Game-Based Uplink Co-tier Interference Control in LTE Smallcell Networks

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Abstract. As the advancements of communication technologies and the demands for high-speed mobile data in indoor environments, deploying smallcell is recognized as one of the feasible solutions to improve the indoor signal quality and, hence, provide high-speed data transmission. However, uplink co-tier interference between smallcells deteriorates the system performance. To solve this problem, this paper adopts the Stackelberg game in which Leader and Followers bargain the uplink transmit power by a two-way pricing mechanism to meet the uplink co-tier interference constraints of Leader and Followers. Simulation results show, by controlling the uplink co-tier interference, the two-way pricing mechanism outperforms the one-way pricing mechanism not only in the power conservation but also in the sum-capacity.

Keywords: Stackelberg game · Two-way pricing mechanism · Smallcell networks · Uplink co-tier interference · LTE

1 Introduction

Due to the widely deployment of 4G LTE/LTE-A mobile communication networks, aside from the mobile data services, more and more real-time multimedia applications are requested by the mobile users. Although the original application scenarios for wireless mobile communication were aimed for outdoor users, an interesting finding in [1] indicates that nearly 70% of data transmissions and 50% of mobile voices are originated from indoor users. In general, the penetration loss caused by outer wall and inner wall are regarded as −20 dB and −5 dB, respectively [2]. As a consequence, it is impossible to provide high data rate to support indoor real-time multimedia applications under such a poor radio signal quality environment.

Recently, due to the flexibility and convenience in deploying smallcell base station (SBS), smallcell has been regarded as one of the feasible solutions to improve indoor

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radio signal quality and support high-speed data transmission. However, unlike the WiFi APs that are operated in the unlicensed band, SBSs are operated in the licensed based. Different SBSs can either operate in the same frequency band (i.e., co-channel mode) or in un-overlapped sub-bands (i.e., dedicated channel mode). In addition, the access mode of an SBS includes open subscribe group (OSG), close subscriber group (CSG), and hybrid modes [3]. In the OSG mode, SBS can be accessed by any user equipment (UE) that is within the coverage of the SBS. In the CSG mode, only authorized UE that is within the coverage of the SBS can do so. In the hybrid mode, the frequency band of an SBS is partitioned into two sub-bands, one of which is for OSG mode and the other one is for CSG mode.

However, as SBSs are widely deployed and operated in the co-channel and CSG modes, interference between them, i.e. co-tier interference, becomes a major problem to deteriorate the system performance. As illustrated in Fig. 1, when UE-f_1 is uplink transmission to SBS-F_1 (i.e., the red solid line in Fig. 1), the radio signal interferes SBS-F_2 in receiving the uplink transmission from UE-f_2 (i.e., the red dashed line in Fig. 1). We call this as the uplink co-tier interference. Similarly, when SBS-F_2 is downlink transmission to UE-f_2 (i.e., the blue solid line in Fig. 1), the radio signal interferes UE-f_1 in receiving the downlink transmission from SBS-F_1 (i.e., the blue dashed line in Fig. 1). This paper mainly focuses on controlling the uplink transmit power of UE in the smallcell networks so that the uplink co-tier interference is mitigated.

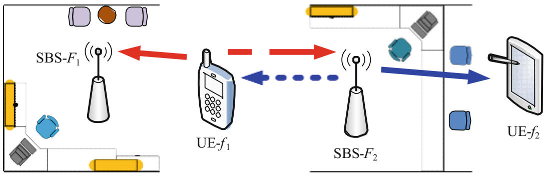

Fig. 1. Co-tier interference in the smallcell network. (Color figure online)

The rest of this paper is organized as follows: The system model is introduced in Sect. 2. In Sect. 3, the Stackelberg game with two-way pricing mechanism is proposed. The simulated parameter values and simulation results are demonstrated in Sect. 4. Section 5 concludes the paper.

2 System Model

In the past years, due to its inception, game theory has been applied to study problems in wired and wireless communication networks [4–6]. To control the uplink co-tier interference in the smallcell networks, this paper first employs the concepts of Stackelberg game to classify all SBSs in the network into Leader and Followers. Then, under the premise that the tolerable uplink co-tier interference constraints of Leader and Followers are not violated, a bargaining procedure together with a two-way pricing mechanism are proposed to find the uplink transmit power of Leader and Followers by adaptively adjusting pricing strategies of Leader and Followers. We consider $(N + 1)$ smallcells that are installed in an indoor environment, e.g., shopping mall or office. Each smallcell consists of one SBS and one UE. All the SBSs are operated in the co-channel and CSG modes. To fit the Stackelberg game, among the $(N + 1)$ smallcells, one is randomly selected as the Leader. The SBS and UE of the Leader smallcell are represented as SBS-L and UE-l, respectively. The rest of N smallcells are regarded as Followers. The SBS and UE of the ith Follower smallcell are represented as SBS-F_i and UE-f_i, respectively, where $i = 1, 2, 3, \ldots, N$. In addition, among the Follower SBSs, one is randomly selected as the delegate of the Followers and is represented as SBS-F. The path loss from UE-x to SBS-Y, $g^{x,Y}$ is based on the model in [7] and is given as follows:

$$g^{x,Y} = 10^{((38.46 + 20\log_{10} d_{x,Y} + X_\sigma)/10)} \quad (1)$$

where x can be $l, f_1, f_2, \ldots, f_N$, Y can be $L, F_1, F_2, \ldots, F_N$, $d_{x,y}$ is the distance between UE-x and SBS-Y in meter, and X_σ is the log normal shadowing with zero mean and standard deviation σ. The log normal shadowing X_σ is assumed to be an independent and identically distributed (i.i.d.) random variable. To focus our study on the uplink co-tier interference, the interference between macrocell and smallcell, i.e., cross-tier interference, is ignored.

Based on the above descriptions, the system model is depicted in Fig. 2. As mentioned earlier, there are $(N + 1)$ smallcells in this system model. One is selected as Leader and the rests are Followers. Each smallcell contains one SBS and one UE. All smallcells are connected by the backhaul network. In this figure, when a UE is uplink to its corresponding SBS (i.e., the solid line), it also interferes the other SBSs simultaneously (i.e., the dash line).

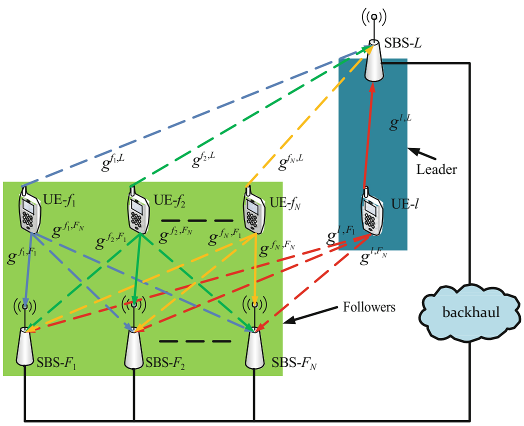

Fig. 2. The system model for a network with $(N + 1)$ smallcells.

3 Game-Based Uplink Co-tier Interference Control

3.1 Stackelberg Game with Two-Way Pricing Mechanism

Inspired by [8], Stackelberg game [9] is used to mitigate the uplink co-tier interference in smallcell networks. Simply speaking, Stackelberg game is a strategy- based game. In this game, utility functions for Leader and Followers are defined in advanced. Then, both Leader and Followers propose a strategy that maximizes its own utility individually. In particularly, Leader has the priority to first propose a strategy that favors itself to Follower. Based on the strategy proposed by Leader, each Follower updates its strategy to maintain its maximal utility and response the updated strategy to Leader. Next, Leader and Followers take turn to update their strategies until their utilities cannot be further improved. When this condition is met, we say the Stackelberg game achieves the Stackelberg Equilibrium (SE) point.

To incorporate the two-way pricing mechanism into the utility functions of Leader and Followers, we first let Q_L and Q_F be the maximal tolerable co-tier interference of Leader and each Follower, respectively. When Leader is interfered by Followers, it proposes a pricing strategy β and charges the Followers based on this pricing strategy. Similarly, when Follower SBS-F_i is interfered by Leader and other Followers, it proposes a pricing strategy α_i. Among the unit price α_i, $i = 1, 2, 3, \ldots, N$. the highest one is selected as the pricing strategy of all Followers, represented as α, and is used to charge the interferers. With this two-way pricing mechanism, as the total amount of co-tier interference approach to Q_L (or Q_F), Leader (or Followers) increases the unit price β (or α) to push the interferers to lower the uplink transmit power.

Let the total co-tier interference from Followers perceived at Leader be I_L (in mW). Based on Fig. 2, I_L can be derived as follows:

$$I_L = \sum_{i=1}^{N} \frac{p^{f_i}}{g^{f_i,L}} \leq Q_L, \tag{2}$$

where p^{f_i} is the uplink transmit power of UE-f_i. From Fig. 2, different from the SBS-L, the interferers of SBS-F_i includes UE-l and all other UE-f_j ($j \neq i$). Let the aggregated co-tier interference be p^{f_i} (in mW) and is obtained by

$$I_{F_i} = \frac{p_i^l}{g^{l,F_i}} + \sum_{j=1, j\neq i}^{N} \frac{p^{f_j}}{g^{f_j,F_i}} \leq Q_F, \tag{3}$$

where p_i^l is the uplink transmit power of UE-l that SBS-F_i suggested. Next, the SINR for SBS-L to receive signal from UE-l can be represented as

$$SINR\_L(p^l, \boldsymbol{p^f}) = \frac{p^l / g^{l,L}}{\sum\limits_{i=1}^{N} \frac{p^{f_i}}{g^{f_i,L} + \eta}}, \tag{4}$$

where p^l is the actual uplink transit power of UE-l, $\boldsymbol{p}^f = [p^{f1,} p^{f2,} \ldots, p^{fN}]$ is a vector of the uplink transmit power of all UEs, η is the power of thermal noise. Based on (4) and the concept of two-way pricing, the utility function of SBS-L is defined as follows:

$$U^L(p^l, \boldsymbol{p}^f, \alpha, \beta) = \lambda B \log_2(1 + SINR\_L(p^l, \boldsymbol{p}^f)) + \sum_{i=1}^{N} \beta \frac{p^{f_i}}{g^{f_i,L}} - \sum_{i=1}^{N} \alpha \frac{p^l}{g^{l,F_i}}, \quad (5)$$

where λ is a capacity transformation gain and is a system parameter, B is the system bandwidth. The meanings of the three terms on the right-hand side of (5) are explained in the follows. In the first term, the Shannon capacity of SBS-L is transferred into utility by λ. The second term is the reward obtained by charging all UE-f_i. The third term is the payoff paid to the FUEs. Again, based on Fig. 2, SINR for SBS-F_i to receive signal from UE-f_i can be expressed as follows:

$$SINR\_F_i(p^l, \boldsymbol{p}^f) = \frac{p^{f_i}/g^{f_i,F_i}}{\sum_{j=1, j \neq 1}^{N} \frac{p^{f_j}}{g^{f_j,F_i}} + \frac{p^l}{g^{l,F_i}} + \eta}. \quad (6)$$

Hence, the utility function of SBS-F_i is obtained as follows:

$$U^{F_i}(p^l, \boldsymbol{p}^f, \alpha, \beta) = \lambda B \log_2(1 + SINR\_F_i(p^l, \boldsymbol{p}^f)) - \beta \frac{p^{f_i}}{g^{f_i,L}} + \alpha \frac{p^l}{g^{l,F_i}}. \quad (7)$$

3.2 Finding the Stackelberg Equilibrium (SE) Point

By combining Stackelberg game and two-way pricing mechanism, our objective is to find the pricing strategies α and β and the corresponding uplink transmit power p^l and $\boldsymbol{p}^f$ that maximize utilities of Leader and Followers without violating the maximal tolerable co-tier interference limits Q_L and Q_F. Hence, the whole problem is modelled as the optimization problem below:

$$\begin{aligned} &\max U^L(p^l, \boldsymbol{p}^f, \alpha, \beta) \text{ and } U^{F_i}(p^l, \boldsymbol{p}^f, \alpha, \beta) \\ &\text{subject to} \\ &0 \le p^l \le 200, I_L \le Q_L, \text{ and } 0 \le p^{f_i} \le 200, I_{F_i} \le Q_F, i = 1, 2, \ldots, N. \end{aligned} \quad (8)$$

Our approach to solve the solution of (8) is to find the SE point of the Stackelberg game with two-way pricing mechanism. First, to satisfy the Karush- Kuhn-Tucker (KKT) condition, a Lagrange multiplier is introduced to (5). Then, taking the partial derivative of (5) with respect to p^{f_i} and let the results to be zero, the optimal uplink transmit power of UE-f_i, p^{f_i} with respect to the pricing strategy β proposed by Leader is derived as follows:

$$p^{f_i} = \left(\frac{\lambda B}{\beta / g^{f_i,L}} - \frac{\sum_{j=1, j \neq 1}^{N} \frac{p_{\max}^{f}}{g^{f_j,F_i}} + \frac{p^l}{g^{l,F_i}} + \eta}{1/g^{f_i,F_i}} \right)^{+}, \tag{9}$$

where $p_{\max}^{f}$ is the maximum uplink transmit power of Follower UE. Similarly, to find the optimal transmit power of UE-l with respect to the pricing strategy proposed by SBS-F_i, α_i, a Lagrange multiplier is introduced to (7). Then, taking the partial derivative of (7) with respect to p^l and let the results to be zero, the optimal uplink transmit power of UE-l with respect to the pricing strategy α_i proposed by SBS-F_i, p_i^l is derived as follows:

$$p_i^l = \left(\frac{\lambda B}{\sum_{i=1}^{N} \frac{\alpha_i}{g^{l,f_i}}} - \frac{\sum_{i=1}^{N} p^{f_i}/g^{f_i,L} + \eta}{(1/g^{l,L})} \right)^{+}. \tag{10}$$

3.3 Bargaining Procedure for Two-Way Pricing Mechanism

Following, a bargaining procedure is introduced for Leader and Followers in a distributed manner to find the pricing strategies α and β and the corresponding uplink transmit power p^l and $\boldsymbol{p}^f$ without violating the maximal tolerable co-tier interference limits Q_L and Q_F. All information required for the bargaining procedures are exchanged through the backhaul network. The detail bargaining procedures are stated as below:

Step 0: The upper and lower bounds of the price strategy proposed by SBS-L are β^H and β^L whose initial values are β_0^H and β_0^L, respectively. The upper and lower bounds of the price strategy proposed by SBS-F_i, α_i, are α_i^H and α_i^L whose initial values are α_0^H and α_0^L respectively. p^l = 200 mW.
Step 1: $\beta^H = \beta_0^H$ and $\beta^L = \beta_0^L$.
Step 2: SBS-L sends $\beta = (\beta^H + \beta^L)/2$ and p^l to each SBS-F_i.
Step 3: After receiving β and p^l each SBS-F_i calculates p^{f_i} based on (9) and sends it to SBS-L and all other follower SBSs.
Step 4: Based on the received p^{f_i}, SBS-L adjusts its pricing strategy β as follows:
If $I_L > Q_L + \varepsilon_L$, $\beta = \beta$ and go to **Step 2**.
If $I < Q_L - \varepsilon_L$, $\beta^H = \beta$ and go to **Step 2**.
Step 5: $\alpha_i^H = \alpha_0^H$ and $\alpha_i^L = \alpha_0^L$.
Step 6: Each SBS-F_i sends its pricing strategy $\alpha_i = (\alpha_i^H + \alpha_i^L)/2$ to SBS-L.
Step 7: With α_i and $\boldsymbol{p}^f$, SBS-L calculates p_i^l based on (10) and sends it back to SBS-F_i.
Step 8: Based on the updated follows: p_i^l each SBS-F_i adjusts its pricing strategy α_i as follows:

If $I_{F_i} > Q_F + \varepsilon_F$, SBS-$F_i$ checks if $p_i^l = 0$ mW. If true, send the updated $p^{f_i} = p^{f_i} - 1$ mW to SBS-L and go to **Step 5**. Otherwise, $\alpha_i^L = \alpha_i$ and go to **Step 6**.

If $I_{F_i} < Q_F - \varepsilon_F$, $\alpha_i^H = \alpha_i$ and go to **Step 6**. Otherwise, each SBS-F_i sends p_i^l to SBS-F.

Step 9: SBS-F sends $p^{l^*} = \min_i p_i^l$ and $\alpha = \max_i \alpha_i$ to SBS-L. If $\left|p^{l^*} - p^l\right| > \omega$, $p^l = p^{l^*}$ and go to **Step 1**. Otherwise, $p^l = p^{i^*}$ and stop the procedures.

In fact, if only **Step 0–Step 4** are considered, it is regarded as the one-way pricing mechanism. In other words, in the one-way pricing mechanism, the Leader power cannot be dynamically adapted. In our simulation, the uplink transmit power p^l is fixed at 200 mW for the one-way pricing mechanism.

4 Simulation Results

The simulation is coded by Matlab. In our simulation, the (N + 1) SBSs are uniformly distributed within square area with size 40 m × 40 m. For each SBS, a UE is randomly deployed between the distance 0.2 m and 10 m to it. During the simulation, each SBS takes turn to be the Leader. Based on the proposed bargaining procedure, Leader and Followers update their pricing strategies β and α alternatively. Then, the corresponding uplink transmit power p^l and $\boldsymbol{p}^f$ are updated accordingly. The simulation is executed 100 times and the detail simulation parameter values are listed in Table 1. The transmit powers and capacities of Leader and Followers for two-way pricing mechanism are collected, analyzed, and compared to that for one-way pricing mechanism as shown in Figs. 3 and 4, respectively. In the one-way pricing mechanism, Q_F is assumed infinite. However, Q_F is assumed to be −40 dBm for the two-way pricing mechanism. The capacity is calculated based on the equation:

$$capacity = \min(90\,\text{Mbps},\, B\log_2(1 + SINR)), \tag{11}$$

where 90 Mbps is the maximum achievable capacity when the most aggressive MSC in [10] is used together with the parameter values listed in Table 1. The SINR in (11) is taken from either (4) or (6) if the calculated capacity is for Leader of Followers, respectively. In Figs. 3 and 4, the red line represents the simulation results for Leader, while the blue line represents the simulation results for Followers. The circle represents

Table 1. Simulated parameter values.

Parameter	Value	Parameter	Value
p^f_{max}	200 mW	λ	5×10^{-8} bps^{-1}
σ	4	ε_L, ε_F	10^{-8} mW
B	20 MHz	α_0^H, β_0^H	10^{15} mW^{-1}
η	−101 dBm	α_0^L, β_0^L	0 mW^{-1}
N	3	Q_L	−100, −95, …, 20 dBm
ω	10^{-3} mW	Q_F	−40 dBm

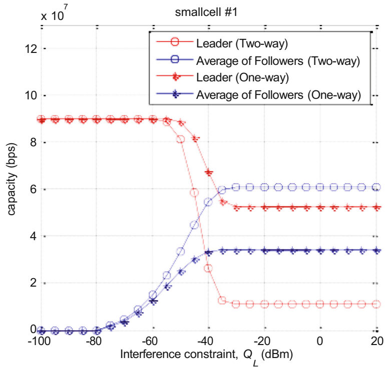

Fig. 3. Comparison of the capacities of Leader and Followers between two-way and one-way pricing mechanisms. (Color figure online)

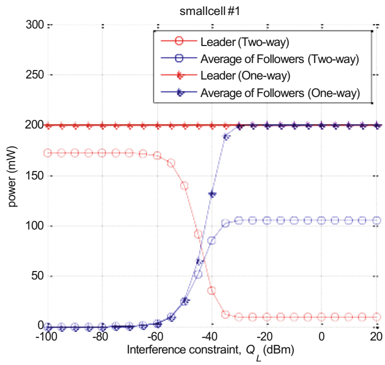

Fig. 4. Comparison of the transmit power between two-way and one-way pricing mechanisms. (Color figure online)

the simulation results for the two-way pricing mechanism, while the asterisk represents the simulation results for the one-way pricing mechanism. In addition, the simulation results demonstrated in Figs. 3 and 4 are obtained when the smallcell number 1 is selected as the Leader.

First, when Q_L <−80 dBm, which means Leader can only tolerate very limited uplink co-tier interference, Leader increases its pricing strategy β to restrain Followers from uplink transmission regardless what pricing mechanism is employed. Hence, the average uplink transmit power of Followers in Fig. 3 is zero. As a consequence, the average capacity of Followers is also zero in Fig. 4. However, different from 200 mW, the uplink transmit powers of UE-l in the one-way pricing mechanism, we can see the uplink transmit powers of UE-l reduces to 170 mw for the two-way pricing mechanism as shown in Fig. 3. The reason is, in the two-way pricing mechanism, the pricing strategy α will be increased in order to satisfy (3). Consequently, the uplink transmit power of UE-l is reduced. Therefore, when Q_L <−80 dBm, the two-way pricing mechanism saves 15% of the uplink transmit power with compared to that in the one-way pricing mechanism while the Leader capacity remains unchanged.

Next, when −80 dBm $\leq$ Q_L <− 30 dBm, i.e., the tolerable uplink co-tier interference of Leader is gradually increased, Leader starts to reduce its pricing strategy β to encourage Followers to increase their uplink transmit powers. Thus, we can see the average transmit powers and capacity of Followers in Figs. 3 and 4 are increased as Q_L increases. However, as the uplink transmit power of Follower increases, the co- tier interference between Followers are increased accordingly. In the two-way pricing mechanism, to satisfy (3), the pricing strategy α is increased to push Leader to reduce its uplink transmit power. This also results in the reduction of SINR of Leader. However, due to the increase of transmit power and the decrease of the co-tier interference from Leader, the SINR of Follower is improved. Hence, this is the reason why the transmit power and capacity of Leader decreased, while that of Follower increased in Figs. 3 and 4, respectively. On the contrary, due to the transmit power of Leader is fixed at 200 mW for the one-way pricing mechanism, the SINR of Leader in the one-way pricing mechanism is better than that in the two-way pricing mechanism. That is the reason why the Leader capacity in the one-way pricing mechanism does not drop so much compared to the one in the two-way pricing mechanism. Meanwhile, due to the higher Leader transmit power in the one-way pricing mechanism, the SINR of Follower is worse than that in the two-way pricing mechanism. Therefore, the capacity of Follower in the one-way pricing mechanism is lower than that in the two-way pricing mechanism.

Finally, when $Q_L \geq -30$ dBm, the transmit powers of all UEs cannot be increased anymore as illustrated in Fig. 3. Consequently, we can see all the capacities in Fig. 4 remain unchanged. Under this circumstance, we can find transmit power of all UEs in the one-way pricing mechanism are 200 mW. However, the transmit powers of Leader and Follower in the two-way pricing mechanism are 9.4 mW and 105 mW, respectively. In other words, the proposed two-way pricing mechanism conserves the transmit powers of Leader and Follower by 95.3% and 47.5%, respectively.

As we mentioned earlier, the results demonstrated in Figs. 3 and 4 are obtained when smallcell number 1 is selected as the Leader. It is hence important to know if different results may be obtained if other smallcell is selected as Leader. In addition, it is also important to compare the sum-capacity achieved by the one-way and two- way pricing mechanisms. Figure 5 shows the obtained sum-capacities for one-way and two-way pricing mechanisms when different smallcell is selected as Leader. According to the discussions for Figs. 3 and 4 above, the sum-capacities in Fig. 5 are obtained for the four values of Q_L, −80 dBm, −50 dBm, −40 dBm, and 0 dBm, respectively. When $Q_L = -80$ dBm, since all Followers are forbidden to transmit, the sum-capacity for one-way and two-way pricing mechanisms are the same. When $Q_L = -50$ dBm and $Q_L = -40$ dBm, the capacities of Followers are quickly increasing. Besides, the capacities of Followers for the two-way pricing mechanism are higher than that for the one-way pricing mechanism. Hence, the sum-capacities of two-way pricing mechanisms are higher than that of one-way pricing mechanism. Since the capacities of Followers achieve the maximal and stable values when $Q_L \geq -30$ dBm, the sum-capacities for the two-way pricing mechanism at $Q_L = 0$ dBm remain higher than

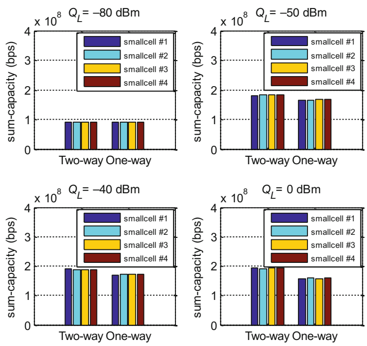

Fig. 5. The sum-capacity between two-way and one-way pricing mechanisms when different smallcell is selected as Leader.

that for the one-way pricing mechanism. In addition, for the four different values of Q_L, it is obviously that the selection of Leader impacts the sum-capacities very limited. In other words, selecting Leader is not an issue when the smallcells are uniformly distributed over the considered area.

5 Conclusions

By partitioning the smallcells into Leader and Followers and bargaining the pricing strategies between Leader and Followers, Stackelberg game with two-way pricing mechanism provides a feasible approach to control the uplink co-tier interference and achieves a higher sum-capacity that that achieved by using one-way pricing mechanism. In addition, simulation results also show that two-way pricing mechanism performs better power consumption. Specifically, up to 95.3% and 47.5% of the power conservations for the transmit powers of Leader and Follower are achieved when $Q_L \geq -30$ dBm.

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