

Review Article

A New Pricing Mechanism for Uplink Power Control in Wireless Data Networks

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Introduction

The rapid development of wireless network makes the large-scale, high-speed data transmission possible, meanwhile raises a higher demand for the accuracy of the information transmission. Since all users use the same frequency band to transport information, one user's signal may disturb the others'. Hence the study of how to coordinate the users to transport more effective information with their limited energy has attracted significant attention.

Goodman et al. [1-5] made use of pricing mechanisms to limit the competition in power control of multi-cell wireless data networks, where they utilized microeconomic utility theory to define the users' payoffs and employed a pricing function based on the users' power to punish users who get high SIR maliciously by increasing their power. By solving a multi-objective optimization problem on two kinds of base station assignment, both better utility and lower power were obtained compared to the methods without a pricing mechanism. Differing from Goodman's work, Tamer Basar et. al [8-10] used an information theoretic approach to study the power allocation problem, where they define the user's utility function via channel capacity. In [11], Mehdi Rasti proposed a new pricing scheme based on Tamer Basar's one cell model, where the pricing function was linearly proportional to the SIR. By choosing a proper price, the proposed pricing scheme can satisfy the fairness requirement in an optimum manner. In [12], a cost function was proposed to ensure the equal SIR, which ensures all users could achieve their desired SIR with suitable cost.

In order to get the information collected more reliable, sometimes, users apply multiple base stations simultaneously to transmit their information. This will accelerate the consumption of node's limited resources. Therefore, how to improve the efficiency of transmission with their limited resources becomes more challenge. In this paper, we consider the situation that nodes associating to two or more base stations and investigate the fairness of users' payment to the network providers. Inspired by [11], we adopt the pricing mechanism that any user possessing more network resource should pay more, and furthermore make an improvement on the unit price paid by each user. Some conditions are developed to guarantee the

Abstract

In this paper, we study the uplink power control problem of wireless data networks, where mobile users can transmit information to multiple base stations. We formulate such problem as a super-modular game, and propose a novel pricing mechanism through the integration of channel gain and the signal-to-interference ratio (SIR). We develop some conditions to guarantee the Nash Equilibrium, and present some simulations to illustrate the effectiveness and fairness of the proposed mechanism.

Keywords: Power Control; Super-modular Game; SIR; Multicell Network

Nash equilibrium, and some simulations are presented to show the effectiveness and fairness of the improved mechanism.

The rest part of the paper is organized as follows. We construct the game model of the non-cooperative power control in Section 2; propose the pricing function based on users' SIR in Section 3. We compare our pricing mechanisms with existed linear pricing mechanisms in Section 4, and give a conclusion in Section 5.

System Model

Assume that there are N users and K base stations in a wireless CDMA data network. All users use the same frequency band to transport information, and therefore any one user's signal can interference with others. Considering that users using different base stations may have different SIR, here we define the SIR of user j with base station i [5] as follows:

$$\gamma_{ij} = \frac{G h_{ij} p_j}{\sum_{k=1, k \neq j}^N h_{ik} p_k + \sigma^2} \quad (1)$$

where G represents the process gain. h_{ij} is the channel gain of user j to base station i and p_j is the power of user j.

$\sum_{k=1, k \neq j}^N h_{ik} p_k + \sigma^2$ is the accumulated interference of all the other users caused to user j, where. σ^2 denotes the background noise.

Two issues will influence the users' quality of service (QoS) when the base station is determined: one is SIR, and the other is the consumed power. We define the j-th user's utility function with the base station i as follows [5]:

$$U_{ij} = \frac{LR}{Mp_j} (1 - e^{-\gamma_{ij}/2})^M \frac{\text{bits}}{\text{Joule}} \quad (2)$$

Where M is the information length of each frame, L is the effective information length of each frame ($L < M$), and R denotes the speed of the user in transferring data.

Game Model

In [1-5], Goodman et al. reduce the energy consumption and improve the user's utility by taking advantage of some pricing mechanisms. Inspired by those pricing mechanisms, we use the following pricing model:

$$F_{ij} = \lambda p_j. \tag{3}$$

Where λ is a constant.

Under the situation that users apply multiple base stations simultaneously to transmit their information, we propose the following optimization problem denoted as P1:

$$P1 : \begin{cases} \max \sum_i^K (U_{ij} - F_{ij}), \forall j \in N \\ s.t. 0 \leq p_j \leq p_{max} \end{cases} \tag{4}$$

With the power-punishment mechanism, sometimes, users enjoying best network services pay the least, while users with the worst network resources pay the most. This might reduce the positivity of users to use the network service, and lead to a waste of network resources.

Notice that users' QoS are related with their SIR. Therefore, we can define a pricing function that monotonically increases with SIR, and moreover the unit price is based on the user's channel gain. Intuitively, in such a way distant users pay a lower price to obtain a poorer network experience, while closer users pay a higher price to acquire a better service such as high throughput and low delay. Hence, we define a new pricing function as illustrated in equations (5) and (6):

$$Q_{ij} = \beta_{ij} \gamma_{ij}. \tag{5}$$

$$\beta_{ij} = \lambda h_{ij}. \tag{6}$$

where β_{ij} is the unit price of user j to base station i .

Accordingly, a new optimization problem denoted as P2 is defined by:

$$P2 : \begin{cases} \max \sum_i^K (U_{ij} - Q_{ij}), \forall j \in N \\ s.t. 0 \leq p_j \leq p_{max} \end{cases} \tag{7}$$

The net utility functions of P1 and P2 are not quasi concave. Based on the super modular game in [13,14], we know that if the utilities of P1 and P2 satisfy the non decreasing differences (NDD) conditions, they will have NE.

Definition 1: A game is a super modular game if it satisfies the following two conditions:

- 1) All participants in the strategy space is a compact set;

$$\frac{\partial^2 U_j(p)}{\partial p_j \partial p_k} \geq 0, \forall k \neq j, j, k \in N.$$

Based on the above analysis, we have the following results:

Theorem 1: P1 exists a NE solution if $\gamma_{ij} \geq 2 \ln(M)$.

Proof: As $0 \leq p_j \leq p_{max}$, all user's strategy space are compact set. For the second condition, the second partial derivation of P1 is:

$$\frac{\partial^2 U_j}{\partial p_j \partial p_k} = \sum_i^K \frac{LR(1-e^{-\gamma_{ij}/2})^M \gamma_{ij}^2 h_{ik}}{4p_j^2 I_{ij} (e^{\gamma_{ij}/2} - 1)^2} (e^{-\gamma_{ij}/2} - M) \geq 0, \tag{8}$$

For inequality (8) we have

$$e^{\gamma_{ij}/2} - M \geq 0, \tag{9}$$

equivalently

$$e^{\gamma_{ij}/2} \geq M, \tag{10}$$

make logarithmic on the both sides of the inequality (11),

$$\gamma_{ij} \geq 2 \ln M. \tag{11}$$

Theorem 2: P2 exists a NE solution if $\gamma_{ij} \geq 2 \ln(M) - 2 \ln(1 + 4I_{ij} \lambda (M-1)e / LRG)$,

where $I_{ij} = \sum_{k=1, k \neq j}^N h_{ik} p_k + \sigma^2$.

Proof: As $0 \leq p_j \leq p_{max}$, all user's strategy space are compact set. For the second condition, the second partial derivation of P2 is:

$$\frac{\partial^2 U_j}{\partial p_j \partial p_k} = \sum_i^K \frac{G h_{ij} h_{ik}}{I_{ij}^2} \left(\frac{LRG h_{ij} e^{-\gamma_{ij}/2}}{4I_{ij}} (1 - e^{-\gamma_{ij}/2})^{M-2} \times (1 - M e^{-\gamma_{ij}/2}) + \lambda h_{ij} \right) \geq 0 \tag{12}$$

For inequality (12), we note that when $\gamma_{ij} \in [0, 2 \ln(M-1)]$, $e^{-\gamma_{ij}/2} (1 - e^{-\gamma_{ij}/2})^{M-2}$ is monotonically increasing. We have

$$e^{-\gamma_{ij}/2} (1 - e^{-\gamma_{ij}/2})^{M-2} \leq (M e^{-e})^{-1}, \tag{13}$$

Take inequality (13) into (12) we have:

$$\frac{LRG h_{ij}}{4I_{ij} (M e^{-e})} (1 - M e^{-\gamma_{ij}/2}) + \lambda h_{ij} \geq 0, \tag{14}$$

$$1 + \frac{4\lambda I_{ij} (M-1)e}{LRG} \geq M e^{-\gamma_{ij}/2}, \tag{15}$$

Make logarithmic on the both sides of the inequality (15),

$$\ln(1 + \frac{4\lambda I_{ij} (M-1)e}{LRG}) \geq \ln M - \gamma_{ij} / 2, \tag{16}$$

$$\gamma_{ij} \geq 2 \ln M - 2 \ln(1 + 4\lambda I_{ij} (M-1)e / LRG). \tag{17}$$

When γ_{ij} meets the conditions in (11) and (17), P1 and P2 are super modular game. Therefore P1 and P2 exists NE solution.

Simulation

In multi-cell CDMA data systems, we assume that all the base stations can correctly receive information, they are fixed frame size and there is no forward error correction. In the following simulations, there are 20 stationary users and 4 base stations. The channel gain utilizes a simple path loss model $h_{ij} = a/d_{ij}^b$ with $a=0.097$ and $b=4$ in this paper.

Let $G=W/R$ and choose $\lambda=10^5$. All the parameters are listed in Table 1.

Algorithm: Consider the non-cooperative power control games of P1 and P2, use iteration to strike the optimal power,

Step 1: set the initial values, $p(0) = 0$, $t(0) = 1$, $\epsilon = 0.000001$, $p_{max} = 2$, $t_{max} = 500$, $k=1$.

Step 2: calculate $p(k)$ to fulfill equation (18) and (19):

$$\gamma_i(k) = \frac{G h_i p_i(k)}{\sum_{j=1, j \neq i}^N h_j p_j(k-1) + \sigma^2}, \forall i \in N, \tag{18}$$

$$p_i(k) \frac{\partial U_i}{\partial p_i(k)} = 0, \forall i \in N. \tag{19}$$

Step 3: check if $|p_i(k) - p_i(k-1)| \leq \epsilon$, if yes go to Step 5, otherwise, go to Step 4.

Step 4: $t(k) = t(k-1) + 1$, check if $t(k) \geq t_{max}$, if yes go to Step 5, otherwise return to Step 2.

Step 5: end.

Table 1: Simulation Parameters.

M, total number of bits per frame	80
L, number of information bits per frame	64
R, chips transmission rate	10^4 bits/second
W, spread spectrum bandwidth	10^6 Hz
modulation	Non-Coherent FSK
P_{max} , max power	2 Watts
σ^2 , background noise(AWGN)	5×10^{-15} Watts

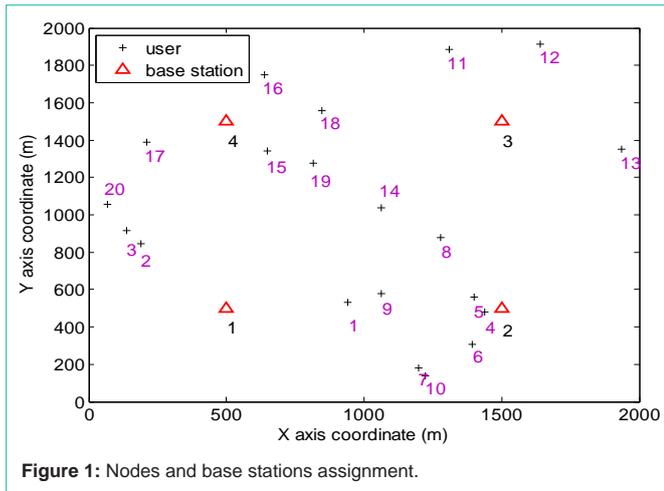


Figure 1: Nodes and base stations assignment.

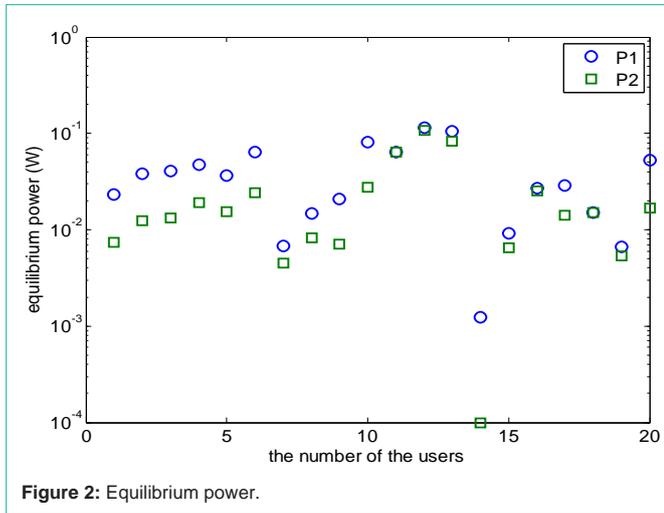


Figure 2: Equilibrium power.

Figure 1 shows the deployments of base stations and nodes. Figure 2 illustrates the powers at the equilibrium, which shows that the pricing mechanism (5)-(6) enable lower power consumption than the linear power mechanism (3). Figure 3 shows the utilities at the equilibrium, which indicates that all users get higher utilities with the pricing mechanism (5)-(6) than the pricing mechanism (3).

Figure 4 shows the prices at the equilibrium. From Figures 3 and 4, we can see that: Under the power pricing mechanism (3), users who obtain less utility usually pay more; while under the pricing mechanism (5)-(6), users with higher QoS should pay more. Therefore, the mechanism (5)-(6) improves the fairness, which can promote the users to participate in using the network effectively. This will reduce energy waste, improve network performance, and avoid

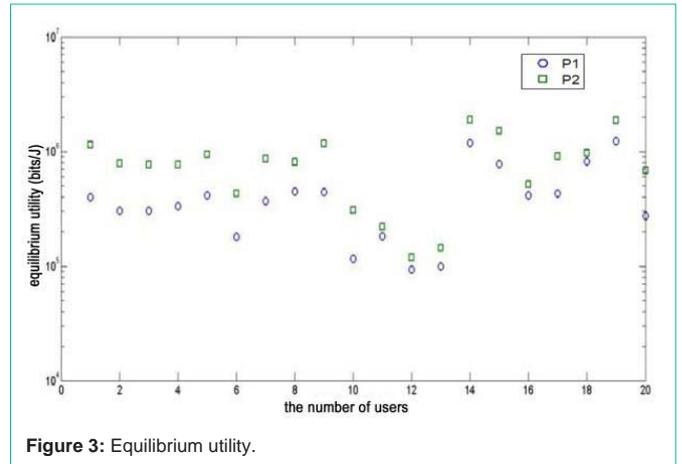


Figure 3: Equilibrium utility.

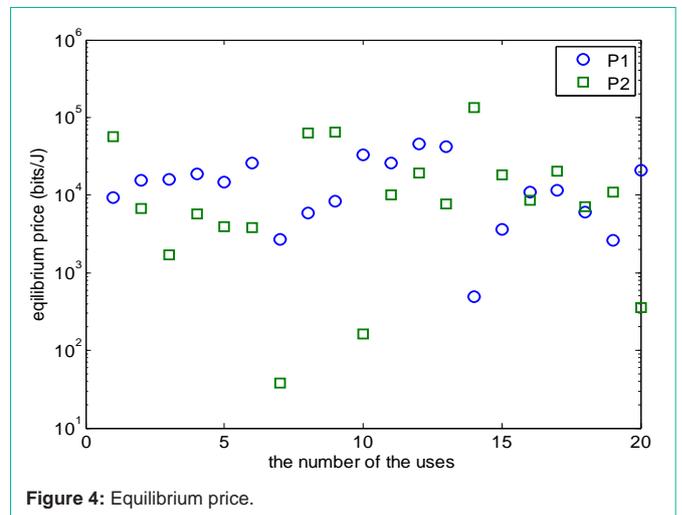


Figure 4: Equilibrium price.

network paralysis.

Conclusions

In this paper, we consider a situation that nodes associate all base stations. Different from the classical linear power pricing mechanism, we introduce a pricing function based on users' SIR and path gain to improve the fairness of utilization, so that users acquire more network resource should pay more. Simulations show that the pricing mechanism performs a better utility and lower power than the linear power pricing mechanism.

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