Joint Network-Centric and User-Centric Radio Resource Management in a Multicell System*

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Abstract

A pricing mechanism to mediate (and allocate resources) between conflicting user and network objectives has been recently proposed [1] in a single-cell system. Here, we extend the results to a multicell system where the autonomous base station assignment and power control are formulated as a non-cooperative game among users. The network prices the resources using two strategies: global pricing that maximizes the revenue and minimax pricing that trades off the revenue for an evener resource allocation.

Index Terms

Power Control, Pricing, Utility, Radio Resource Management, Revenue Maximization

I. Introduction

Pricing, and more generally microeconomic principles, have recently emerged as powerful tools for resource allocation in wireless networks [2–5]. For example, pricing was used as a policing mechanism to improve user behavior and system efficiency for the up-link of a CDMA data system in [2, 3]. In [4], pricing was a potential simplification of explicit admission control. Pricing in [5] was applied for the down-link of a CDMA voice system to maximize the total utilities or revenues. In our most recent work [1], we considered joint user-centric and network-centric radio resource management for an uplink *single-cell* CDMA system where pricing was a mediating mechanism between users and network. In the single-cell system, each user adjusted its power unilaterally to maximize its net utility; while the network chose the unit price that maximized the total revenue. The net result is a tradeoff between the two seemingly conflicting user and network objectives.

In this paper, we extend the work in [1] to a multicell system. We let each user choose the base station assigned to which the user's net utility is maximized. Therefore, the power control and base-station (BS) assignment are integrated in the user-centric optimization. For the network-centric optimization, we apply two approaches: one is global pricing where the network seeks a unit price for global revenue maximization and the other is minimax pricing where a unit price is assigned based on maximizing the revenue at the BS with the smallest local optimum unit price.

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We describe the problem formulation in Sec. II and III and present numerical results in Sec. IV.

II. System Model

We consider the up-link of a CDMA system with K cells serving N mutually interfering users.

A. User Metric: Utility Function

We assume that one user is connected to only one base station (BS) at any time. The quality of service (QoS) received by user i can be translated quantitatively into a utility function. While several notions of utilities are possible [2–6], we use the one chosen here [2] since it combines the two important criteria of wireless transmission: throughput, T, and transmitter powers, $\mathbf{p} = (p_1, p_2, ..., p_N)$. The utility function $U_i(a_i, \mathbf{p})$ of user i when it is assigned to BS a_i is defined as the average number of information bits of user i received correctly at BS a_i per Joule of battery energy expended:

$$U_i(a_i, \mathbf{p}) \triangleq \frac{T_i(a_i, \mathbf{p})}{p_i}, \tag{1}$$

where $T_i(a_i, \mathbf{p})$ is the throughput of user i received at BS a_i. The received signal to interference plus noise ratio (SINR) of user i at BS a_i is given as $\gamma_i(a_i, \mathbf{p}) = G_i \frac{h_{a_i i} p_i}{\sum_{j \neq i} h_{a_i j} p_j + \sigma^2}$, where G_i, $h_{a_i i}$ and σ^2 represent the processing gain, path gain and noise variance for the i^{th} user. We assume a frame in error is retransmitted until received correctly. The dependence of the throughput on the SINR is similar to that in [1].

B. Network Metric: Revenue

A natural metric of the network satisfaction is its revenue. We assume that the network broadcasts a common unit price λ to all the users. Given a base-station and power vector assignment, the payment by each user is explicitly a function of λ: $\rho_i(\lambda) \triangleq \lambda T_i(a_i, \mathbf{p})$. Further, if we denote β_k as the set of users connected to the BS k ($i \in \beta_k$ if and only if $a_i = k$), the revenue collected by the BS k is defined as:

$$\rho^k(\lambda) \triangleq \sum_{i \in \beta_k} \lambda T_i(a_i, \mathbf{p}). \tag{2}$$

The revenue that the network collects is $\rho(\lambda) \triangleq \sum_{k=1}^{K} \rho^k(\lambda) \equiv \sum_{i=1}^{N} \rho_i(\lambda)$.

As in the single cell case [1], we propose pricing as a mediator between possibly conflicting user and network objectives. While such a pricing scheme can be expressed in terms of monetary units, the actual transformation remains a topic of future study.

III. Joint User and Network Optimization

A. User Problem: Autonomous Base-Station Assignment and Non-cooperative Power Control Game

With the network broadcasted unit price λ, the user objective is for each user to unilaterally maximize its net utility, defined as the difference between its utility and its payment:

$$[\textbf{User Problem}] \quad \max_{p_i \in S_i, a_i \in A} U_i^{\mathrm{net}}(a_i, p_i, \mathbf{p}_{-i}, \lambda) \;=\; \max_{p_i, a_i} \Big\{ U_i(a_i, \mathbf{p}) - \lambda T_i(a_i, \mathbf{p}) \Big\}, \quad \forall i. \tag{3}$$

Given the minimum and maximum power constraints $p_i^{\min}$ and $p_i^{\max}$ and the total number of base stations K, $S_i \triangleq [p_i^{\min}, p_i^{\max}]$ and $A \triangleq \{1, 2, ..., K\}$ in the above equation form the strategy space of the i^{th} user. Unlike the user-centric problem in a single-cell system where each user maximizes its net utility over its transmitter power only, the user-centric objective is to optimize the net utility over two dimensions: its transmitter power and its BS assignment. Searching over all possible BS assignments and performing net utility optimizations over transmitter powers for every combination would be computationally intensive. We can greatly simplify the **User Problem** by noting that U_i^{net} is monotonically increasing in γ_i, and therefore:

Theorem III.1: Given an interference vector $\mathbf{p}_{-i} \triangleq (p_1, p_2, ..., p_{i-1}, p_{i+1}, ..., p_N)$*, the BS assignment based on the net utility maximization is equivalent to the one based on maximizing SINR:*

$$a_i^* \triangleq \arg\max_k U_i^{\mathrm{net}}(k, p_i, \mathbf{p}_{-i}, \lambda) \equiv \arg\max_k \gamma_i(k, \mathbf{p}). \tag{4}$$

It states that the BS assignment based on net utility maximization is equivalent to that based on SINR maximization. Further, user i's SINR maximization over BS assignment is independent of its power p_i. Therefore, the user problem can be solved by assigning base station first, followed by power control. The user problem can be regarded as a non-cooperative game and we now present some properties of this game.

1) Nash Equilibrium and Its Existence: If all the users' optimization attempts settle down, the game achieves an equilibrium called a *Nash equilibrium* with equilibrium power vector and BS assignment vector $(\mathbf{p}^*(\lambda), \mathbf{a}^*(\lambda))$, where power and BS assignment vectors are defined as $\mathbf{p}^* = (p_1^*, p_2^*, ..., p_N^*)$ and $\mathbf{a}^* = (a_1^*, a_2^*, ..., a_N^*)$ respectively. Formally, the Nash equilibrium power and BS assignment vector is the one at which no single user can improve its net utility by unilaterally changing its power and its BS assignment. Mathematically,

$$p_i^* = \arg\max_{\xi_i \in S_i} U_i^{\mathrm{net}}\left(a_i^*, \xi_i, \mathbf{p}_{-i}^*, \lambda\right) \text{ and } a_i^* = \arg\max_k \gamma_i(k, \mathbf{p}^*), \qquad \forall i. \tag{5}$$

Theorem III.2: A Nash equilibrium exists for the multi-cell non-cooperative power control game if $\mathrm{BER}(\gamma)$ *decays exponentially in SINR denoted by* γ*.*

The proof is similar to that of the existence of a Nash equilibrium in a single-cell system [1].

2) Iterative Algorithm and Its Convergence: The iterative algorithm for the user-centric optimization is for each user in a round-robin way first to do the BS assignment based on maximizing its SINR, then to find the transmitter power that optimizes its net utility:

$$a_i(t+1) = \arg \max_k \gamma_i\left(k, \mathbf{p}(t)\right); \; p_i(t+1) = \arg \max_{\xi_i \in S_i} U_i^{\text{net}}\left(a_i(t+1), \xi_i, \mathbf{p}_{-i}(t), \lambda\right), \tag{6}$$

where $\mathbf{p}(t)$ is the power vector at the t^{th} iteration. If we express this update rule as $\mathbf{p}(t+1) = \mathbf{X}\left(\mathbf{p}(t)\right)$ and use a proof similar to the analogous one in [1], we can show that $\mathbf{X}(\cdot)$ is a standard interference function [7]. We apply the results in [7] directly and prove the following theorem:

Theorem III.3: Given any unit price λ, starting from any initial point, the iteration specified in equation (6), always converges to a unique Nash equilibrium.

In summary, the user-centric optimization realizes autonomous BS assignment and power control, i.e., for every given value of unit price λ, the resulting power and BS assignment vectors converge to the fixed values denoted as $\mathbf{p}^*(\lambda)$ and $\mathbf{a}^*(\lambda)$

B. Network Optimization

We will discuss in the following two different network problems characterized by different strategies for finding the optimum unit price.

1) Global Pricing: The network aims to find its highest revenue by searching over $\lambda \geq 0$:

$$[\textbf{Network Problem(G)}] \;\; \max_{\lambda \geq 0} \;\; \rho(\lambda), \;\; \text{where } \rho(\lambda) = \sum_{i=1}^{N} \lambda T_i(\mathbf{a}^*(\lambda), \mathbf{p}^*(\lambda)). \tag{7}$$

Theorem III.4: The revenue $\rho(\lambda)$ as a function of the unit price λ has the following desirable properties: $\rho(\lambda) \geq 0$, $\rho(\lambda = 0) = 0$, $\rho(\lambda) < \infty$ when N is finite, and $\lim_{\lambda \to \infty} \rho(\lambda) = 0$.

The proof of the above theorem is very similar to that for a single-cell system [1]. These properties together with the continuity of revenue yield:

Corollary III.1: There exists an optimum unit price λ_G which maximizes the revenue $\rho(\lambda)$. Further, both λ_G and $\rho(\lambda_G)$ are finite.

While we do not have a formal proof for the uniqueness of the optimum unit price, all our numerical results seem to support such a hypothesis.

2) Minimax Pricing: Here, the network chooses the unit price as follows. First, the optimum unit price that maximizes the revenue ρ^k at the k^{th} BS is found. Then the unit price, called the minimax price, λ_M, is chosen to be the smallest among the K optimum unit prices obtained at each of the BS. Mathematically, the network problem in this case can be stated as:

$$[\textbf{Network Problem(M)}] \;\; \min \left\{ \arg \{\max_{\lambda} \rho^1(\lambda)\}, \ldots, \arg \{\max_{\lambda} \rho^K(\lambda)\} \right\}. \tag{8}$$

It is easy to verify that λ_M exists. Minimax pricing results in an evener distribution of achieved QoS compared to global pricing, as will be discussed in the following.

IV. Numerical Results and Discussions

We consider a multicell CDMA system with $K = 4$ BS serving $N = 30$ users. We assume that path gain decays with the fourth power of the distance to BS. The modulation used is non-coherent FSK. Users are randomly located in the 2×2 neighboring cells, each of which has a BS in the center. We want to compare in the following the two network optimization strategies. We plot in Figure 1 the revenue of each BS and the total revenue as a function of the unit price, where we observe that the network collects more revenue using the global pricing scheme compared to the minimax one. However, as shown in Figure 2(b), the network obtains its revenue mainly from the few users with best channels when using λ_G; while the network collects non-trivial fractions of the revenue from more users when using λ_M. Besides the payment, another user metric is the frame success rates (FSR), i.e., the normalized throughput. We can see in Figure 2(a), that under global pricing, only two users have FSR that are significantly higher than zero; while under minimax pricing, there are significantly more number of users with such FSR. We can observe from Figure 3 that under both pricing schemes, users who pay more obtain proportionally better service, measured in terms of their utilities, which is consistent with our main results for a single-cell system in [1]. In the global network optimization, the network is so greedy in collecting revenue that most of the network resources are distributed to the very few users with best channels. The minimax pricing, however, reduces the degree of monopoly that the global pricing results in. The network resources are allocated to more users even though the total revenue collected is lowered. One can view this as a trade off between the network revenue and an evener distribution of network resources.

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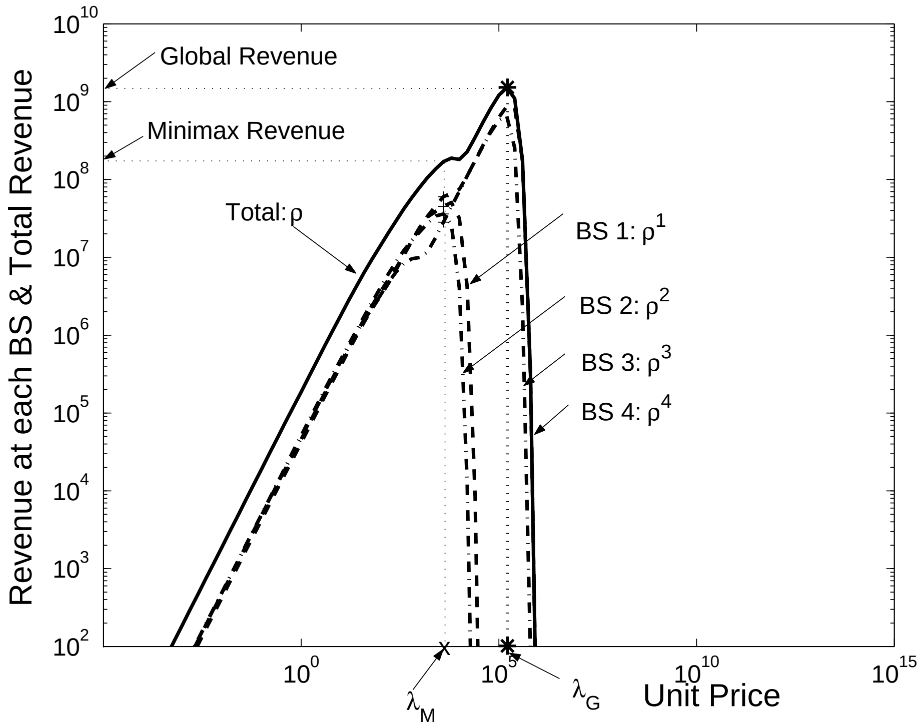
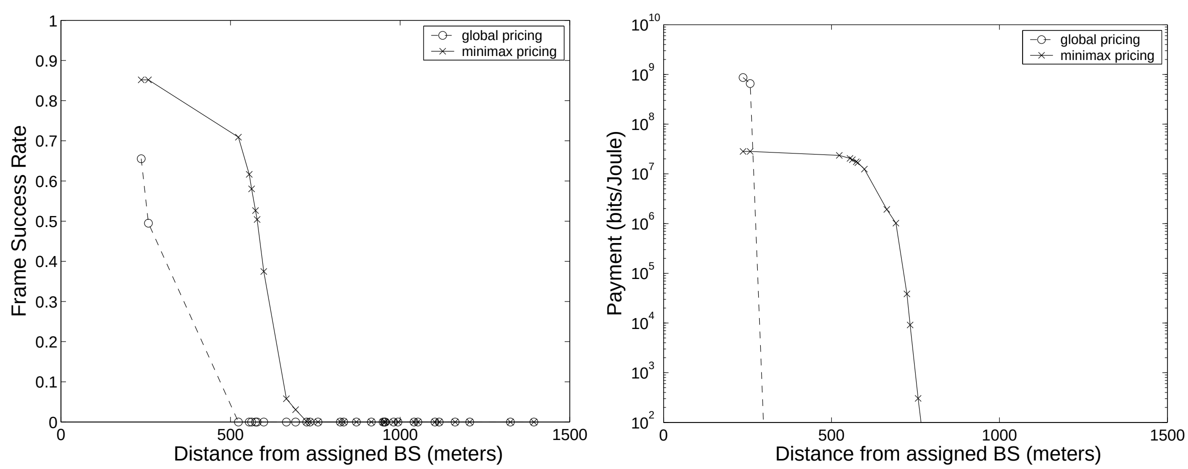


Fig. 1. Comparisons of revenues at global pricing optimum and at the stationary point of minimax pricing. Note that ρ^4 almost overlaps ρ for $\lambda > \lambda_{\mathrm{G}}$.



(a) FSR

(b) Payment

Fig. 2. Comparisons of user metrics under global and minimax pricing.

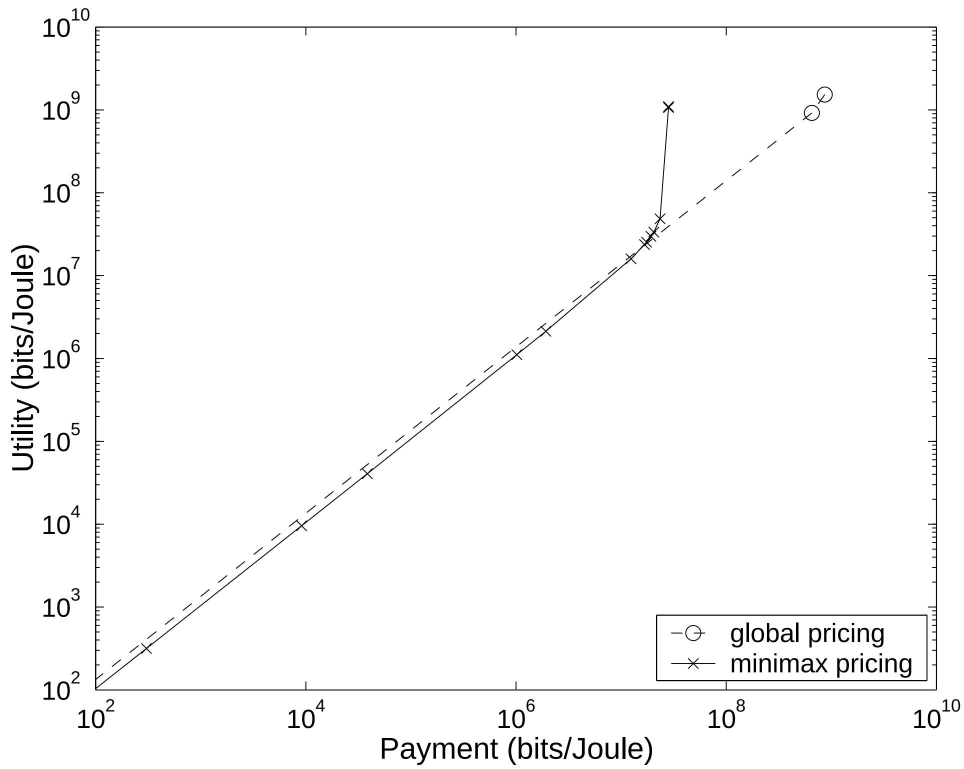


Fig. 3. Proportionality between QoS (utility) achieved and payment.