First Price Sealed-Bid Auction Based Cell Selection in 5G Ultra Dense Networks

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Abstract. The users in the ultra dense networks are faced with the problem of how to choose the right small cell to access. Reasonable choices can not only give the users a better quality of service, but also enhance the effectiveness of the overall system. A novel first-price sealed-bid auction based distributed cell selection algorithm is proposed in this paper, and it can be used to solve the problem existed in ultra dense networks. And it can be concluded from the results that the proposed algorithm achieves better performance in terms of user throughput and reception probability compared to the random access mechanisms.

1. Introduction

The traffic of mobile data in the whole world has expected a sevenfold increase in 2021. Ultra dense networks (UDNs) is an effective way to solve the problem that the increased data in 5G mobile networks by deploying the hot spots that small base stations and low-power in indoor and outdoor [1]. In the ultra dense networks, it is important for the designers to guarantee the quality of services (QoS) of users and revenue for service providers by an appropriate mechanism of cell selection. The mission of the cell selection is to ensure the required QoS for users and maintain them on a high-quality cell. At the same time, cell selection can balance the load and performance of the system.

In the algorithm, the players and auctioneers are the small cell base stations and users, respectively. The users have the right to choose the small cell to make their own utility maximized. Moreover, in each round, there will be signaling interaction among the small cells to broadcast the game results so that the small cells can adjust the bids to participate in the next round of the auction game. This distributed algorithm not only takes the real-life operating conditions into consideration, but also protects the users’ QoS and it is an effective cell selection scheme.

The best cell is selected to provide service for users through the cell selection. Much studies on the method of cell selection have been reported. The reported papers [3] and [4], the researchers have proposed a new cell selection scheme for data traffic optimization in Heterogeneous wireless systems. In reference [5] the authors have studied the different bias values for the two cell selection methods that signal received power (RSRP) and cell range extension (CRE), respectively. In reference [6], the authors have done an analysis on CRE method when they make the offsets fixed and adaptive. In papers [7] and [8], a new cell selection algorithm is proposed. The new user can select the best serving cell by the algorithm to attain maximum effective data rate and association probability. However, to protect the users’ QoS, users have the right to select the small cell to access to. Thus, we propose first
price sealed-bid auction based cell selection in ultra dense networks.

2. System model

In ultra dense networks, the macrocell wants the users to be able to access to a small cell to offload rather than the macrocell, especially in the crowded place. As shown in Figure 1, in our system, we study the scenario of uplink transmission in ultra dense networks with small cells that the number is N, and they within the coverage of a single macrocell. The total number of users to be accessed is K. Each small cell i has Li users originally, the QoS requirement of each user is u_k and it is to be guaranteed. We also considered QoS requirement is the user’s data rate in this paper.

![System Model of Cell Selection](image)

3. Auction Based Cell Selection Algorithm

We will study the framework with the utility functions of the small cells and the users in this section, respectively. And the distributed mechanism is called auction. In the view of the game theoretic, small units and users are reasonable agents, and they will only maximize their own utility. And for the small cells, they want to have appropriate users and they will bid for the users. For the users, they want to earn high rates after accessing to the small cell.

The proposed first price sealed-bid auction game based mechanism can be divided into two stages. In the first stage, the small cell base stations compete for user access rights according to their own conditions, such as the original number of users, the number of sub-channels and so on. Operators will reward the small cells for competing for the users. Of course, the user’s access brings a cost to the small cell on power and sub-channels allocation. In the second stage, users will choose the small cell which makes their own utility maximized.

3.1. Utility of the small cells

Their utility include three parts: V_i^S, C_i^S, and E_i(B_{ik}) in the view of small cells. Where the V_i^S represents the utility of the original users, C_i^S represents a function of the submitted bids that are attained by the service provider, and E_i(B_{ik}) is additional user and they need to pay the energy loss of the server. Therefore, the utility function of the small cells be defined with a formulation and the formulation is Utility = Revenue – Cost.

Here, the small cells have two parts of revenue, namely, V_i^S and C_i^S. We define the utility functions as V_i^S = $\lambda \sum_{k=1}^{K} u_k$ and C_i^S = $\frac{B_{ik}}{B_{ik} + \alpha} \Phi_{ik}$. Here $\lambda$ is a revenue unit, u_k refers to the rate of user k in small cell i. Wherein, B_{ik} represents the bid of the small cell i for the user k. $\Phi_{ik}$ is a appropriate value that selected by the small cells. And it means the small cell will accept the user with higher priority if the value of $\Phi_{ik}$ is larger. $\alpha$ is the reserved price to protect the interests of the small cells. $B_{ik}/(B_{ik}+\alpha)$ is the ratio of the reality bid to the reserved price, and the B_{ik} is attained by the small cell i. The
corresponding UEs attain the power from the small base station according to the rate requirement $u_{ik}$. The energy lost to serve additional users is a major loss for small cells. Here, the cost is defined as

$$E_i(B_i) = \ln\left(\frac{P_{\text{sum}}(L_i+1)}{P_{\text{sum}}(L_i)}\right) \cdot B_i$$

wherein, $\frac{P_{\text{sum}}(L_i+1)}{P_{\text{sum}}(L_i)}$ represents the proportion between the total power consumption in the small cell $i$ for serving the original $L_i$ users with and without additional user. And we have $P_{\text{sum}}(L_i+1) = \sum_{k=1}^{L_i+1} p_k$

Reference [9] shows that the small cell $i$ has the following relationship between the allocated power $p_k$ of the user $k$ and the data rate $u_k$: $p_k = \frac{1}{\alpha_k} \sum_{j=k}^{K} 2^{u_j} - K + 1$, where $K$ represents the total number of users. Thus, the function of the small cell is:

$$U_{\text{total}} = \sum_{k=1}^{L_i} u_k + \frac{B_i}{\Phi_{ik} \cdot \ln\left(\frac{P_{\text{sum}}(L_i+1)}{P_{\text{sum}}(L_i)}\right) \cdot B_i - \Phi_{ik}}$$

(2)

3.2. User’s utility function
As the auctioneer with selfishness, the users have the right to choose which small cell to access to. In addition to the price $B_{ik}$, the users also receive the rate of the small cells can offer. Therefore, for the user $k$, the utility function can be expressed as $U_k = \tau B_{ik} + \beta u_{ik}$. where, $\tau$ and $\beta$ represent weight values respectively, and $\tau + \beta = 1$. The user $k$ can adjust the weights according to the user intensity of their own. For the user $k$, it will choose the small cell which can make their own utility function maximized.

3.3. Solutions for the auction game

3.3.1. Bid solution for small cell base stations. For small cells, the utility function $U_{\text{total}}$ is only relevant to its own bid $B_{ik}$ and it would always choose the bid that makes the utility maximized. The bid is described as follows

$$B_{ik}^* = \arg \max_{B_{ik}} U_{\text{total}} = \arg \max_{B_{ik}} \left[ \lambda L_i u_k + \frac{B_{ik}}{\Phi_{ik}} \cdot \ln\left(\frac{P_{\text{sum}}(L_i+1)}{P_{\text{sum}}(L_i)}\right) \cdot B_i \right].$$

(3)

This is an optimization problem which needs to be proved whether the utility function is convex so that the second derivative could be employed. We obtain $\frac{\partial^2 U_{\text{total}}}{\partial^2 B_{ik}} = -\frac{2\alpha \Phi_{ik}}{(B_{ik} + \alpha)^3}$. Since $\alpha > 0$, $\Phi_{ik} > 0$, it must be $\frac{\partial^2 U_{\text{total}}}{\partial^2 B_{ik}} < 0$. So the value of the second derivative of the utility function of small cells is less than zero, then the utility function is concave. Therefore, we can attain the optimal bid by solving the first derivative of $U_{\text{total}}$ with respect to $B_{ik}$, i.e.,

$$\frac{\partial U_{\text{total}}}{\partial B_{ik}} = \frac{\alpha}{(B_{ik} + \alpha)^2} \Phi_{ik} \cdot \ln\left(\frac{P_{\text{sum}}(L_i+1)}{P_{\text{sum}}(L_i)}\right) \cdot B_i = 0.$$  

(4)

Therefore, the optimal solution is
3.3.2. Cell selection for users. As the auctioneer of the game auction, the user has the right to decide to access which small cell. That is, according to its own utility function, the base station $i^*$ is chosen to make the utility function maximized, namely $i^* = \arg \max_{i} U_{i_{a}} = \arg \max_{i} (\tau B_{i_{a}} + \beta u_{i_{a}})$.

So far, the chosen mechanism of small cells based on first price sealed-bid auction is accomplished. That is, the choosing process of small cells for the user $k$ is accomplished.

3.3.3. Access process for multiple users. For the bid auction process of multiple users and multiple small cells, the rules could be defined as follows. 1) After the user $k$ receives the price and the rate from each small cell, the user $k$ must choose a small cell base station to access, for this is the first price sealed-bid auction game based cell selection mechanism. 2) Only after the end of each auction game round, each small cell knows whether the bid is successful or not, because this is enclosed auction game. Meanwhile, signaling interactions will be distributed among the small cells, and each small cell will know the bids of the other small cells, so that during the next round of auction game they could adjust their bids and modify the preference values according to their own load conditions. In each round of the auction game, the game is a first price sealed-bid auction process.

4. Performance Evaluation
The system performance of the algorithm that first price sealed-bid auction based cell selection is verified in this part. We consider the number of small cells and base price is 4 and 3, respectively. The applied system bandwidth is 15MHz and the diameter of the small cell is 40m. The maximum transmission power of each small cell base station and original number of users in this system is 15dBm and 7, 10, 6, 3, respectively. Other simulation parameters are $\lambda = 4$, $\tau = 0.4$ and $\beta = 0.6$.

Based on the above simulation environment, we obtain simulation Figures 2 and 3.

Figure 2 shows the relationship between the utility function value and the bids of small cells. From the results in Figure 2, it can be concluded that the utility functions of four small cell base stations are concave, so that there is an optimal bid that makes their utility functions maximized. However, due to the original number of users of the single small cell is not the same, namely the load of each small cell is not the same, the utility function changes are different. However, from this figure the optimal bid for each small cell base station could be obtained. That is, the best price of the small cell 1–4 are 15, 12, 14 and 16, respectively. Small cells achieve maximum utility value at the best price.
Figure 3 represents the relationship between the weighting factor $\tau$ and the utility function of users. Users that receive bids from each small cell base station will seek to make their own utility function maximized. It can be seen from the figure that the relationship between the utility function that users received from small cell base stations and their own set of weighting factors is linear. And it can be seen from the figure that the small cell base station 4 enables users to maximize their utility functions. Compared with the optimal price obtained from Figure 2, with the changes of utility function values from Figure 3, it can be seen that the high bid is not necessarily for users to achieve better effectiveness. Users also take into account the rate of small cell base station can provide. This is proven in Figure 3.

Figure 4 and 5 show the simulation comparisons of first price sealed-bid auction based distributed cell selection algorithm and users random access cell selection algorithm. Figure 4 shows the relationship between the number of users stayed to be accessed and the possibility of successful access. It can be concluded from the figure 4 that all the users that use the algorithm can access to a small cell when the number of users is less than 22. However, with the number of users increases, the capacity of the small cells reaches the maximum value, there will be no small cell base stations in the auction, then the probability of success at this time will be smaller. However, for users using the random access algorithm, due to the random access request and rate or carriers in demand sometimes, there may be the case that the station does not meet users’ needs. In which case, the user will access small cell unsuccessfully. Therefore, the probability of success is lower than that of using the algorithm provided by this paper.

Figure 5 represents the relationship between the number of users and the average rate of users accessing the small-cell base station. From the figure 5, it can be concluded that the average rate of the algorithm provided by this paper is higher than that of random access algorithm. Since in our algorithm there is a direct relationship between the user’s utility function and the rate, more users will choose the small cell that could make their own access rate high, fully taking into account the QoS of users. But the random access algorithm is regardless of the user’s rate problem. Therefore, in the case of increasing number of users, the advantages of our algorithm is also more evident.

5. Conclusions

In 5G ultra-dense networks, cell selection is an important issue. This paper proposes a novel first price sealed-bid auction based distributed cell selection algorithm, which can protect the users’ QoS. From the simulation results, it can be demonstrated that the proposed algorithm in this paper achieves better performance in terms of user throughput and reception probability compared to the random access mechanisms.
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