

# An Energy-Efficient Approach to Power Control and Receiver Design in Wireless Data Networks

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**Abstract**—In this work, the cross-layer design problem of joint multiuser detection and power control is studied using a game-theoretic approach that focuses on energy efficiency. The uplink of a direct-sequence code division multiple access (DS-SS) data network is considered and a non-cooperative game is proposed in which users in the network are allowed to choose their uplink receivers as well as their transmit powers to maximize their own utilities. The utility function measures the number of reliable bits transmitted by the user per joule of energy consumed. Focusing on linear receivers, the Nash equilibrium for the proposed game is derived. It is shown that the equilibrium is one where the powers are SIR-balanced with the minimum mean square error (MMSE) detector as the receiver. In addition, this framework is used to study power control games for the matched filter, the decorrelator, and the MMSE detector; and the receivers' performance is compared in terms of the utilities achieved at equilibrium (in bits/Joule). The optimal cooperative solution is also discussed and compared with the non-cooperative approach. Extensions of the results to the case of multiple receive antennas are also presented. In addition, an admission control scheme based on maximizing the total utility in the network is proposed.

**Index Terms**—Power control, game theory, Nash equilibrium, utility function, multiuser detectors, cross-layer design.

## I. INTRODUCTION

Power control is used for resource allocation and interference management in both the uplink and the downlink of Code Division Multiple Access (CDMA) systems. In the uplink, the purpose of power control is for each user to transmit enough power so that it can achieve the required quality of service (QoS) at the uplink receiver without causing unnecessary interference to other users in the system. One approach that has been very successful in providing insights into design of power control algorithms for data networks is the game-theoretic approach studied in [1]–[12]. In [1], the authors provide motivations for using game theory to study communication systems, and in particular power control. In [2] and [3], power control is modeled as a non-cooperative

game in which users choose their transmit powers in order to maximize their utilities, where utility is defined as the ratio of throughput to transmit power. In [4], a network-assisted power control scheme is proposed to improve the overall utility of the system. The authors in [5] and [6] use pricing to obtain a more efficient solution for the power control game. Similar approaches are taken in [7]–[10] for different utility functions. Joint network-centric and user-centric power control is discussed in [11]. In [12], the authors propose a power control game for multi-carrier CDMA systems. In all the work done so far, the receiver is assumed to be a simple matched filter. No work has taken into account the effects of the receiver on power control. Also, all prior work in this area has concentrated on single antenna receivers.

This work is the first one that tackles the cross-layer design problem of joint multiuser detection and power control in the context of a non-cooperative game-theoretic setting. It attempts to bring a cross-layer design perspective to all the earlier work that has studied power control from a game-theoretic point of view. Our focus throughout this work is on energy efficiency. We are mainly concerned with applications where it is more important to maximize the number of bits transmitted per joule of energy consumed than to maximize throughput. We first propose a non-cooperative (distributed) game in which users are allowed to choose their uplink receivers as well as their transmit powers. We focus on linear receivers and derive the Nash equilibrium for the proposed game. In addition, we use this framework to study power control for the matched filter, the decorrelator [13] and the minimum mean square error (MMSE) [14] receiver. We show that regardless of the type of receiver, the Nash equilibrium is an SIR-balancing solution with the same target SIR (signal to interference plus noise ratio) for all receiver types<sup>1</sup>. Using a large-system analysis, we derive explicit expressions for the utilities achieved at equilibrium for each receiver type. This allows us to compare the performance of these receivers in terms of energy efficiency (i.e., the number of bits transmitted per joule of energy consumed). In addition, the performance of our non-cooperative approach is compared with the optimal cooperative (centralized) approach. It is shown that only for the matched filter is the difference in performance between these two approaches significant. For the decorrelator, the two solutions are identical, and for the MMSE receiver, the utility achieved by the Pareto-optimal solution is only slightly greater than that achieved by the non-cooperative approach. We also

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<sup>1</sup>This can also be shown to be true even for some non-linear receivers [15].

extend our analysis to the case where multiple receive antennas are used at the uplink receiver. The effects of power pooling and interference reduction, which are the benefits of using multiple receive antennas, are demonstrated and quantified for the matched filter, the decorrelator, and the MMSE receiver in terms of the utilities achieved at equilibrium. A utility-maximizing admission control scheme is also presented. We show that using the proposed scheme, the number of admitted users for the MMSE receiver is greater than or equal to the total number of admitted users for the matched filter and decorrelator combined. These results constitute the first study of power control and receiver design in a unified framework.

The organization of this paper is as follows. In Section II, we provide the background for this work, while the system model is given in Section III. We describe our proposed power control game in Section IV and derive the Nash equilibrium for this game. In Section V, we use the game-theoretic framework along with a large-system analysis to compare the performance of various linear receivers in terms of achieved utilities. The Pareto-optimal solution to the power control game is discussed in Section VI and its performance is compared with that of the non-cooperative approach. Extensions of our analysis to multi-antenna systems are given in Section VII. We then present a utility-maximizing admission control scheme in Section VIII. Numerical results and conclusions are provided in Sections IX and X, respectively. Throughout this work, we concentrate on the uplink of a synchronous direct-sequence CDMA (DS-CDMA) wireless data network.

## II. BACKGROUND

Consider the uplink of a DS-CDMA data network where each user wishes to locally and selfishly choose its action in such way as to maximize its own utility. The strategy chosen by a user affects the performance of other users in the network through multiple-access interference. In such a multiple-access network, there are several questions to ask concerning the interaction among the users. First of all, what is a reasonable choice of a utility function that measures energy efficiency? Secondly, given such a utility function, what strategy should a user choose in order to maximize its utility? If every user in the network selfishly and locally picks its utility-maximizing strategy, will there be a stable state at which no user can unilaterally improve its utility (Nash equilibrium)? What are some of the properties of such an equilibrium? How does such a non-cooperative approach compare with a cooperative scheme?

Game theory is the natural framework for modeling and studying such an interaction. To pose the power control problem as a non-cooperative game, we first need to define a utility function suitable for measuring energy efficiency for data applications. Most data applications are sensitive to error but tolerant to delay. It is clear that a higher SIR level at the output of the receiver will result in a lower bit error rate and hence higher throughput. However, achieving a high SIR level often requires the user terminal to transmit at a high power which in turn results in low battery life. These issues can be quantified (as in [2]) by defining the utility function of a user

to be the ratio of its throughput to its transmit power, i.e.,

$$u_k = \frac{T_k}{p_k}. \quad (1)$$

Throughput here is the net number of information bits that are transmitted without error per unit time.

Let  $f_s(\gamma_k)$  represent the probability that a packet is received without an error, where  $\gamma_k$  is the SIR for user  $k$ . Our assumption is that if a packet has one or more bit errors, it will be retransmitted. Assuming that retransmissions are independent, the average number of transmissions necessary to receive a packet correctly is equal to  $\frac{1}{f_s(\gamma_k)}$ . Therefore, we have

$$T_k = \frac{L}{M} R_k f_s(\gamma_k), \quad (2)$$

where  $L$  and  $M$  are the number of information bits and the total number of bits in a packet, respectively; and  $R_k$  is the transmission rate for the  $k^{\text{th}}$  user, which is the ratio of the bandwidth to the processing gain. The packet success rate (PSR), which is represented by  $f_s(\gamma_k)$ , depends on the details of the data transmission such as modulation, coding, and packet size. In most practical cases, however,  $f_s(\gamma_k)$  is increasing and has a sigmoidal shape. For example, when the modulation is BPSK (binary phase shift keying) and the noise is additive white Gaussian,  $f_s(\gamma_k)$  is given by  $(1 - Q(\sqrt{2\gamma_k}))^M$ , where  $Q(\cdot)$  is the complementary cumulative distribution function of a standard normal random variable. Notice that, in this case,  $f_s(0) = 2^{-M}$  is strictly positive due to the possibility of random guessing at the receiver. This means that based on our definition for the utility function, a user can potentially achieve infinite utility by transmitting zero power.

To prevent the above undesirable situation, we replace the PSR with an *efficiency function*,  $f(\gamma_k)$ , when calculating the throughput for our utility function. The efficiency function should closely approximate the PSR and have the desirable property that  $f(0) = 0$ . The efficiency function can for example be defined as  $f(\gamma_k) = f_s(\gamma_k) - f_s(0)$ . In almost all practical cases and for moderate to large values of  $M$  (e.g.  $M = 100$ ),  $f_s(0)$  is very small and, hence,  $f(\gamma_k) \simeq f_s(\gamma_k)$ . In addition, for this efficiency function we have  $f(0) = 0$ . The plot of  $f(\gamma_k)$  for the BPSK modulation and additive white Gaussian noise is given in Fig. 1 with  $M = 100$  (see [16] for a detailed discussion of this efficiency function).

The exact expression for the efficiency function is not crucial. Our analysis throughout this paper is valid for any efficiency function that is increasing and S-shaped<sup>2</sup> with  $f(0) = 0$  and  $f(+\infty) = 1$ , and has a continuous derivative. These assumptions are valid in many practical systems. Throughout this paper, we assume that all users have the same efficiency function. Generalization to the case where the efficiency function is dependent on  $k$  is straightforward. Note that the throughput  $T_k$  in (2) could also be replaced with the Shannon capacity formula if the utility function in (1) is appropriately modified to ensure that  $u_k = 0$  when  $p_k = 0$ .

<sup>2</sup>An increasing function is S-shaped if there is a point above which the function is concave, and below which the function is convex.

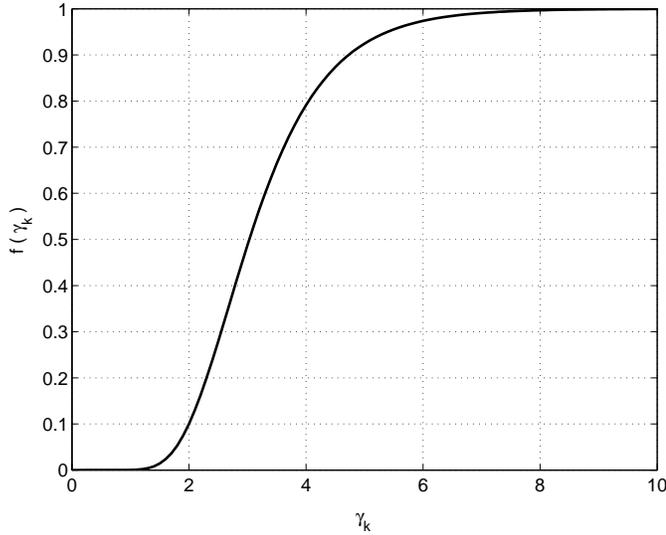


Fig. 1. A typical efficiency function.

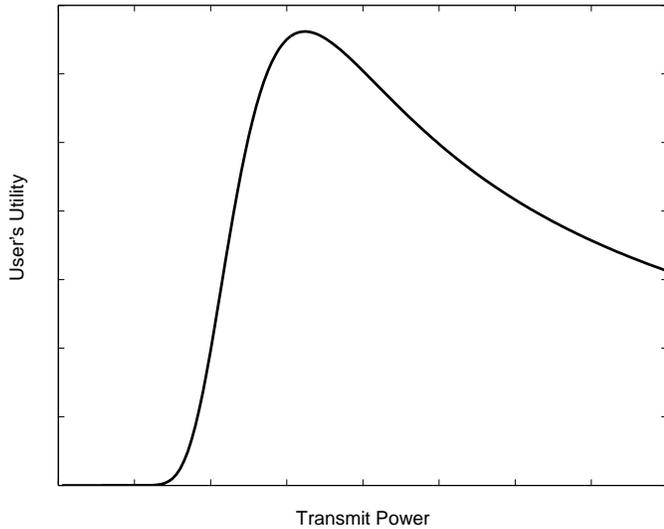


Fig. 2. User's utility as a function of transmit power for fixed interference.

Combining (1) with (2), and replacing the PSR with the efficiency function, we can write the utility function of the  $k^{\text{th}}$  user as

$$u_k = \frac{L}{M} R_k \frac{f(\gamma_k)}{p_k}. \quad (3)$$

This utility function, which has units of *bits/Joule*, represents the total number of data bits that are delivered to the destination without an error per joule of energy consumed. This utility function captures very well the tradeoff between throughput and battery life and is particularly suitable for applications where saving power is more important than achieving a high throughput. For the sake of simplicity, we assume that the transmission rate is the same for all users, i.e.,  $R_1 = \dots = R_K = R$ . All the results obtained here can be easily generalized to the case of unequal rates. Fig. 2 shows the shape of the utility function in (3) as a function of transmit power keeping other users' transmit powers fixed.

Power control is modelled as a non-cooperative game in

which each user tries to selfishly maximize its own utility. It is shown in [17] that, when matched filters are used as the uplink receivers, if user terminals are allowed to choose only their transmit powers for maximizing their utilities, then there exists an equilibrium point at which no user can improve its utility given the power levels of other users (Nash equilibrium). In this work, we extend this game-theoretic approach to study the cross-layer design problem of joint multiuser detection and power control. In particular, we propose a non-cooperative game in which the users are allowed to choose their uplink receivers as well as their transmit powers.

### III. SYSTEM MODEL

We consider the uplink of a DS-CDMA system with processing gain  $N$  (defined as the ratio of symbol duration to chip duration). We assume that there are  $K$  users in the network and focus on a single cell. Thus, we assume that all  $K$  user terminals transmit to a receiver at a common concentration point, such as a cellular base station or other network access point. For now, we assume that each of the transmitters and the receiver has one antenna. The signal received by the uplink receiver (after chip-matched filtering) sampled at the chip rate over one symbol duration can be expressed as

$$\mathbf{r} = \sum_{k=1}^K \sqrt{p_k} h_k b_k \mathbf{s}_k + \mathbf{w}, \quad (4)$$

where  $p_k$ ,  $h_k$ ,  $b_k$  and  $\mathbf{s}_k$  are the transmit power, channel gain, transmitted bit and spreading sequence of the  $k^{\text{th}}$  user, respectively, and  $\mathbf{w}$  is the noise vector which is assumed to be Gaussian with mean  $\mathbf{0}$  and covariance  $\sigma^2 \mathbf{I}$ . We assume random spreading sequences for all users, i.e.,  $\mathbf{s}_k = \frac{1}{\sqrt{N}} [v_1 \dots v_N]^T$ , where the  $v_i$ 's are independent and identically distributed (i.i.d.) random variables taking values  $\{-1, +1\}$  with equal probabilities.

Let us represent the linear uplink receiver of the  $k^{\text{th}}$  user by a coefficient vector,  $\mathbf{c}_k$ . The output of this receiver can be written as

$$\begin{aligned} y_k &= \mathbf{c}_k^T \mathbf{r} \\ &= \sqrt{p_k} h_k b_k \mathbf{c}_k^T \mathbf{s}_k + \sum_{j \neq k} \sqrt{p_j} h_j b_j \mathbf{c}_k^T \mathbf{s}_j + \mathbf{c}_k^T \mathbf{w}. \end{aligned} \quad (5)$$

Given (5), the SIR of the  $k^{\text{th}}$  user at the output of its receiver is

$$\gamma_k = \frac{p_k h_k^2 (\mathbf{c}_k^T \mathbf{s}_k)^2}{\sigma^2 \mathbf{c}_k^T \mathbf{c}_k + \sum_{j \neq k} p_j h_j^2 (\mathbf{c}_k^T \mathbf{s}_j)^2}. \quad (6)$$

In all the previous work in this area, the receive filter is assumed to be a simple matched filter and maximization of the utility function is done over the transmit power only. In the following section, we extend this approach by allowing the users to choose their receivers in addition to their transmit powers. It should be noted that although we focus on flat fading channels in this paper, all of our analysis can be easily extended to frequency-selective channels by appropriately defining an effective spreading sequence for each user. In particular, the effective spreading sequence for user  $k$  is the response of the frequency-selective channel to the transmitted spreading sequence of user  $k$ .

#### IV. THE NON-COOPERATIVE POWER CONTROL GAME

Here, we propose a non-cooperative game in which each user seeks to maximize its own utility by choosing its transmit power and the receive filter coefficients. Let  $G = [\mathcal{K}, \{A_k\}, \{u_k\}]$  denote the proposed non-cooperative game where  $\mathcal{K} = \{1, \dots, K\}$ , and  $A_k = [0, P_{max}] \times \mathcal{R}^N$  is the strategy set for the  $k^{th}$  user. Here,  $P_{max}$  is the maximum allowed power for transmission. Each strategy in  $A_k$  can be written as  $\mathbf{a}_k = (p_k, \mathbf{c}_k)$  where  $p_k$  and  $\mathbf{c}_k$  are the transmit power and the receive filter coefficients, respectively, of user  $k$ . Hence, the resulting non-cooperative game can be expressed as the following maximization problem:

$$\max_{\mathbf{a}_k} u_k = \max_{p_k, \mathbf{c}_k} u_k(p_k, \mathbf{c}_k) \quad \text{for } k = 1, \dots, K. \quad (7)$$

Assuming equal transmission rates for all users, (7) can be expressed as

$$\max_{p_k, \mathbf{c}_k} \frac{f(\gamma_k(p_k, \mathbf{c}_k))}{p_k} \quad \text{for } k = 1, \dots, K, \quad (8)$$

where we have explicitly shown that  $\gamma_k$  is a function of  $p_k$  and  $\mathbf{c}_k$  as expressed in (6). A Nash equilibrium is a set of strategies such that no user can unilaterally improve its own utility [18]. We now state and prove the following proposition.

*Proposition 1:* The Nash equilibrium for the non-cooperative game in (7) is given by  $(p_k^*, \mathbf{c}_k^*)$  where  $\mathbf{c}_k^*$  is the vector of MMSE receiver coefficients and  $p_k^* = \min(p_k^{MMSE}, P_{max})$ . Here,  $p_k^{MMSE}$  is the transmit power that results in an SIR equal to  $\gamma^*$ , the solution to  $f(\gamma) = \gamma f'(\gamma)$ , at the output of the MMSE receiver. Furthermore, this equilibrium is unique (up to a scaling factor for the MMSE filter coefficients).

*Proof:* We first show that at Nash equilibrium the receiver has to be the MMSE receiver. Since the choice of receiver is independent of the transmit power, we can write

$$\begin{aligned} \max_{p_k, \mathbf{c}_k} \frac{f(\gamma_k(p_k, \mathbf{c}_k))}{p_k} &= \max_{p_k} \frac{\max_{\mathbf{c}_k} f(\gamma_k(p_k, \mathbf{c}_k))}{p_k} \\ &= \max_{p_k} \frac{f(\max_{\mathbf{c}_k} \gamma_k(p_k, \mathbf{c}_k))}{p_k}, \end{aligned} \quad (9)$$

where the second equality is due to the fact that  $f(\gamma)$  is an increasing function of  $\gamma$ . It is well known that for any given set of transmit powers, the MMSE receiver achieves the maximum SIR among all linear receivers [19]. Therefore, the MMSE receiver achieves the maximum utility among all linear receivers. For any output SIR, a user can always choose the MMSE detector to achieve the desired SIR at a lower transmit power compared to any other linear receiver. A lower transmit power directly translates into a higher utility for the user. Therefore, at Nash equilibrium (if it exists), the receiver must be the MMSE receiver.

The SIR at the output of the MMSE receiver is given by  $\gamma_k^{MMSE} = p_k h_k^2 (\mathbf{s}_k^T \mathbf{A}_k^{-1} \mathbf{s}_k)$ , where  $\mathbf{A}_k = \sum_{j \neq k} p_j h_j^2 \mathbf{s}_j \mathbf{s}_j^T + \sigma^2 \mathbf{I}$ . Since  $\frac{\partial \gamma_k^{MMSE}}{\partial p_k} = \frac{\gamma_k^{MMSE}}{p_k}$ , maximizing the utility function for each user is equivalent to finding  $\gamma^*$  that is the (positive) solution

to  $f(\gamma_k) = \gamma_k f'(\gamma_k)^3$ . If the required power for achieving  $\gamma^*$  is larger than  $P_{max}$ , the utility function is maximized when  $p_k = P_{max}$ . Note that  $\gamma^*$  is independent of  $k$  as long as all users have the same efficiency function.

So far, we have shown that at Nash equilibrium (if it exists), the receiver is the MMSE detector and each user's transmit power is chosen to maximize the utility function with this set of filter coefficients. Therefore, as in [6], the existence of the Nash equilibrium for the game in (7) can be shown via the quasiconcavity of each user's utility function in its own power<sup>4</sup>. For an S-shaped efficiency function, with the MMSE detector as the receive filter,  $\frac{f(\gamma_k)}{p_k}$  is quasiconcave in  $p_k$  and, hence, a Nash equilibrium always exists.

Furthermore, for an S-shaped efficiency function,  $f(\gamma_k) = \gamma_k f'(\gamma_k)$  has a unique solution,  $\gamma^*$ , which is the (unique) maximizer of the utility function [20]. Because of the uniqueness of  $\gamma^*$  and the one-to-one correspondence between the transmit power and achieved SIR at the output of the MMSE receiver, the above Nash equilibrium is unique. ■

The above equilibrium can be reached using the following iterative algorithm. Given any set of users' transmit powers, the receiver filter coefficients can be adjusted to the MMSE coefficients. Each user can then adjust its transmit power to achieve  $\gamma^*$  at the output of the receiver. These steps can be repeated until convergence is reached (see [21] for the proof of convergence). It should be noted that  $\gamma^*$  is the only SIR value at which a line tangent to the curve describing  $f(\gamma)$  passes through the origin (see [20]). Throughout this paper, we assume that  $P_{max}$  is sufficiently large that  $\gamma^*$  can be achieved by all users.

In contrast to the traditional CDMA voice networks (e.g., IS-95) where the target SIR is determined by the desired voice quality, the common SIR here is determined by the utility function which in turn is a function of the throughput which depends on the modulation and coding schemes as well as the packet size.

#### V. COMPARISON OF POWER CONTROL GAMES FOR LINEAR RECEIVERS

In the previous section, we showed that the MMSE receiver achieves the maximum utility among all linear receivers and hence is the receiver chosen by users at the Nash equilibrium. In this section, we fix the receiver type and allow users to choose their transmit powers only. We focus on the matched filter, the decorrelator, and the MMSE detector and obtain the Nash equilibrium for the corresponding power control games. We show that irrespective of the receiver type, the Nash equilibrium is an SIR-balancing solution with the same target SIR for all receiver types. A large-system analysis is then used to obtain closed-form expressions for the utilities achieved at equilibria. This allows us to compare the performance of these

<sup>3</sup>This is shown by taking the derivative of  $u_k$  with respect to  $p_k$  and equating it to zero.

<sup>4</sup>A function is quasiconcave if there exists a point below which the function is non-decreasing, and above which the function is non-increasing.

receivers in terms of the number of bits transmitted per joule of energy consumed.

By picking a particular receiver, the power control game reduces to

$$\max_{p_k} \frac{f(\gamma_k)}{p_k} \quad \text{for } k = 1, \dots, K. \quad (10)$$

The relationship between the achieved SIR and transmit power depends on the particular choice of the receiver. A necessary condition for Nash equilibrium is that  $\frac{\partial u_k}{\partial p_k} = 0$ , i.e.,

$$p_k \frac{\partial \gamma_k}{\partial p_k} f'(\gamma_k) - f(\gamma_k) = 0. \quad (11)$$

We now examine this condition for the three detectors under consideration.

For the conventional matched filter, we have  $\mathbf{c}_k = \mathbf{s}_k$  and, hence,

$$\gamma_k^{MF} = \frac{p_k h_k^2}{\sigma^2 + \sum_{j \neq k} p_j h_j^2 (\mathbf{s}_k^T \mathbf{s}_j)^2}. \quad (12)$$

For the decorrelator, we have  $\mathbf{C} = [\mathbf{c}_1 \dots \mathbf{c}_K] = \mathbf{S}(\mathbf{S}^T \mathbf{S})^{-1}$  (for  $K \leq N$ ), where  $\mathbf{S} = [\mathbf{s}_1 \dots \mathbf{s}_K]$ . Hence,

$$\gamma_k^{DE} = \frac{p_k h_k^2}{\sigma^2 \mathbf{C}_k^T \mathbf{C}_k}. \quad (13)$$

The filter coefficients for the MMSE receiver are given by  $\mathbf{c}_k = \frac{\sqrt{p_k} h_k}{1 + p_k h_k^2 (\mathbf{s}_k^T \mathbf{A}_k^{-1} \mathbf{s}_k)} \mathbf{A}_k^{-1} \mathbf{s}_k$  (up to a scaling factor), where  $\mathbf{A}_k = \sum_{j \neq k} p_j h_j^2 \mathbf{s}_j \mathbf{s}_j^T + \sigma^2 \mathbf{I}$ . This results in

$$\gamma_k^{MMSE} = p_k h_k^2 (\mathbf{s}_k^T \mathbf{A}_k^{-1} \mathbf{s}_k). \quad (14)$$

It is observed that for all three receivers, we have

$$\frac{\partial \gamma_k}{\partial p_k} = \frac{\gamma_k}{p_k}. \quad (15)$$

Therefore, maximizing the utility function for each user is equivalent to finding  $\gamma^*$  that is the solution to

$$f(\gamma) = \gamma f'(\gamma). \quad (16)$$

It is known that if  $K$  and  $N$  are large, the interference plus noise term at the output of the matched filter can be approximated as a Gaussian random variable [22]. For the decorrelator, since the multiple-access interference is removed completely, the noise term at the output of the receiver is Gaussian. In the case of the MMSE receiver, it has been shown that the interference plus noise term at the output is well approximated by a Gaussian random variable [23]. Therefore, it is reasonable to assume that  $f(\gamma)$  is the same for these receivers. In addition, since the solution to (16) is the same for all users (provided that all users have the same modulation and packet size), the solution to the power control game is SIR-balanced with the same target SIR,  $\gamma^*$ , independent of the choice of receiver. Of course, the amount of transmit power needed to achieve  $\gamma^*$  is dependent on the uplink receiver used and the channel gain (which will depend, for example, on the distance between transmitter and receiver). This means that while all the users achieve the same throughput, their utilities will depend on their channel gains and their receivers. In contrast to voice systems in which the target SIR depends only on the desired quality of voice, here the target SIR is dependent

on the efficiency function and is influenced by the modulation and packet size. It should be noted that as long as the efficiency function is increasing and sigmoidal,  $f(\gamma) = \gamma f'(\gamma)$  has a unique solution.

Based on (12)–(14), the amount of transmit power required to achieve the target SIR,  $\gamma^*$ , will depend on the random spreading sequence of each user. In order to obtain quantitative results for the utility function corresponding to each receiver, we appeal to a large system analysis similar to that presented in [24]. We consider the asymptotic case where  $K, N \rightarrow \infty$  and  $\frac{K}{N} \rightarrow \alpha < \infty$ . This allows us to write SIR expressions that are independent of the spreading sequences of the users. It has been shown in [24] that, for large systems, the SIR expressions for the matched filter, the decorrelator and the MMSE receiver are approximately given by

$$\gamma_k^{MF} = \frac{p_k h_k^2}{\sigma^2 + \frac{1}{N} \sum_{j \neq k} p_j h_j^2}, \quad (17)$$

$$\gamma_k^{DE} = \frac{p_k h_k^2 (1 - \alpha)}{\sigma^2} \quad \text{for } \alpha < 1, \quad (18)$$

$$\text{and } \gamma_k^{MMSE} = \frac{p_k h_k^2}{\sigma^2 + \frac{1}{N} \sum_{j \neq k} I(p_j h_j^2, p_k h_k^2, \gamma_k^{MMSE})} \quad (19)$$

where  $I(a, b, c) = \frac{ab}{b+ac}$ .

It is clear that both  $\gamma_k^{MF}$  and  $\gamma_k^{DE}$  satisfy  $\frac{\partial \gamma_k}{\partial p_k} = \frac{\gamma_k}{p_k}$ . It can also be verified that any  $\gamma_k$  which satisfies  $\frac{\partial \gamma_k}{\partial p_k} = \frac{\gamma_k}{p_k}$  is a solution to (19). As a result, we claim that similar to the previous section, finding the solution to power control in large systems is equivalent to finding the solution of  $f(\gamma) = \gamma f'(\gamma)$ , independent of the type of the receiver used. Here again, the solution to this equation is independent of  $k$  which means that all users will seek to achieve the same SIR,  $\gamma^*$ , at the output of the uplink receiver.

The minimum power solution for achieving  $\gamma^*$  by all users is given by the following equations for the three different receivers (see [24]):

$$p_k^{MF} = \frac{1}{h_k^2} \frac{\gamma^* \sigma^2}{1 - \alpha \gamma^*} \quad \text{for } \alpha < \frac{1}{\gamma^*}, \quad (20)$$

$$p_k^{DE} = \frac{1}{h_k^2} \frac{\gamma^* \sigma^2}{1 - \alpha} \quad \text{for } \alpha < 1, \quad (21)$$

$$\text{and } p_k^{MMSE} = \frac{1}{h_k^2} \frac{\gamma^* \sigma^2}{1 - \alpha \frac{\gamma^*}{1 + \gamma^*}} \quad \text{for } \alpha < 1 + \frac{1}{\gamma^*}. \quad (22)$$

Combining (20)–(22) with  $u_k = \frac{L}{M} R \frac{f(\gamma^*)}{p_k}$ , we obtain

$$u_k = \frac{LR f(\gamma^*) h_k^2}{M \gamma^* \sigma^2} \Gamma, \quad (23)$$

where  $\Gamma$  is dependent on the type of receiver. In particular,

$$\Gamma^{MF} = 1 - \alpha \gamma^* \quad \text{for } \alpha < \frac{1}{\gamma^*}, \quad (24)$$

$$\Gamma^{DE} = 1 - \alpha \quad \text{for } \alpha < 1, \quad (25)$$

$$\text{and } \Gamma^{MMSE} = 1 - \alpha \frac{\gamma^*}{1 + \gamma^*} \quad \text{for } \alpha < 1 + \frac{1}{\gamma^*}. \quad (26)$$

It can be seen that  $u_k^{MMSE} \geq u_k^{DE}$  and  $u_k^{MMSE} \geq u_k^{MF}$  which confirms our earlier claim that the MMSE receiver achieves the maximum utility among all linear receivers. The

utility achieved by the decorrelator is higher than that of the matched filter except when  $\gamma^* < 1 (= 0dB)$ .

## VI. SOCIAL OPTIMUM

The solution to the power control game is Pareto optimal if there exists no other power allocation for which one or more users can improve their utilities without reduction in the utilities of the other users. It can be shown that the Nash equilibrium presented in the previous section is not Pareto optimal. This means that it is possible to improve the utility of one or more users without hurting other users. On the other hand, it can be shown that the solution to the following social problem gives the Pareto optimal frontier (see [17]):

$$\max_{p_1, \dots, p_K} \sum_{k=1}^K \beta_k u_k(p_1, \dots, p_K). \quad (27)$$

Pareto optimal solutions are in general difficult to obtain. Here, we consider the case of equal output SIRs among all users (i.e., SIR balancing). This ensures fairness among users in terms of throughput and delay. We also assume that  $\beta_1 = \dots = \beta_K = 1$ , which means we are interested in maximizing the sum of users' utilities. Therefore, the maximization in (27) can be written as

$$\max_{p_1, \dots, p_K} f(\gamma) \sum_{k=1}^K \frac{1}{p_k}. \quad (28)$$

Equal output SIRs among users is achieved with minimum power consumption when the received powers are the same for all users, i.e.,  $p_1 h_1^2 = p_2 h_2^2 = \dots = p_K h_K^2 = q$ , where

$$q^{MF}(\gamma) = \frac{\gamma \sigma^2}{1 - \alpha \gamma} \quad \text{for } \alpha < \frac{1}{\gamma}, \quad (29)$$

$$q^{DE}(\gamma) = \frac{\gamma \sigma^2}{1 - \alpha} \quad \text{for } \alpha < 1, \quad (30)$$

$$\text{and } q^{MMSE}(\gamma) = \frac{\gamma \sigma^2}{1 - \alpha \frac{\gamma}{1+\gamma}} \quad \text{for } \alpha < 1 + \frac{1}{\gamma}. \quad (31)$$

Therefore, the maximization in (28) can equivalently be expressed as

$$\max_{\gamma} \frac{f(\gamma)}{q(\gamma)} \sum_{k=1}^K h_k^2. \quad (32)$$

The solution to (32) must satisfy  $\frac{\partial}{\partial \gamma} \left( \frac{f(\gamma)}{q(\gamma)} \right) = 0$ . Using this fact, combined with (29)–(31), gives us the equations that must be satisfied by the solution to the maximization problem in (32) for the three linear receivers:

$$MF : f(\gamma) = \gamma(1 - \alpha \gamma) f'(\gamma), \quad (33)$$

$$DE : f(\gamma) = \gamma f'(\gamma), \quad (34)$$

$$\text{and } MMSE : f(\gamma) = \gamma \left[ 1 - \frac{\alpha \gamma}{(1 + \gamma)^2 - \alpha \gamma^2} \right] f'(\gamma) \quad (35)$$

It should be noted that while the maximizations in (10) and (32) look similar, there is an important difference between them. In (10), the assumption is that there is no cooperation among users. This means each user chooses its transmit power independent of other users' powers. On the other hand,

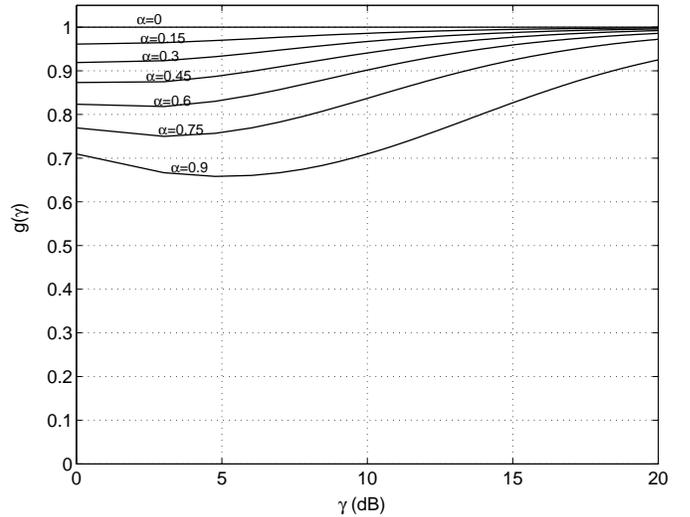


Fig. 3. Plot of  $g(\gamma) = 1 - \frac{\alpha \gamma}{(1 + \gamma)^2 - \alpha \gamma^2}$  for different values of system load.

(32) assumes that users cooperate in choosing their transmit powers. The consequence is that the relationship between the user's SIR and transmit power is different from the non-cooperative case.

We see from (33)–(35) that for the decorrelator the Pareto optimal solution is the same as the solution obtained by the non-cooperative utility-maximizing method. This is because the equilibrium transmit power of each user is independent of other users' transmit powers (see (13) and (18)). Another observation is that as shown in Fig. 3, for a large range of values of  $\alpha$ ,  $1 - \frac{\alpha \gamma}{(1 + \gamma)^2 - \alpha \gamma^2} \simeq 1$ . This means that for the MMSE receiver, the target SIR for the non-cooperative game,  $\gamma^*$ , is close to the target SIR for the Pareto-optimal solution. This will be verified in Section IX using simulation.

## VII. EXTENSIONS TO MULTI-ANTENNA SYSTEMS

We now extend the analysis presented in the previous sections to multi-antenna systems. In particular, we focus on the case of receive diversity, i.e., multiple antennas at the uplink receiver.

We assume that each user terminal has one transmit antenna and there are  $m$  receive antennas at the uplink receiver. The received signal (after chip-matched filtering and chip-rate sampling) can be represented as an  $N \times m$  matrix,  $\mathbf{R}$ , where the  $l^{th}$  column represents the  $N$  chips received at the  $l^{th}$  antenna, i.e.,

$$\mathbf{R} = \sum_{k=1}^K \sqrt{p_k} b_k \mathbf{s}_k \mathbf{h}_k^T + \mathbf{W}, \quad (36)$$

where  $p_k$ ,  $b_k$  and  $\mathbf{s}_k$  are the transmit power, transmitted bit and spreading sequence of the  $k^{th}$  user, respectively. Here,  $\mathbf{h}_k = [h_{k1} \dots h_{km}]^T$  represents the gain vector in which  $h_{k1}, \dots, h_{km}$  are the channel gains from the transmitter of the  $k^{th}$  user to the  $m$  receive antennas and are assumed to be independent and identically distributed. In the above equation,  $\mathbf{W}$  is the noise matrix. We assume that the noise is Gaussian and both spatially and temporally white.

Let  $\mathbf{C}_k$  be the  $N \times m$  coefficient matrix for the spatial-temporal filter of the  $k^{\text{th}}$  user at the base station. This filter performs linear spatial and temporal processing on the received signal. The output of this receiver can be written as

$$y_k = \text{tr}(\mathbf{C}_k^T \mathbf{R}), \quad (37)$$

where  $\text{tr}(\mathbf{A})$  is the *trace* of  $\mathbf{A}$ .

Here, following an approach similar to that in Section IV, we propose a game in which users in the network are allowed to choose their uplink linear spatial-temporal receivers as well as their transmit powers. Hence, the resulting non-cooperative game can be expressed as the following maximization problem:

$$\max_{p_k, \mathbf{C}_k} u_k(p_k, \mathbf{C}_k) \quad \text{for } k = 1, \dots, K. \quad (38)$$

This maximization can equivalently be expressed as

$$\max_{p_k, \bar{\mathbf{c}}_k} u_k(p_k, \bar{\mathbf{c}}_k) \quad \text{for } k = 1, \dots, K, \quad (39)$$

where  $\bar{\mathbf{c}}_k$  is a vector with  $mN$  elements. It is obtained by stacking the columns of  $\mathbf{C}_k$  on top of each other. To see this, notice that  $y_k$  in (37) can be alternatively written as

$$y_k = \bar{\mathbf{c}}_k^T \bar{\mathbf{r}}, \quad (40)$$

where  $\bar{\mathbf{r}}$  is a vector obtained by placing columns of  $\mathbf{R}$  on top of each other, i.e.,

$$\bar{\mathbf{r}} = \sum_{k=1}^K \sqrt{p_k} b_k \bar{\mathbf{s}}_k + \bar{\mathbf{w}}, \quad (41)$$

where  $\bar{\mathbf{s}}_k = [h_{k1} \mathbf{s}_k^T \dots h_{km} \mathbf{s}_k^T]^T$  is the *effective signature* and  $\bar{\mathbf{w}}$  is the noise vector consisting of columns of  $\mathbf{W}$  stacked on top of each other.

The game expressed in (39) is very similar to the one in (7). As a result, all of our analysis for the single antenna case can be carried over to the multi-antenna scenario. Hence, we skip the analysis and state the main results:

- The MMSE receiver, whose coefficients are given by

$$\bar{\mathbf{c}}_k = \frac{\sqrt{p_k}}{1 + p_k (\bar{\mathbf{s}}_k^T \bar{\mathbf{A}}_k^{-1} \bar{\mathbf{s}}_k)} \bar{\mathbf{A}}_k^{-1} \bar{\mathbf{s}}_k, \quad (42)$$

achieves the maximum utility among all linear receivers.

Here,  $\bar{\mathbf{A}}_k = \sum_{j \neq k} p_j \bar{\mathbf{s}}_j \bar{\mathbf{s}}_j^T + \sigma^2 \mathbf{I}$ .

- Given the MMSE receiver coefficients, maximizing the utility function for each user is again equivalent to finding the solution  $\gamma^*$  to  $f(\gamma) = \gamma f'(\gamma)$ .
- Nash equilibrium is reached when all user terminals use the MMSE detector for their uplink receivers and transmit at a power level that results in an SIR equal to  $\gamma^*$  (SIR-balancing). This equilibrium is unique.

We now fix the receiver type and allow users to choose their transmit powers only, as we did in Section V. We again focus on the matched filter, the decorrelator and the MMSE detector. We discuss the resulting Nash equilibria for these three receivers and compare their performance using a large-system analysis.

The matched filter is assumed to have perfect knowledge of the channel gains of the desired user but knows only the statistics of the fading levels of the interferers. It basically

performs despreading at each receive antenna and then applies maximal ratio combining (MRC). The decorrelating detector is assumed to have perfect knowledge of the channel gains for the desired user but no knowledge about the interferers (except for their spreading sequences). It applies a decorrelator at each receive antenna and then performs maximal ratio combining. The MMSE detector is assumed to have perfect knowledge of the channel gains of all users. The filter coefficients for the MMSE receiver are given by (42).

It is straightforward to show that for all three receivers, we have

$$\frac{\partial \gamma_k}{\partial p_k} = \frac{\gamma_k}{p_k}. \quad (43)$$

Therefore, maximizing the utility function for each user is again equivalent to finding  $\gamma^*$  that is the solution to  $f(\gamma) = \gamma f'(\gamma)$ . Using a large-system analysis similar to the one presented in Section V, the achieved utility for user  $k$  can be expressed as

$$u_k = \frac{LRf(\gamma^*) \bar{h}_k^2}{M \gamma^* \sigma^2} \bar{\Gamma}, \quad (44)$$

where  $\bar{\Gamma}$  depends on the receiver:

$$\bar{\Gamma}^{MF} = 1 - \bar{\alpha} \gamma^* \quad \text{for } \bar{\alpha} < \frac{1}{\gamma^*}, \quad (45)$$

$$\bar{\Gamma}^{DE} = 1 - \alpha \quad \text{for } \alpha < 1, \quad (46)$$

$$\text{and } \bar{\Gamma}^{MMSE} = 1 - \bar{\alpha} \frac{\gamma^*}{1 + \gamma^*} \quad \text{for } \bar{\alpha} < 1 + \frac{1}{\gamma^*}, \quad (47)$$

with  $\bar{\alpha} = \frac{\alpha}{m}$  and  $\bar{h}_k^2 = \sum_{l=1}^m h_{kl}^2$ . It is observed that for the case of the matched filter and the MMSE detector, using more antennas at the receiver provides both power pooling (through  $\bar{h}_k$ ) and interference reduction (through  $\bar{\alpha}$ ). This means that the system behaves like a single-antenna system with processing gain  $mN$  and received power equal to the sum of the received powers at the individual antennas. The decorrelator, on the other hand, benefits only from power pooling and there is no pooling of the degrees of freedom. This is because the decorrelating detector has no knowledge about the channel gains for the interferers. Therefore, each interferer effectively occupies  $m$  degrees of freedom [25].

## VIII. UTILITY-MAXIMIZING ADMISSION CONTROL

We have used a large-system analysis to derive explicit expressions for the utilities achieved at Nash equilibrium for the matched filter, the decorrelator, and the MMSE detector. We now pose admission control as a maximization problem in which the load in the network (i.e.,  $\alpha$ ) is chosen such that the total utility in the network (per degree of freedom) is maximized:

$$\alpha^* = \arg \max_{\alpha} \frac{1}{N} \sum_{k=1}^K u_k. \quad (48)$$

Given (23), as  $K, N \rightarrow \infty$ , we can use the law of large numbers to write

$$\alpha^* = \arg \max_{\alpha} \alpha \frac{LRf(\gamma^*)}{M \gamma^* \sigma^2} \Gamma \mathbb{E}\{h^2\}, \quad (49)$$

or equivalently

$$\alpha^* = \arg \max_{\alpha} \alpha \Gamma. \quad (50)$$

To find  $\alpha^*$ , we set  $\frac{\partial}{\partial \alpha}(\alpha \Gamma) = 0$  and solve for  $\alpha$ . It is easy to show that  $\alpha^*$  is the solution to  $\Gamma = \frac{1}{2}$ . This is also true for the Pareto-optimal solution discussed in Section VI. Given (24)–(26), we have

$$\alpha_{MF}^* = \frac{1}{2\gamma^*}, \quad (51)$$

$$\alpha_{DE}^* = \frac{1}{2}, \quad (52)$$

$$\text{and } \alpha_{MMSE}^* = \frac{1}{2} + \frac{1}{2\gamma^*}. \quad (53)$$

Following an argument similar to that above, it can be shown that for the case of multiple receive antennas, the total utility per degree of freedom is maximized when  $\alpha$  is chosen to be the solution to  $\bar{\Gamma} = \frac{1}{2}$ . Notice that using this utility-maximizing admission control scheme, the number of admitted users for the MMSE receiver is greater than or equal to the total number of admitted users for the matched filter and decorrelator combined (depending on the number of antennas employed at the uplink receiver).

## IX. NUMERICAL RESULTS

In this section, we present numerical results for the analysis presented in the previous sections. We consider the uplink of a DS-CDMA system. We assume that each packet contains 100 bits of information and no overhead (i.e.,  $L = M = 100$ ). The transmission rate,  $R$ , is 100Kbps and the thermal noise power,  $\sigma^2$ , is  $5 \times 10^{-16}$  Watts. The processing gain is 100 to satisfy the large system assumption. A useful example for the efficiency function is  $f(\gamma) = (1 - e^{-\gamma})^M$ . This serves as an approximation to the PSR that is very reasonable for moderate to large values of  $M$ . We use this efficiency for our simulations. Using this, with  $M = 100$ , the solution to (16) is  $\gamma^* = 6.48 = 8.1$  dB.

We first look at the case of one receive antenna. The channel gains are assumed to have the Rayleigh distribution with mean equal to  $\frac{0.3}{d^2}$ , where  $d$  is the distance of the user from the uplink receiver. Fig. 4 shows the average utility of a user as a function of the system load for the matched filter, decorrelator and MMSE receivers. The user is assumed to be 100 meters away from the uplink receiver. The averaging is done over 5000 channel realizations. The solid and dashed lines correspond to the non-cooperative and Pareto-optimal solutions, respectively. It is seen from the figure that the utility improves considerably when the matched filter is replaced by a multiuser detector. Also, the system capacity (i.e., the maximum number of users that can be accommodated by the system) is larger for the multiuser receivers as compared with the matched filter. As expected, the MMSE receiver achieves the highest utility. While the difference between the non-cooperative approach and the Pareto-optimal solution is significant for the matched filter, the solutions are identical for the decorrelator and are quite close to each other for the MMSE receiver. It is seen that for the matched filter, as the system load increases, the gap between the non-cooperative and Pareto-optimal solutions

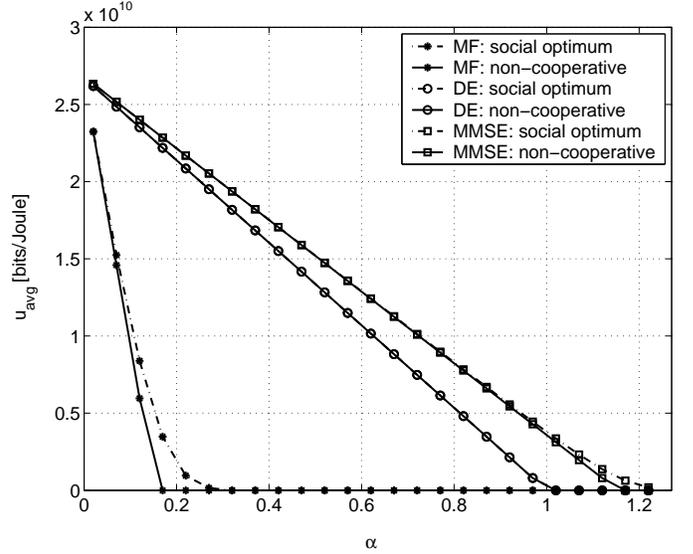


Fig. 4. Average utility vs load for the matched filter (MF), the decorrelator (DE), and the MMSE receiver (single receive antenna).

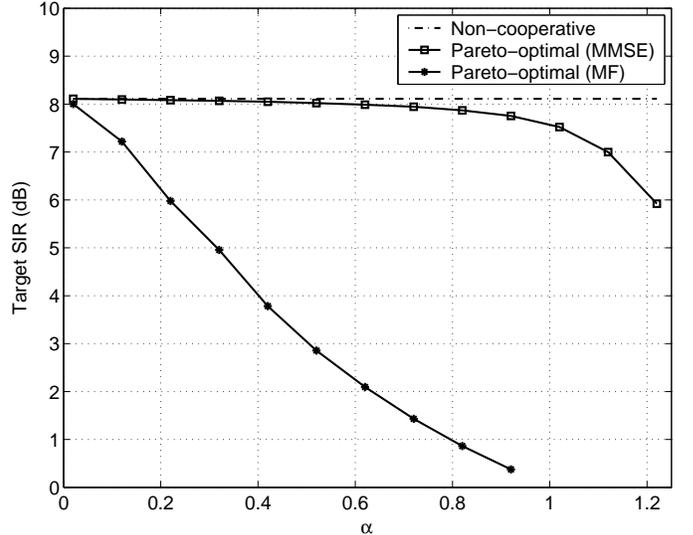


Fig. 5. Comparison of the target SIRs for the non-cooperative and Pareto-optimal solutions.

becomes larger. This is also true for the MMSE receiver (although much less noticeably). Fig. 5 compares the target SIR of the non-cooperative solutions with the target SIRs of the Pareto-optimal solutions for the matched filter and the MMSE detector. It is seen that for the MMSE receiver, the target SIR for the Pareto-optimal solution is very close to the target SIR for the non-cooperative approach.

Fig. 6 shows the average utility as a function of the system load for one and two receive antennas. The user is 100 meters away from the uplink receiver and the channel gains are assumed to be i.i.d. with a Rayleigh distribution having a mean equal to  $\frac{0.3}{d^2}$ . The averaging is done over 5000 realizations of the channel gains. For each realization, we use (44) to calculate the user's utility. The figure shows the achieved utilities for the matched filter, the decorrelator and the MMSE

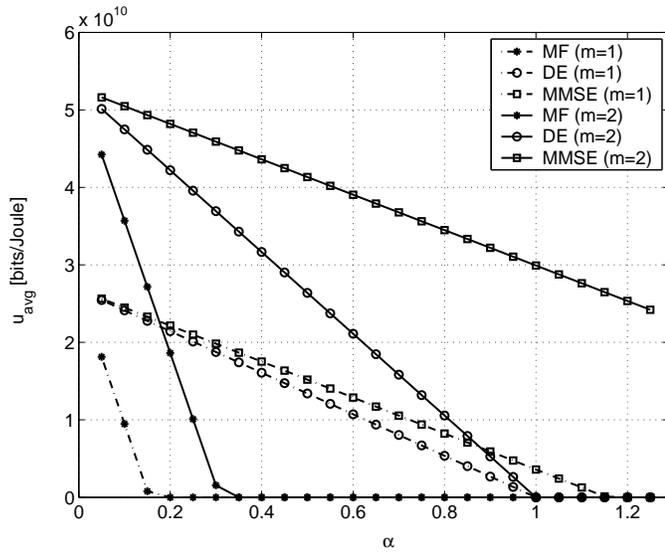


Fig. 6. Average utility vs load for the matched filter (MF), the decorrelator (DE), and the MMSE receiver with one and two receive antennas.

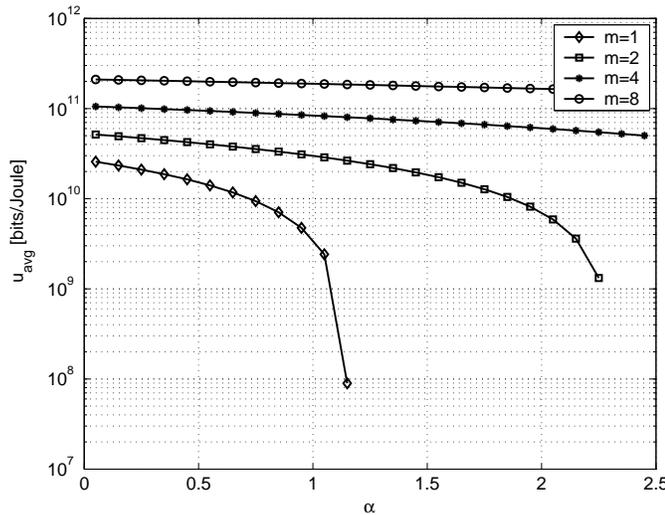


Fig. 7. Average utility vs load for the MMSE receiver with  $m$  receive antennas.

receiver. The dashed lines correspond to  $m = 1$  (single receive antenna) and the solid lines represent the case of  $m = 2$  (two receive antennas). Significant improvements in user utility and system capacity are observed when two receive antennas are used compared to the single antenna case. As expected, the improvement is more significant for the matched filter and the MMSE receiver as compared with the decorrelating detector. This is because the matched filter and the MMSE receiver benefit from both power pooling and interference reduction whereas the decorrelating detector benefits only from power pooling. Fig. 7 shows the average utility versus system load for the MMSE receiver for the cases of one, two, four and eight receive antennas. It is seen that adding more antennas at the uplink receiver results in considerable gains in the achieved utility as well as system capacity.

We now look at the utility-maximizing admission control.

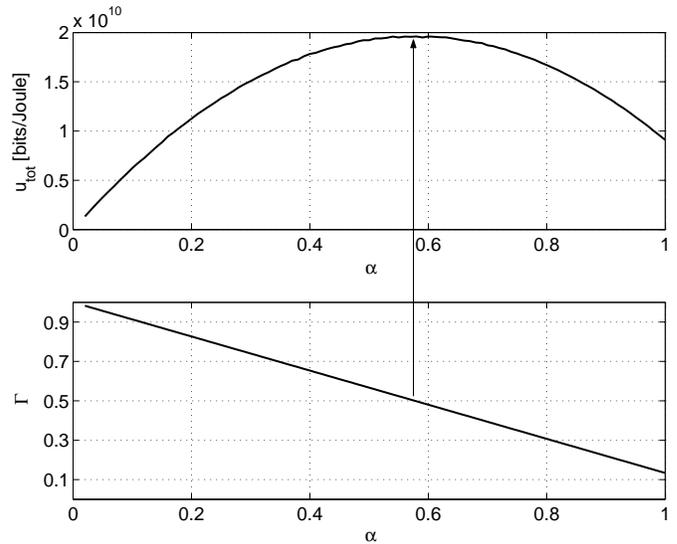


Fig. 8. Plots of total utility and  $\Gamma$  vs load for the MMSE receiver (single receive antenna).

We consider the MMSE receiver and plot the total utility as a function of system load. For each value of  $\alpha$ , we distribute the users in the cell and calculate each user's utility according to (23). We then calculate the total utility and repeat this over 10 000 realizations of the users' locations. Fig. 8 shows the plot of average total utility versus system load. We have also plotted  $\Gamma$  as a function of  $\alpha$ . As expected, the total utility is maximized when  $\Gamma = \frac{1}{2}$ . This corresponds to a system load of 58%.

### X. CONCLUSIONS

In this work, we have examined the cross-layer design problem of joint multiuser detection and power control in the uplink of CDMA systems using a game-theoretic approach. A non-cooperative game is proposed in which users are allowed to choose not only their transmit powers but also their uplink receivers to maximize their utilities. Focusing on linear receivers, we have shown that there is a unique Nash equilibrium for the proposed game. The equilibrium is achieved when all users pick the MMSE detector as their uplink receivers and choose their transmit powers such that their output SIRs are all equal to  $\gamma^*$ . We have further shown that the Nash equilibrium remains an SIR-balancing solution when we replace the MMSE receiver with a matched filter or a decorrelating detector (or any other linear receiver). The target SIR is affected by the modulation as well as the packet size but is independent of the receiver. However, the utilities achieved at equilibria do depend on the receiver. Using a large-system analysis, we have obtained explicit expressions for the utilities achieved at equilibrium by the matched filter, the decorrelator and the MMSE detector, and compared their performance in terms of number of bits transmitted per joule of energy consumed. Significant improvements in achieved utilities and system capacity have been observed when multiuser detectors are used in place of the conventional matched filter. We have also discussed the optimum cooperative solution and

compared its performance with that of the non-cooperative approach. It has been shown that the difference in performance is not significant especially for the decorrelator and the MMSE receiver.

We have also extended our approach to systems with multiple receive antennas. Conclusions similar to those for the single antenna case have been made. We have shown that considerable gains in achieved utilities and system capacity are obtained when multiple antennas are employed at the uplink receiver. These gains, which are due to power pooling and interference reduction, are quantified in terms of number of bits transmitted per joule of energy. A utility-maximizing admission control scheme has also been proposed. We have shown that using the proposed scheme, the total number of admitted users for the MMSE receiver is greater than or equal to the total number of admitted users for the matched filter and decorrelator, depending on the number of receive antennas. This work has provided a unified game-theoretic formulation for studying power control and receiver design in DS-CDMA networks.

#### REFERENCES

- [1] A. B. MacKenzie and S. B. Wicker, "Game theory in communications: Motivation, explanation, and application to power control," *Proceedings to the IEEE Global Telecommunications Conference*, pp. 821–826, San Antonio, TX, USA, 2001.
- [2] D. J. Goodman and N. B. Mandayam, "Power control for wireless data," *IEEE Personal Communications*, vol. 7, pp. 48–54, April 2000.
- [3] H. Ji and C.-Y. Huang, "Non-cooperative uplink power control in cellular radio systems," *Wireless Networks*, vol. 4, pp. 233–240, April 1998.
- [4] D. J. Goodman and N. B. Mandayam, "Network assisted power control for wireless data," *Proceedings of the IEEE Vehicular Technology Conference (VTC)*, pp. 1022–1026, Rhodes, Greece, Spring 2001.
- [5] C. U. Saraydar, N. B. Mandayam, and D. J. Goodman, "Pricing and power control in a multicell wireless data network," *IEEE Journal on Selected Areas in Communications*, vol. 19, pp. 1883–1892, October 2001.
- [6] C. U. Saraydar, N. B. Mandayam, and D. J. Goodman, "Efficient power control via pricing in wireless data networks," *IEEE Transactions on Communications*, vol. 50, pp. 291–303, February 2002.
- [7] M. Xiao, N. B. Shroff, and E. K. P. Chong, "Utility-based power control in cellular wireless systems," *Proceedings of the Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM)*, pp. 412–421, Alaska, USA 2001.
- [8] C. Zhou, M. L. Honig, and S. Jordan, "Two-cell power allocation for wireless data based on pricing," *Proceedings of the 39<sup>th</sup> Annual Allerton Conference on Communication, Control, and Computing*, Monticello, IL, USA, October 2001.
- [9] T. Alpcan, T. Basar, R. Srikant, and E. Altman, "CDMA uplink power control as a noncooperative game," *Proceedings of the 40<sup>th</sup> IEEE Conference on Decision and Control*, pp. 197–202, Orlando, FL, USA, December 2001.
- [10] C. W. Sung and W. S. Wong, "A noncooperative power control game for multirate CDMA data networks," *IEEE Transactions on Wireless Communications*, vol. 2, pp. 186–194, January 2003.
- [11] N. Feng, S.-C. Mau, and N. B. Mandayam, "Pricing and power control for joint network-centric and user-centric radio resource management," *IEEE Transactions on Communications*, vol. 52, pp. 1547–1557, September 2004.
- [12] F. Meshkati, M. Chiang, S. C. Schwartz, H. V. Poor, and N. B. Mandayam, "A non-cooperative power control game for multi-carrier CDMA systems," *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 606–611, New Orleans, LA, USA, March 2005.
- [13] R. Lupas and S. Verdú, "Linear multiuser detectors for synchronous code-division multiple access channels," *IEEE Transactions on Information Theory*, vol. 35, pp. 123–136, January 1989.
- [14] U. Madhow and M. L. Honig, "MMSE interference suppression for direct-sequence spread-spectrum CDMA," *IEEE Transactions on Communications*, vol. 42, pp. 3178–3188, December 1994.
- [15] F. Meshkati, D. Guo, H. V. Poor, S. C. Schwartz, and N. B. Mandayam, "A unified approach to power control for multiuser detectors," *Proceedings of the 2<sup>nd</sup> Workshop on Signal Processing for Wireless Communications*, King's College, London, UK, June 2004.
- [16] V. Rodriguez, "Robust modeling and analysis for wireless data resource management," *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 717–722, New Orleans, LA, USA, March 2003.
- [17] C. U. Saraydar, *Pricing and Power Control in Wireless Data Networks*. PhD thesis, Department of Electrical and Computer Engineering, Rutgers University, Piscataway, NJ, 2001.
- [18] D. Fudenberg and J. Tirole, *Game Theory*. MIT Press, Cambridge, MA, 1991.
- [19] X. Wang and H. V. Poor, *Wireless Communication Systems: Advanced Techniques for Signal Reception*. Prentice-Hall, Upper Saddle River, NJ, 2004.
- [20] V. Rodriguez, "An analytical foundation for resource management in wireless communication," *Proceedings of the IEEE Global Telecommunications Conference (Globecom)*, pp. 898–902, San Francisco, CA, USA, December 2003.
- [21] R. D. Yates, "A framework for uplink power control in cellular radio systems," *IEEE Journal on Selected Areas in Communications*, vol. 13, pp. 1341–1347, September 1995.
- [22] M. B. Pursley, "Performance evaluation for phase-coded spread-spectrum multiple-access communication - Part I: System analysis," *IEEE Transactions on Communications*, vol. 25, pp. 795–799, August 1977.
- [23] H. V. Poor and S. Verdú, "Probability of error in MMSE multiuser detection," *IEEE Transactions on Information Theory*, vol. 43, pp. 858–871, May 1997.
- [24] D. N. C. Tse and S. V. Hanly, "Linear multiuser receivers: Effective interference, effective bandwidth and user capacity," *IEEE Transactions on Information Theory*, vol. 45, pp. 641–657, March 1999.
- [25] S. V. Hanly and D. N. C. Tse, "Resource pooling and effective bandwidths in CDMA networks with multiuser receivers and spatial diversity," *IEEE Transactions on Information Theory*, vol. 47, pp. 1328–1351, May 2001.

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