INTERFERENCE CANCELLATION USING ANTENNA ARRAYS *

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ABSTRACT

A limiting factor for the performance of the conventional CDMA receiver is the near-far effect. Practical CDMA systems use power control to overcome this problem, which requires additional circuitry at the mobile. On the other hand, optimal and suboptimal multiuser detectors have been proposed which are shown to be near-far resistant, and thus increase the capacity of the system significantly. The major drawback of these detectors is their computational complexity which makes them less attractive for implementation. This paper describes a simple detector which is a spatio-temporal interference canceller. The receiver employs an array of M antennas, which allows it to discriminate between the users based on their spatial diversity. The received signal goes through a bank of K beamformers, each matched to one user, followed by a bank of matched filters. The K outputs are compared to rank the users in the order of their strength. Multiple access interference from each user is cancelled successively from the received signal based on this order. This detector is compared with a single antenna interference canceller and also the conventional detector and it is shown that using multiple antennas improves the performance of the interference canceller and compensates for nonzero crosscorrelations between the users' signature waveforms.

1. INTRODUCTION

Dramatic changes in the nature of mobile communications in the recent years have prompted the search for a new system with increased capacity. One of the techniques which has received considerable attention is CDMA, which is believed to offer greater improvement over other proposed schemes. The conventional (matched filter) CDMA receiver is susceptible to the *near-far effect*. This is mainly because of nonzero crosscorrelation between the set of signature waveforms (due to bandwidth limitations and different delays), which prevent the matched filters from effectively nulling the interference terms. A commercial CDMA cellular system uses strict power control to get around the near-far problem; the mobiles adjust their transmitted power, so that the received power at the base station is the same for all users [1]. An alternative to the conventional CDMA receiver, which is an optimum single user demodulator, is a multiuser detector. Optimum and different suboptimum multiuser detectors have been proposed in the literature [2]-[5]. Although these detectors show significant performance improvement over the conventional detector, this is achieved at the price of excessive computational complexity. Most of these receivers attempt to detect all the users simultaneously, and therefore employ a parallel structure, which contributes to the complexity of the scheme. An alternative would be to use a serial scheme, where only one user is detected at each stage. Successive cancellation techniques discussed in [6]-[8] are of the latter type. The scheme used in [6], which assumes no knowledge of the users' energies shows improvement over the conventional receiver, while maintaining relative simplicity. In this method, after the received signal goes through a bank of matched filters, the strongest user is detected by comparing the correlators' outputs, and is subtracted from the received signal after being encoded again with its signature sequence. This process is repeated until the weakest user is decoded.

In this paper, we address the extension of the interference cancellation scheme described in [6] to a system with multiple antennas at its receiver. Employing multiple antennas enables the system to make use of the spatial diversity among different users. This receiver can now discriminate between the users not only by their temporal signature waveforms, but also by their *spatial signatures*. Application of antenna arrays in CDMA communication systems was discussed in [9]-[11]. In [8], an adaptive antenna array system combined with a parallel canceller of interference was proposed. In that system, only one set of weights was used to form a beam towards the desired user. In the system proposed in this paper, each user is matched both in spatial and temporal domains at the receiver and this provides a better estimate of the transmitted data by each user, and thus a better cancellation of the multiple access interference.

The remainder of the paper is organized as follows. Section 2. gives a description of the signal model. In Section 3., we explain the combined spatio-temporal interference canceller and analyze the performance of this system. Simulations and results are described in Section 4., with a comparison between this system and the single antenna interference canceller. The conclusion is given in Section 5..

2. SIGNAL MODEL

Consider a synchronous CDMA system, where K users transmit simultaneously over a passband channel. The channel bandwidth is assumed to be large enough, so that intersymbol interference can be ignored. The receiver consists of an antenna with M elements. The received signals are narrowband, i.e. the demodulated outputs of the array are the same except for a complex gain. Assuming the knowledge of phase of the received signal at each antenna element (i.e. coherent demodulation), the lowpass equivalent of the received signal can be modelled as :

$$\mathbf{r}(t) = \sum_{k=1}^{K} \mathbf{a}_k e_k c_k(t) b_k(t) + \mathbf{n}(t) \tag{1}$$

where

$$\mathbf{r}(t) = [r_1(t) \cdots r_M(t)]^T$$

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is the vector of the received signals,

$$\mathbf{a}_k = [a_{1k} \cdots a_{Mk}]^T$$

is the array response vector for user k, with a_{mk} being the complex gain from user k to the m^{th} antenna element; e_k^2 is the energy of the k^{th} user which is assumed to be unknown to the receiver; $c_k(t)$ is the normalized signature waveform for the k^{th} user ($\int_0^T c_k(t)^2 dt = 1$), which is restricted to a symbol interval of duration T; $b_k \in \{-1, +1\}$ is the transmitted bit by user k and $\mathbf{n}(t)$ is the vector of the additive white Gaussian noise at the antenna elements which are assumed to be independent, i.e. $E\{\mathbf{n}(t)\mathbf{n}^H(t)\} = \sigma^2 \mathbf{I}$.

The optimum demodulator for user l computes the following decision variable:

$$\begin{aligned} Z_l &= \text{Re}\left\{ \int_0^T \frac{\mathbf{a}_l^H}{||\mathbf{a}_l||} \mathbf{r}(t) c_l(t) dt \right\} \\ &= ||\mathbf{a}_l|| e_l b_l + \sum_{\substack{k=1 \\ k \neq l}}^{K} \rho_{kl}^c \rho_{kl}^a \, ||\mathbf{a}_k|| \, e_k b_k + n_l' \qquad (2) \end{aligned}$$

where

$$\rho_{kl}^c = \int_0^T c_l(t) c_k(t) dt$$

is the cross-correlation between the signature waveforms, and

$$\rho_{kl}^a = \frac{\text{Re}[\mathbf{a}_l^H \mathbf{a}_k]}{||\mathbf{a}_k|| \, ||\mathbf{a}_l||}$$

is the correlation between the array response vectors of users l and k and n_l' is a zero mean Gaussian random variable with variance $\frac{\sigma^2}{2}$. To perform matched filtering, we assume the array response vectors are known to the receiver, but in reality only estimates are available. It can be shown that the set of $\{Z_l; l = 1, \cdots, K\}$ form a set of sufficient statistics for the detection of the corresponding transmitted bits.

3. INTERFERENCE CANCELLATION FOR MULTIELEMENT RECEIVERS

In this section, we develop a simple demodulation scheme which employs successive interference cancellation, while exploiting the spatial diversity among the users. The block diagram of the first stage of such a system is shown in Fig. 1. The idea is to detect the strongest user and cancel the interference caused by this user from the received signal. The strongest user is obtained by comparing the decision variables for all K users. These correlation values are also used to find the order of cancellation for the different users. The detected bit is respread with the user's signature waveform and multiplied by its array response vector, and the result is subtracted from the received signal vector. The same procedure is repeated K times until all the users are detected. For the case of $M = 1$, the system reduces to the one proposed in [6].

Without loss of generality, we assume that the users are ordered by the strength of their received amplitude, with user 1 being the strongest. The decision variable for user 1 is:

$$Z_1 = ||\mathbf{a}_1|| \, e_1 b_1 + I_1 \qquad (3)$$

where

$$I_1 = \sum_{k=2}^{K} \rho_{1k}^c \rho_{1k}^a \, ||\mathbf{a}_k|| \, e_k b_k + n_1'$$

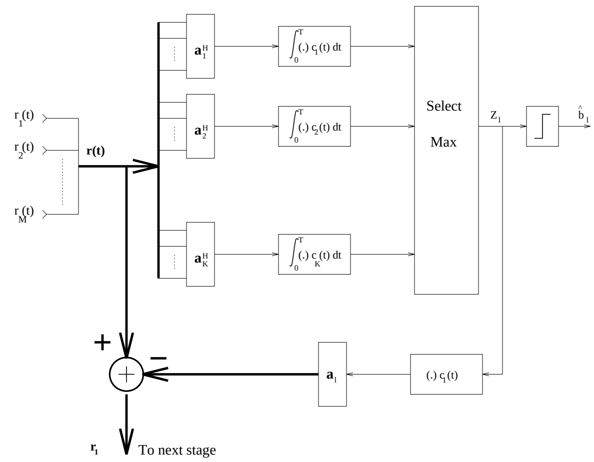

Figure 1: Block diagram of a Multielement interference canceller

Cancelling the effect of user 1, we get

$$\mathbf{r}_1 = \mathbf{r} - Z_1 \frac{\mathbf{a}_1}{||\mathbf{a}_1||} c_1 = \sum_{k=2}^{K} \mathbf{a}_k e_k c_k b_k + \mathbf{n} - I_1 \frac{\mathbf{a}_1}{||\mathbf{a}_1||} c_1 \qquad (4)$$

For the second strongest user, the same procedure is repeated. Now, $\mathbf{r}_1$ is used to compute the decision variable,

$$Z_2 = ||\mathbf{a}_2|| \, e_2 b_2 + I_2 \qquad (5)$$

where

$$I_2 = \sum_{k=3}^{K} \rho_{2k}^c \rho_{2k}^a \, ||\mathbf{a}_k|| \, e_k b_k + n_2' - I_1 \rho_{12}^c \rho_{12}^a$$

Similarly, for the $(j-1)^{th}$ cancellation,

$$\mathbf{r}_j = \mathbf{r}_{j-1} - Z_j \frac{\mathbf{a}_j}{||\mathbf{a}_j||} c_j \qquad (6)$$

and Z_j is given by

$$Z_j = ||\mathbf{a}_j|| \, e_j b_j + I_j$$

where

$$I_j = \sum_{k=j+1}^{K} \rho_{jk}^c \rho_{jk}^a \, ||\mathbf{a}_k|| \, e_k b_k + n_j' - \sum_{i=1}^{j-1} I_i \rho_{ij}^c \rho_{ij}^a$$

It can be seen that while at each stage the multiple access interference from the strongest user is cancelled, a residual term is added to the total interference in that stage. This is due to nonzero correlations between the signature waveforms as well as array response vectors. It will be shown later that this term is very small compared to the remaining multiple access interference. The transmitted bit by the j^{th} user is detected using the decision variable in (2),

$$\hat{b}_j = \text{sgn}(Z_j) \qquad (7)$$

The variance of the interference term I_j, conditioned on e_k, is

$$\begin{aligned} \eta_j &= Var[I_j | e_k] = \sum_{k=j+1}^{K} e_k^2 \, ||\mathbf{a}_k||^2 \; Var[\rho_{jk}^c \rho_{jk}^a] \\ &\quad + Var[n_j'] + \sum_{i=1}^{j-1} \eta_i \, Var[\rho_{ij}^c \rho_{ij}^a] \qquad (8) \end{aligned}$$

For a spreading gain of $N \gg 1$, it is straightforward to show that ρ_{ij}^c is zero mean and

$$Var[\rho_{ij}^c] = \frac{1}{N} \tag{9}$$

To analyze the spatial correlation ρ_{ij}^a, a model must be adopted for the array response vectors. We assume that the propagation between the transmitters and the receiver antenna is plane wave, and that the users are uniformly distributed around the receiver. This is true for the situations where the scatterers are distant enough from the receiver so that the reflected waves are contained in a narrow range of directions [12]. For a linear array, the array response vector is modelled as:

$$\mathbf{a}_k = [1 \; e^{-j\phi_k} \; e^{-j2\phi_k} \; \cdots e^{-j(M-1)\phi_k}]^T$$

where $\phi_k = \frac{2\pi d \sin\theta_k}{\lambda}$, θ_k is the angle of arrival for user k, d is the spacing between the elements and λ is the wavelength. For this model $||\mathbf{a}_k|| = \sqrt{M}$, and defining $\omega = \frac{2\pi d}{\lambda}$, we derive the following expressions for the mean and variance of ρ_{ij}^a :

$$E\{\rho_{ij}^a\} = \frac{1}{M}\sum_{k=0}^{M-1} J_0^2(\omega k) \tag{10}$$

$$Var\{\rho_{ij}^a\} = \frac{1}{M^2}\sum_{k=0}^{M-1}\sum_{l=0}^{M-1}\Big[\frac{1}{2}\big(J_0^2(\omega(k+l)) + J_0^2(\omega(k-l))\big) - J_0^2(\omega k)J_0^2(\omega l)\Big] \tag{11}$$

where J_0 is the zeroth order Bessel function of the first kind. Using (9)-(11),

$$Var\left[\rho_{ij}^c\rho_{ij}^a\right] = \frac{1}{NM^2}\sum_{k=0}^{M-1}\sum_{l=0}^{M-1}\Big[\frac{1}{2}\big(J_0^2(\omega(k+l)) + J_0^2(\omega(k-l))\big)\Big] = \frac{1}{N}E[(\rho_{ij}^a)^2] \tag{12}$$

For simplicity we define

$$v(M) = E[(\rho_{ij}^a)^2]$$

So, η_j can be written as:

$$\eta_j = \frac{M}{N}v(M)\sum_{k=j+1}^{K} e_k^2 + \sigma^2 + \frac{1}{N}v(M)\sum_{i=1}^{j-1}\eta_i \tag{13}$$

and the signal-to-noise ratio is given by:

$$\gamma_j = \frac{Me_j^2}{\eta_j} \tag{14}$$

Assuming Gaussian distribution, the Probability of error can be calculated as:

$$\mathcal{P}_e^j = Q(\sqrt{\gamma_j}) \tag{15}$$

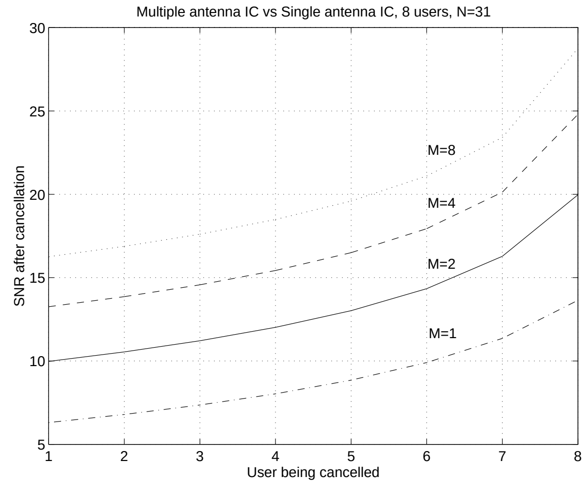

Figure 2: SNR of each user after cancellation, for $M = 1, 2, 4$ and 8 antennas

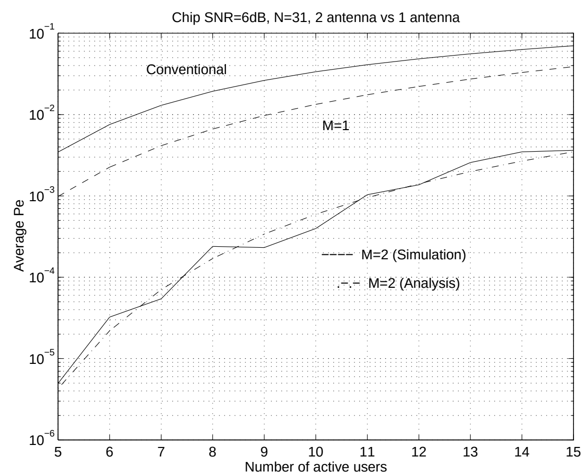

Figure 3: Average probability of error vs number of users

4. SIMULATIONS AND RESULTS

In Fig. 2, using (14), we compare the signal-to-noise ratio of each user after cancellation, for systems with $M = 1, 2, 4$ and 8 antennas. As can be seen, at each stage of cancellation, the signal-to-noise ratio becomes larger as the number of antennas are increased. In this case, there are 8 users under ideal power control. The chip SNR is 6 dB and the spreading gain is $N = 31$.

In Fig. 3, the average probability of error is shown as a function of number of active users. The probability of error for the conventional detector is also shown for comparison. We can see that the probability of error decreases substantially as one antenna is added to the original successive interference canceller. We have also performed simulations of the multiple antenna system to compare with the analysis. Fig. 3 shows the simulation results match well with the theoretical results. Results in Fig. 3 are also for a system with ideal power control. Next we consider a worst case scenario, where all the users have the same energy except one, which is weaker than the others. Fig. 4 shows the probability of error for the weak user as a function of its signal-to-noise ratio. Again a multiple antenna interference canceller is compared with a single antenna system and the

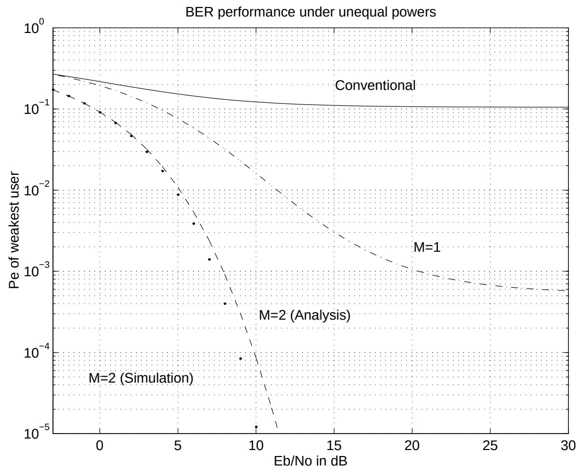

Figure 4: Average probability of error vs signal-to-noise ratio of the weak user

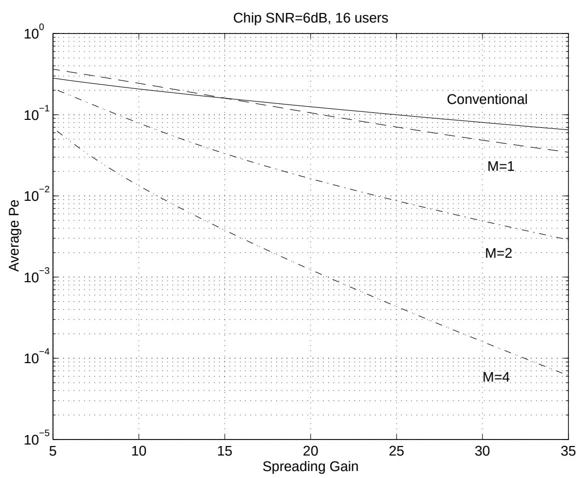

Figure 5: Probability of error vs processing gain

conventional detector. The power of the weak user is 4.5 dB less than the other users and $N = 31$. Simulation results are also shown.

Fig. 5 shows the probability of error as a function of processing gain of the CDMA system, with M the variable parameter. It is known that for a system with bandwidth B, the maximum number of orthogonal waveforms that can be transmitted simultaneously and are time limited to T is equal to $2BT$ [13], and by allowing some crosscorrelation between the signature waveforms, the number of now *non*-orthogonal waveforms can be increased. So increasing the processing gain in a system with constant bandwidth will limit the maximum number of users, and to accommodate larger number of users, the processing gain has to be reduced, which aggravates the near-far problem. From Fig. 5, we can see that as the processing gain is reduced, the performance of the single antenna interference canceller drops and even becomes worse than the conventional detector. The multiple antenna interference canceller is more immune to this problem, because it tries to spatially decorrelate the signals received from different users and compensate for the poor characteristic of the temporal correlation.

5. CONCLUSION

In this paper we proposed a simple detector for a synchronous multiuser CDMA system. The detector is an interference canceller that exploits the spatial diversity of the users to decrease the crosscorrelation between the users by employing multiple antennas at the receiver. It is shown that the performance of this system is better than a single antenna interference canceller. Also we show that this detector can make use of the spatial distribution of the mobile users to overcome the large crosscorrelation between the signature waveforms of different users, when the bandwidth is limited or the number of users exceeds a certain limit.

This system requires knowledge of the array response vectors. Since this may not be fully practical, this work is currently being extended to a noncoherent demodulation where the information about the phase of the received signal is not available. Further work will consider asynchronous systems, and will also include the effects of multipath fading.

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