE is eligible to access the FBS. Stackelberg game is a game played by leader and follower to iteratively update their strategies in response to the new strategy proposed by the opponent. While playing the game, leader is with the first priority to propose its strategy. Then, based on the strategy proposed by the leader, follower proposes its strategy. Basically, each strategy proposed by each player is to maximize its own utility. To apply the Stackelberg game to study the problem of co-tier uplink interference, the system model we used is depicted in Fig. 2. As we can see in this figure, one of the femtocells is randomly selected as the leader and the FBS and FUE of this selected femtocell are named as FBS-0 and FUE-0, respectively. We also assume that the uplink transmission power of FUE-0 p_0 is fixed at the maximum possible transmission power $p_{\max}$. The rests of the femtocells are regarded as the followers. The FBS and the FUE of the i-th follower femtocell are named as FBS-i and FUE-i where $i = 1,\ldots, N$. The uplink transmission power of a follower FUE-i is $p_{\mathrm{i}} \geq 0$. The channel gain from FUE-i to FBS-j is $g_{i,j}$ for any $i = 0, \ldots, N$ and $j = 0, \ldots, N$. Specifically, the channel gains between leader and follower are depicted as the red dashed lines, while the channel gains between followers are depicted as the blue dashed lines. The noise of the channel is assumed to be an Additive White Gaussian Noise (AWGN) with zero mean and variance σ^2.

2.2 Stackelberg Game with Pricing Mechanism

As shown in Fig. 2, when follower FUEs uplink to their corresponding FBSs, they will interfere with the leader FBS-0 in receiving the uplink transmission from the FUE-0. Accordingly, the utility of the leader is reduced. To indemnify such a utility loss, a pricing

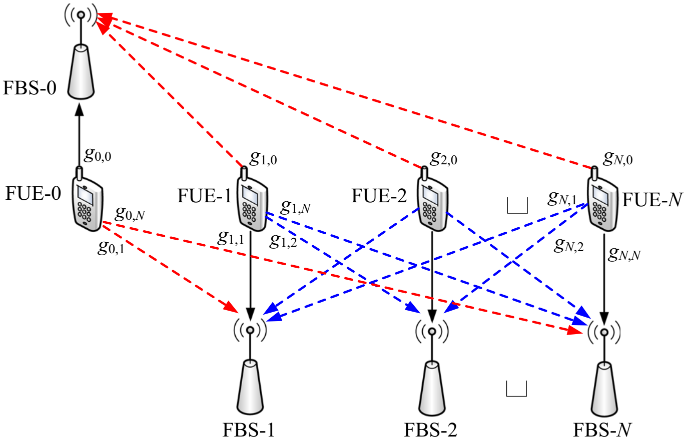


Fig. 2 System model

mechanism is included for leader to charge followers for the co-tier uplink interference they introduced. In response to the price proposed by the leader, each follower needs to update its transmission power to obtain the maximum utility. As the game is played, the utilities of the leader and the followers will be continuously improved. However, if the utilities of the leader and the followers cannot be further improved by any other strategies, the Stackelberg equilibrium (SE) is achieved and the game is over. Following, we start to formulate the considered problem into a Stackelberg game with pricing mechanism.

First, we assume the maximum co-tier uplink interference that the leader can withstand is Q. In other words, the maximum aggregated co-tier uplink interference from all followers to the leader cannot be greater than Q. This constraint is expressed as

$$\sum_{i=1}^{N} p_i g_{i,0} \le Q. \tag{1}$$

Let $\mathbf{p} = [p_0, p_1, \ldots, p_N]$ be the vector representing the transmission power of all FUEs. The SINR perceived at the leader can be represented as

$$\gamma_0(\mathbf{p}) = \frac{p_0 g_{0,0}}{\sum_{i=1}^{N} p_i g_{i,0} + \sigma^2}. \tag{2}$$

Thus, under the condition that $\mathbf{p}$ is known to the leader, the utility of the leader is defined by

$$U_0(\beta|\mathbf{p}) = \lambda \log_2(1 + \gamma_0(\mathbf{p})) + \beta \sum_{i=1}^{N} p_i g_{i,0} - \alpha \sum_{i=1}^{N} p_0 g_{0,i}, \tag{3}$$

where λ (in Hz/bps) is a system parameter used to transfer the capacity into a utility value, β (in 1/mW) is the price per unit co-tier uplink interference from the followers proposed by the leader, and α (in 1/mW) is a system parameter used to represent the compensation per unit co-tier uplink interference to the followers paid by the leader. As can be seen from the right-hand side of (3), the first term is the Shannon capacity per unit Hz, the second term is the total profit gained by selling the co-tier uplink interference tolerance to the followers, while the third term is the total compensation that needs to pay to the followers for its co-tier uplink interference to them. According to the Stackelberg game with pricing mechanism, the strategy for the leader to maximize its utility is to update the price β. Hence, under the constraint that the total co-tier uplink interference from the followers cannot exceed the maximum co-tier uplink interference that the leader can endure Q, the utility optimization problem for the leader is formulated as

$$\max_{\beta \ge 0} U_0(\beta|\mathbf{p}) \tag{4}$$

$$\text{subject to } \sum_{i=1}^{N} p_i g_{i,0} \le Q. \tag{5}$$

Let $\mathbf{p}_{-i} = [p_0, \ldots, p_{i-1}, p_{i+1}, \ldots, p_N]$ be the vector representing the transmission power of all FUEs other than FUE-i and $i \ne 0$. From the perspective of the i-th follower, given $\mathbf{p}_{-i}$, if the transmission power of FUE-i is p_i, the SINR perceived at the follower FBS-i, i = 1, 2,…, N, can be expressed as

$$\gamma_i(p_i|\mathbf{p}_{-i}) = \frac{p_i g_{i,i}}{\sum\limits_{j=0,j\neq i}^{N} p_j g_{j,i} + \sigma^2}. \tag{6}$$

Hence, given β and $\mathbf{p}_{-i}$ are known to the i-th follower, the utility of the i-th follower with the transmission power p_i is defined by

$$U_i(p_i|\beta, \mathbf{p}_{-i}) = \lambda \log(1 + \gamma_i(p_i|\mathbf{p}_{-i})) - \beta p_i g_{i,0} + \alpha p_0 g_{0,i}. \tag{7}$$

In the right-hand side of (7), the first term is the Shannon capacity per unit Hz, while the second and third terms are the cost paid to the leader and the compensation given by the leader, respectively. Besides, since all followers are assumed in the same coalition, the cost paid to and the profit gained from other followers are ignored. From (7), we can find that the maximum utility of the i-th follower can be achieved if the transmission power p_i is well controlled. Hence, given β and $\mathbf{p}_{-i}$, without violating the maximum tolerable co-tier uplink interference Q, the objective of the i-th follower, $i = 1, 2, \ldots, N$, is to maximize its utility by adjusting the transmission power of p_i and is formulated by

$$\max_{p_i \geq 0} U_i(p_i|\beta, \mathbf{p}_{-i}). \tag{8}$$

Thus far, formulations to maximize the utilities of the leader and the followers in (4), (5), and (8) constitute the Stackelberg game with pricing mechanism.

2.3 Finding the Stackelberg Equilibrium (SE)

To solve the Stackelberg game with pricing mechanism, we need to find the optimum price proposed by the leader β^* and the optimum transmission power of the i-th follower p_i^* that satisfy the SE. In other words, we want to find $\beta^* \geq 0$ and $p_i^* \geq 0$ that satisfy

$$U_0(\beta^*|\mathbf{p}^*) \geq U_0(\beta|\mathbf{p}^*), \tag{9}$$

$$U_i(p_i^*|\mathbf{p}_{-i}^*, \beta^*) \geq U_i(p_i|\mathbf{p}_{-i}^*, \beta^*), i = 1, \ldots, N. \tag{10}$$

3 Finding p_i^* and β^*

In this section, based on the utility optimization problems formulated in (4), (5), and (8), we will derive the formula to obtain the optimum transmission power p_i^* and present a distributed bargaining procedure to find the optimum price proposed by the leader β^*, respectively. Since p_0 is fixed, we assume $p_0^* = p_0$ in our analyses.

First, given $\mathbf{p}_{-i}^*$, by substituting (6) into (7), (8) can be re-written as follows

$$\max_{p_i \geq 0}\left(\lambda \log_2\left(1 + \frac{p_i g_{i,i}}{\sum\limits_{j=0,j\neq i}^{N} p_j^* g_{j,i} + \sigma^2}\right) - \beta p_i g_{i,0} + \alpha p_0 g_{0,i}\right), \quad \forall i \in \{1, 2\ldots, N\}. \tag{11}$$

Since p_i is the only unknow variable in (11), the optimum value of p_i^* to maximize (11) can be easily obtained by letting the first derivative of (11) with respect to p_i equal to 0 and is given by

$$p_i^* = \min\left(p_{\max}, \max\left(0, \frac{\lambda}{\beta g_{i,0}} - \frac{\sum\limits_{j=0,j\neq i}^{N} p_j^* g_{j,i} + \sigma^2}{g_{i,i}}\right)\right), \quad \forall i \in \{1, 2, \ldots, N\}, \tag{12}$$

where $p_{\max}$ is the maximum allowable transmission power of a FUE. From (12), we know the i-th follower will cease the transmission by setting the transmission power to 0 if the price β proposed by the leader is greater than $\lambda g_{i,i} \Big/ \left(g_{i,0}\left(\sum_{j=0,j\neq i}^{N} p_j^* g_{j,i} + \sigma^2\right)\right)$.

Next, we need to solve the optimization problem formulated by (4) and (5) to find the optimum price β^* proposed by the leader. By substituting (2) into (3), the optimization problem in (4) can be rewritten by

$$\max_{\beta \geq 0} \lambda \log_2(1 + \frac{p_0 g_{0,0}}{\sum\limits_{i=1}^{N} p_i g_{i,0} + \sigma^2}) + \sum_{i=1}^{N} \beta p_i g_{i,0} - \sum_{i=1}^{N} \alpha p_0 g_{0,i}. \tag{13}$$

An intuitive and direct approach to solve (13) is using the techniques from the optimization theory. However, it is very complex. In addition, given a price β proposed by the leader, from (12), we can easily find the optimum transmission power of the i-th follower p_i^* depends on the optimum transmission power of the other $(N-1)$ followers. As a consequence, a non-cooperative subgame with N players is played by the followers. To solve this subgame, we need to find a Nash equilibrium (NE) at which no follower achieves better utility by further updating its transmission power under the condition that the transmission power of all other followers is not updated. However, theoretically, there exists more than one NE. Hence, as mentioned in [17], to reduce the implementation complexity and the number of information exchanges among all femtocells, a distributed bargaining procedure that comply with the concepts of Stackelberg game with pricing mechanism to find the optimum transmission power of the i-th follower p_i^* and the optimum price proposed by the leader β^* is introduced below.

Step 0 The transmission power of all follower FUEs are initially set to $p_{\max}$. The value of β is upper and lower bounded by β_U and β_L with the initial values $\beta_{U,init}$ and $\beta_{L,init}$, respectively.

Step 1 The price proposed by the leader is $\beta = (\beta_U + \beta_L)/2$ and is notified to all followers through the backhaul network.

Step 2 With the notified price β, each follower FUE-i updates its transmission power p_i based on (12) and notifies leader and all other followers about the updated p_i in terms of the backhaul network.

Step 3 After all followers update their transmission power, leader updates the price β based on the following conditions and broadcasts the updated β to all followers through the backhaul network.

3.1 If the perceived interference $\sum_{i=1}^{N} p_i g_{i,0} < (Q - \delta)$, update $\beta_U = \beta$ and $\beta = (\beta_U + \beta_L)/2$. Then, go to Step 2.

3.2 If the perceived interference $\sum_{i=1}^{N} p_i g_{i,0} > (Q + \delta)$, update $\beta_L = \beta$ and $\beta = (\beta_U + \beta_L)/2$. Then, go to Step 2.
Step 4 $\beta^* = \beta$ and $p_i^* = p_i$, i = 1, 2, …, N.

Obviously, the main advantage of this distributed bargaining procedure is only the price β and the transmission power p_i, i = 1, 2, …, N, need to be exchanged between leader and followers. In addition, by introducing the parameter δ, the interval $\left|\sum_{i=1}^{N} p_i g_{i,0} - Q\right| \le \delta$ is used as the stopping criterion of the distributed bargaining procedure.

4 Numerical Analyses and Discussions

Numerical analyses are used to verify the effectiveness and efficiency of the proposed approach. To simplify our study, we consider the femtocell network with five femtocells among which one is selected as the leader and the rests are regarded as the followers. In addition, the channel gains between all femtocells are fixed. All the parameter values are given in Table 1.

4.1 The Effectiveness in Finding β^*

Finding a valid β^* is important in validating the effectiveness of the distributed bargaining procedure. Firstly, Fig. 3 demonstrates, given any Q value, a corresponding optimum price β^* can always be obtained by using the distributed bargaining procedure. Furthermore, in this figure, given a fixed value of λ, we can find a higher optimum price β^* is required to restrain the followers from the uplink transmissions as the value of Q is decreased. On the contrary, a lower optimum price β^* is required to encourage the followers to proceed the uplink transmission as the value of Q is increased. Hence, the distributed bargaining procedure is effective in finding the optimum price β^*.

To evaluate the efficiency of the distributed bargaining procedure in finding an optimum price β^*, the first 12 iterations of the distributed bargaining procedure in searching the optimum price β^* for different values of λ are illustrated in Fig. 4. Obviously, in any case, we find the optimum price β^* can be converged within 10 iterations. Hence, the distributed bargaining procedure is an efficient approach to find the optimum price β^* proposed by the leader. In addition, we can clearly find higher value of β^* is obtained for higher value of λ. The reason is as follows. From (12), if only the value of λ is increased, the transmission power p_i is increased accordingly. Hence, the aggregated co-tier uplink interference

Table 1 Simulation parameter values

Parameter	Value
Number of femtocells	5
$p_{\max}$	200 mW
σ^2	0.1
$g_{i,i}$ $\forall i$	0.01
$g_{i,j}$ $\forall i,j$ and $i \neq j$	0.001
$\beta_{U,init}$	100
$\beta_{L,init}$	0
δ	0.0001

perceived at the leader is also increased. Consequently, in order not to violate the Q value, the leader has no choice but to increase the price. Specifically, for $Q < 0$ dBm, if the value of λ is doubled, the value of β^* is doubled also.

4.2 The Optimum Transmission Power p_i^*

The optimum transmission power p_i^* with respect to different values of Q are shown in Fig. 5. In this figure, we can find the optimum transmission power p_i^* approaches to zero when $Q < -30$ dBm. In other words, under such a stringent tolerable co-tier uplink interference, followers decide to stop their uplink transmissions. In fact, we can also come up with this result from Fig. 3. This is mainly because Fig. 3 has already shown the strategy for the leader to keep the aggregate co-tier uplink interference from exceeding the required Q when $Q < -30$ dBm is to raise the price as possible as it can. Under such a high price, the only strategy that each follower FUE-i would adopt to maximize its utility is to give up the transmission by setting $p_i = 0$. When $Q \geq -30$ dBm, due to larger amount of co-tier uplink interference can be tolerated by the leader, followers are welcome to transmit. To achieve this, the leader starts to reduce the price, which can be confirmed in Fig. 3, so that the optimum transmission power p_i^* in Fig. 5 is increased accordingly. The optimum transmission power p_i^* is continuously increased until reaching the upper bound $p_{\max}$ when $Q = 0$ dBm. This is mainly because the optimum price β^* in Fig. 3 is zero when $Q \geq 0$ dBm, which results the value of p_i in (12) equals to $p_{\max}$.

4.3 Capacities of the Leader and the Followers

As discussed in Sects. 4.1 and 4.2, given a maximum tolerable co-tier uplink interference Q, the distributed bargaining procedure determines the optimum values of the price and the transmission power for the leader and the followers, respectively. With such optimum values, the capacity of the leader and the average capacity of the four followers are depicted in Figs. 6 and 7, respectively. In addition to showing the capacity of the leader, the capacities obtained in the ideal case and the worst case are also depicted in Fig. 6 as the

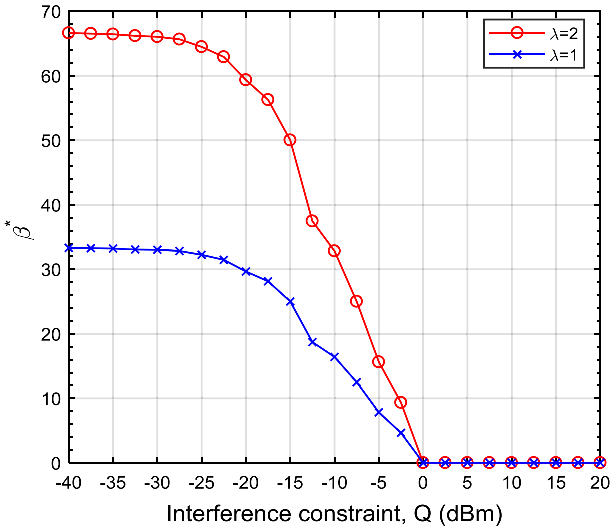


Fig. 3 The effectiveness in finding β^* when $\alpha = 0.5$

Fig. 4 The efficiency in finding β^* when $\alpha = 0.5$

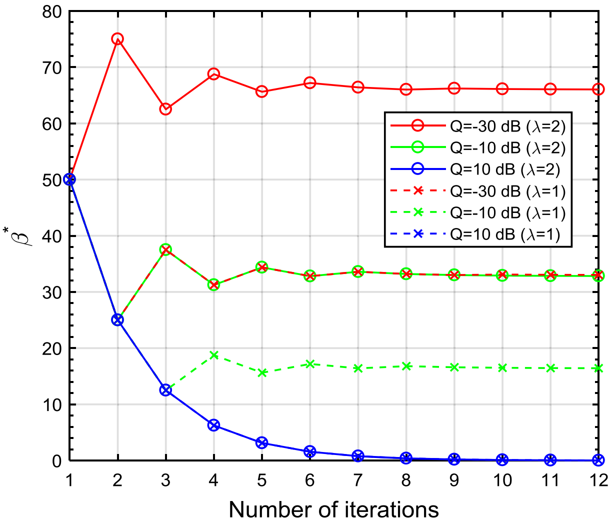
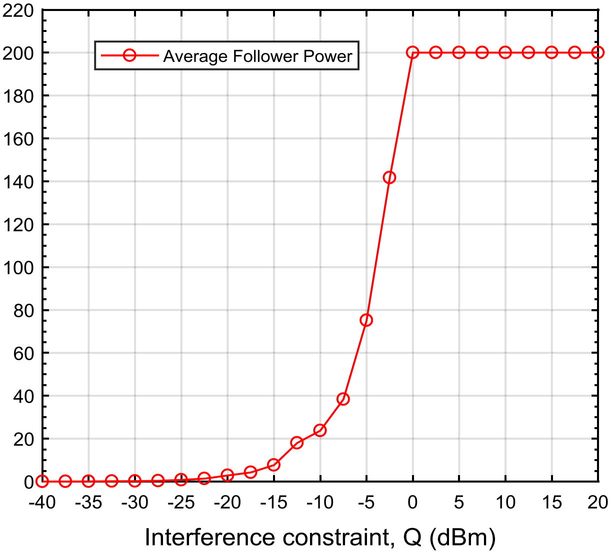


Fig. 5 The optimum transmission power when $\alpha = 0.5$ and $\lambda = 1$



upper and lower bounds of the leader capacity, respectively. The capacity of the leader in the ideal case is defined as the capacity obtained when there is no co-tier uplink interference from the followers. The capacity of the leader in the worst case is regarded as the capacity obtained when the transmission power of each follower equals to $p_{\max}$. As we can see in Fig. 6, the capacity of the leader approaches to the upper bound when $Q < -30$ dBm. According to the discussions in Sects. 4.1 and 4.2, all followers decline to transmit when $Q < -30$ dBm, which causing no co-tier uplink interference imposed on the leader. Hence, the capacity of the leader approaches to the upper bound due to the high SINR. When -30 dBm $\leq Q < 0$ dBm, due to the co-tier uplink interference perceived at the leader increases as the value of Q increases, the capacity of the leader decreases accordingly. When $Q \geq 0$ dBm, the co-tier uplink interference perceived at the leader achieves the maximum, which results in the poorest SINR perceived at the leader. Therefore, the capacity of the leader approaches to the lower bound.

The average capacity of the followers is shown in Fig. 7. Similarly, it can be seen from the figure that when the interference limit is stringent, i.e. $Q < -30$ dBm, the average capacity of the followers approaches to zero since all the four followers would rather not to transmit than to pay a high price to the leader. When the co-tier uplink interference limit is relaxed (that is, the increase of the Q value), the optimum price is reduced and the optimum transmission power is increased. As a result, the average capacity of the followers is increased accordingly. Finally, due to the optimum price becomes to zero and the optimum transmission power becomes to $p_{\max}$ as $Q \geq 0$ dBm, the average capacity of the followers achieves the maximum.

4.4 The Profit and Compensation of the Leader

As mentioned in Sect. 2.2, the second and third terms on the right-hand side of (3) are the profit gained from all followers and the compensation paid to all followers, respectively. Based on the discussions in Sect. 4.2, we have shown the followers will not transmit if $Q < -30$ dBm. Hence, the leader gets zero profit from the followers if $Q < -30$ dBm. However, due to the transmission of the leader, compensations are required to pay to the followers. Consequently, the composite effect, i.e. 'profit' minus 'compensation', goes to negative as illustrated in Fig. 8. Then, as shown in Fig. 5, due to the increase of the transmission power when -30 dBm $\leq Q < 0$ dBm, the leader starts gaining profit from the followers. This results in the composite effect increases from negative to positive and achieves the maximum when $Q = -2.5$ dBm. After that, since the optimum price changes to zero when $Q \geq 0$ dBm, which has been shown in Fig. 3, the profit gained from the followers equals to zero again. Therefore, the composite effect goes to negative again. Since the fundamental ideas for the second and third terms on the right-hand side of (7) are similar to the profit and compensation on the right-hand side of (3), we will omit the discussions for them.

Fig. 6 Capacity of the leader when $\alpha = 0.5$ and $\lambda = 1$

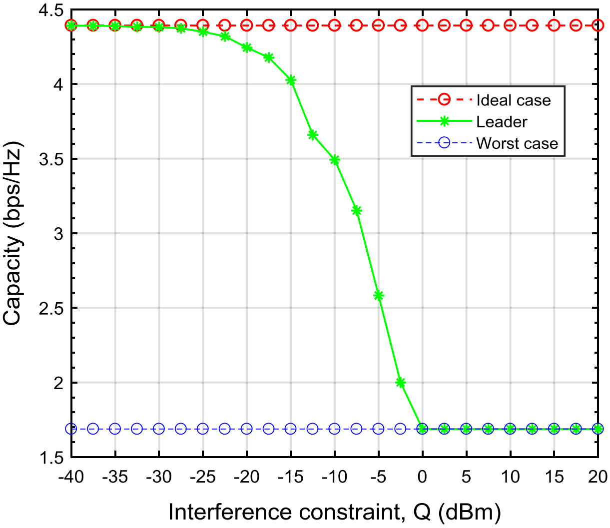
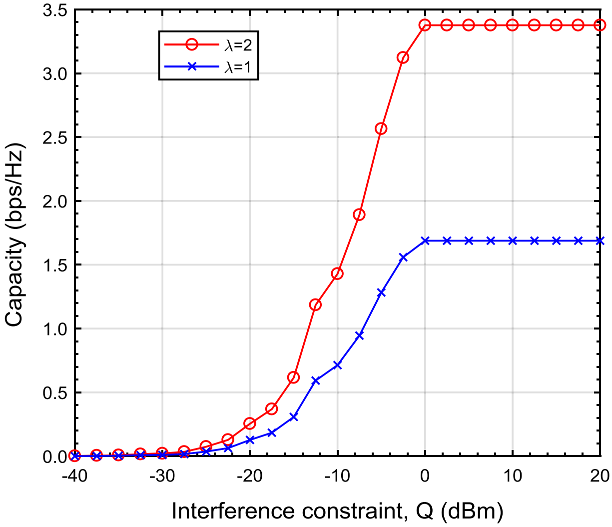


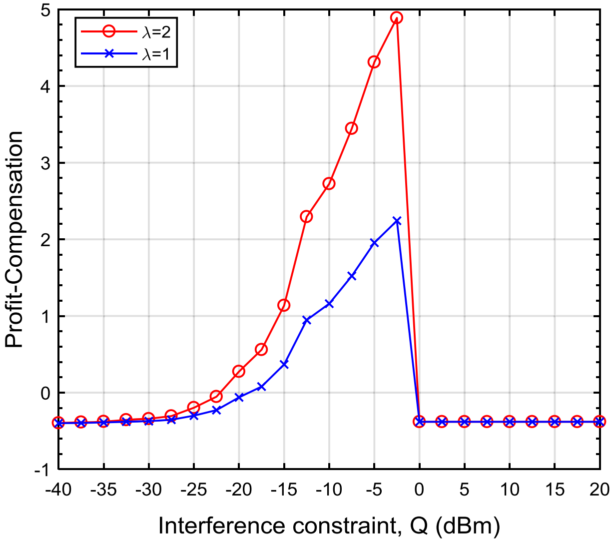
Fig. 7 The average capacity of the followers when $\alpha = 0.5$



4.5 Utilities of the Leader and the Follower

By integrating Figs. 6, 7, and 8, we can obtain the utility of the leader and the average utility of the four followers with respect to the maximum tolerable co-tier uplink constraint Q. The resulted utilities are shown in Fig. 9 for different values of λ. Starting from the left of this figure, the utility of the leader is much higher than the average utility of the followers. The reason for this is, in order not to violate such a small value of Q, the leader needs to strictly limit the co-tier uplink interference from the followers. To achieve this goal, the strategy that the leader adopts is to raise the optimum price (this can be confirmed from Fig. 3). In response to such an expensive price, the strategy adopted by each follower

Fig. 8 The composite effect of the leader when $\alpha = 0.5$



is to give up the transmission by setting the optimum transmission power to 0 (this can be confirmed from Fig. 5). Due to there is no co-tier uplink interference perceived at the leader, based on (3), the utility of the leader achieves the maximum and is equal to the capacity minus the compensation paid to the followers. Due to giving up the transmission, based on (7), the average utility of the four followers equals to the compensation paid by the leader. Based on the parameter values we selected, the compensation is very limited. Hence, the average utility of the four followers is small. Next, when -30 dBm $\leq Q < 0$ dBm, as the increase of the value of Q, the leader starts reducing the optimum price (this can be confirmed from Fig. 3). As a result, the optimum transmission power of the followers is increased accordingly (this can be confirmed from Fig. 5). Thus, the average utility of the four followers starts increasing. But, this also results in the increase of the co-tier uplink interference imposed on the leader. Hence, the leader starts gaining profits from the four followers. This is the reason why both the utility of the leader and the average utility of the four followers achieved when -30 dBm $\leq Q < 0$ dBm are greater than that achieved when $Q < -30$ dBm. However, as $Q = 0$ dBm, the optimum price equals to zero (this can be confirmed from Fig. 3), which causing a cliff effect for the utility of the leader. Meanwhile, according to (12), the optimum transmission power of each follower is upper bounded by $p_{\max}$ (this can be confirmed from Fig. 5). Furthermore, Figs. 3 and 5 also show both the optimum price and the optimum transmission power are no longer be updated as $Q \geq 0$ dBm. Hence, based on (3) and (7), we confirm that the utility of the leader and the average utility of the four followers are fixed if $Q \geq 0$ dBm. Lastly, in Fig. 9, we can also find both the utilities are roughly proportional to the value of λ. This can also be confirmed by (3) and (7).

4.6 Impact of the Value of α on the Utilities of the Leader and the Followers

According to the definitions of the utilities of leader and the follower in (3) and (7), α (in 1/mW) is used by the leader as a compensation per unit co-tier uplink interference for its interference imposed on the followers. Thus, it is an important parameter affects the utility

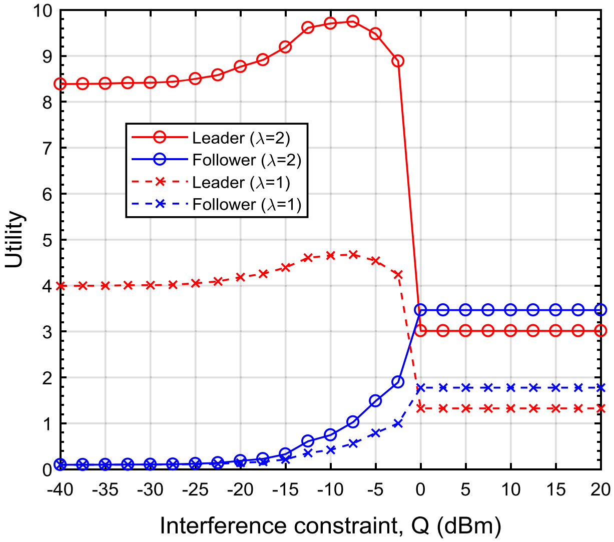


Fig. 9 Utilities of the leader and the follower when $\alpha = 0.5$

of the leader and the aggregate utility of the four followers. The impact of the value of α on these two utilities are shown in Fig. 10 for $\alpha = 0.5$, $\alpha = 1$, and $\alpha = 2$, respectively. Based on (3), since higher value of α means leader agrees to pay larger amount of compensation to followers, lower utility of the leader is thus achieved. On the contrary, from (7), higher aggregate utility of the four followers are achieved due to gaining the compensation paid from the leader. Consequently, in Fig. 10, we can see these two utilities are decreased and increased as the value of α is increased, respectively. In fact, it is the compensation that keeps the aggregate utility of the four followers positive even when all these four followers give up their transmissions while $Q < -30$ dBm. In addition, the decrease of the leader utility caused by the increase of α when $Q \geq 0$ dBm shows there exists a maximum value of α so that the leader utility remains positive.

4.7 The Total Network Capacity

To evaluate the overall network performance, we define the summation of the capacities of the leader and the four followers as the total network capacity. According to Figs. 6 and 7, the total network capacity can be obtained and is depicted in Fig. 11. This figure shows that the minimum total network capacity occurs when leader can only tolerate very limited co-tier uplink interference. Based on our previous discussions, we know that only the leader can transmit under such a small tolerable co-tier uplink interference. In addition, this is the case where the leader enjoys the maximum capacity. From the followers' aspect, this can be imputed to the selfish behavior of the leader. However, from the engineering aspect, the maximum tolerable co-tier uplink interference of the leader turns out to be the most critical parameter to achieve a higher system capacity since the total network capacity can be improved provided that the maximum tolerable co-tier uplink interference at the leader side is improved.

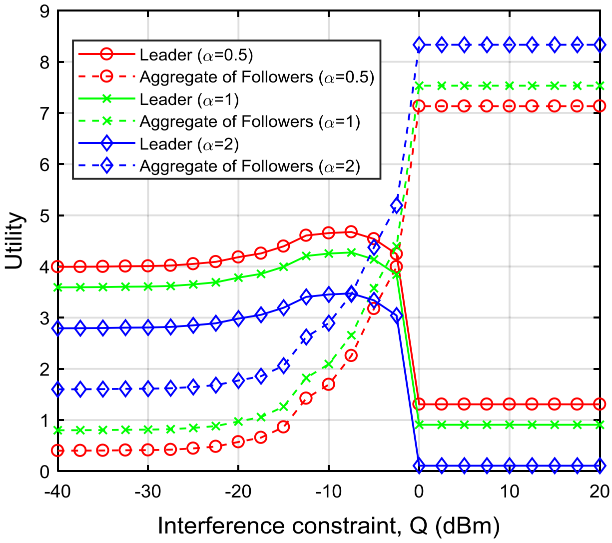
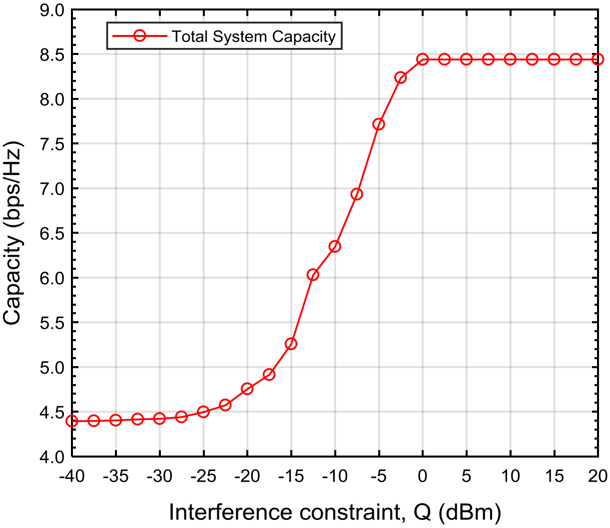


Fig. 10 Impact of the value of α on the utilities of the leader and the followers when $\lambda = 1$

Fig. 11 Total network capacity when $\alpha = 0.5$ and $\lambda = 1$



5 Conclusions

Due to many fancy properties, femtocell technologies have been regarded as one of the feasible solutions to boost the availability and achievability of the LTE technology in indoor environments. However, as the femtocells are widely deployed, the interference between them due to the simultaneous uplinks of the FUEs, i.e. the co-tier uplink interference, will become one of the key factors to deteriorate the network performance. To this end, this paper adopts the concept of Stackelberg game together with the pricing mechanism to analyze and evaluate the impacts of co-tier uplink interference on the network performance. To detailly understand the impacts of each parameter to the network performance, numerical results for parameters with different values are presented and discussed. By using the distributed bargaining procedure, given a maximum tolerable co-tier uplink interference Q, we show the leader and the followers can come up with an agreement, i.e. the optimum transmission power of the followers and the optimum price of the leader, that results in the optimum utilities of the leader and the followers within a small number of iterations. This not only confirms the effectiveness but also the efficiency of the distributed bargaining procedure. Numerical results also show a higher total network capacity can be achieved as long as the leader can tolerate larger amount of co-tier uplink interference from the followers.

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