A CDMA INTERFERENCE CANCELLING RECEIVER WITH AN ADAPTIVE BLIND ARRAY *

Vafa Ghazi-Moghadam *Mostafa Kaveh*

Department of Electrical Engineering, University of Minnesota Minneapolis, MN 55455

ABSTRACT

Interference cancelling receivers have been suggested as low complexity receivers for CDMA systems. A multi-element interference cancelling receiver was proposed in [4], and it was demonstrated that using spatial information about the users will improve the performance of the receiver. In this paper, an adaptive multi-element interference canceller is formulated, and it is shown that without requiring any additional information, the receiver can spatially discriminate between the users and improve the error performance.

1. INTRODUCTION

A major limiting factor for the performance of the conventional CDMA receiver is the *near-far effect*. Existing standard(IS-95) calls for power control to overcome this problem. Although approximate power control has important advantages, the fine control necessary to combat the near-far effect degrades the performance of stronger users, thereby limiting the overall system performance. Optimal and suboptimal *multiuser* detectors for CDMA systems have been suggested for CDMA systems which, depending on their level of complexity, provide full or partial immunity to the near-far effect. These detectors take advantage of the known structure of multiuser interference, and thus improve the receiver performance significantly, without requiring stringent power control.

For a system with limited bandwidth, as the number of users grow, it becomes necessary to assign signature waveforms which have relatively large correlations. This motivates the use of multiple antennas at the receiver to provide increased discrimination between the users. Using the spatial samples of received signals, the users can now be matched in both temporal and spatial domains. In addition, antenna arrays can be used to filter out the interfering users that are spatially separated from the desired user, thereby reducing the amount of interference seen by the desired user.

The optimum performance by a multiple antenna receiver is achieved, when the array response vectors of all the users are available. Due to the dynamic nature of cellular communications and severe fading conditions, the array response vectors vary rapidly, making it impossible for the receiver to know their exact value at a given time. Therefore, it is desirable for a multiple antenna receiver to be able to track and follow the array response vectors in an adaptive fashion. Most of the reported beamforming algorithms require either a training sequence or the knowledge of array response vector of the desired user to calculate the optimum beamformer. In a CDMA environment, the knowledge of the desired user's signature sequence can be exploited to design a *blind* adaptive antenna array receiver, where no training sequence needs to be transmitted [1]. A multiuser detector with blind adaptive antenna array was studied in [2]. It was shown that when certain requirements are met, the detector will outperform its single-element counterpart, without requiring any additional knowledge about the users, but under some conditions, its performance may degrade.

Among the least complex multiuser detectors are the *interference cancelling* receivers. These receivers attempt to cancel the interference caused by one user from the other ones, based on either *hard* or *soft* decisions on the interfering user, in either a serial or parallel fashion. In particular, the receiver in [3] estimates the energies of the users based on the output of the bank of matched filters, and successively cancels and detects the strongest user, until all the users are detected. This receiver is not fully near-far resistant, but it has a simple structure and performs better than the conventional detector(matched filter). The knowledge of spatial distribution of the users can be used to improve the performance of the interference cancelling receivers, which was shown in [4] for the successive cancellation scheme, where improvement was achieved in both the energy estimates and the error performance.

In this paper, a successive interference cancelling receiver with a blind adaptive antenna is proposed. Two schemes are proposed to adapt each stage to one of the users and to cancel that user from the signal going into the next stage. The performances of these schemes are compared, and it is shown that this receiver can outperform the single-element interference cancelling receiver without requiring any additional information.

The remainder of the paper is organized as follows. Section 2. gives a description of the signal model. In Section 3., the combined spatio-temporal interference canceller is formulated. In Section 4., two methods for adapting the beamformer weights are explained. Simulations and results are presented in Section 5. and the conclusion is given in Section 6.

*THIS WORK WAS SUPPORTED IN PART BY THE NATIONAL SCIENCE FOUNDATION UNDER GRANT MIP-9202081.

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 transmissions are received by an array of M antennas. The propagation delay between antenna elements is assumed to be small relative to the inverse of the transmission bandwidth, so the received signals at the M baseband array outputs are identical to within a complex constant. The received signal at the antenna array can be modelled as :

$$\mathbf{x}(t) = \sum_{k=1}^{K} \mathbf{a}_k e_k b_k s_k(t) + \sigma \mathbf{n}(t), \tag{1}$$

where $\mathbf{x}(t) = [x_1(t) \cdots x_M(t)]^T$, $\mathbf{a}_k = [a_{1k} \cdots a_{Mk}]^T$ is the array response vector for user k, e_k^2 is the energy, $s_k(t)$ is the normalized signature waveform over symbol interval T, and $\mathbf{n}(t)$ is the vector of the additive white Gaussian noise. The $\{s_k(t)\}$ are real, linearly independent with chip rate $T_c = T/N$. Using vector representation for signature waveforms, we can rewrite the received signal as an $M \times N$ matrix:

$$\mathbf{X} = \begin{bmatrix} \mathbf{x}_1^H \\ \vdots \\ \mathbf{x}_M^H \end{bmatrix} = \sum_{k=1}^{K} \mathbf{a}_k e_k b_k \mathbf{s}_k^T + \sigma \mathbf{N}. \tag{2}$$

3. MULTIELEMENT INTERFERENCE CANCELLING RECEIVER

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 a multielement interference cancelling receiver 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 $M = 1$, the system reduces to the one proposed in [3].

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

$$\begin{aligned} y_1 &= \mathbf{w}_1^H \mathbf{X}_1 \mathbf{s}_1 \qquad (3) \\ &= (\mathbf{w}_1^H \mathbf{a}_1) e_1 b_1 + \underbrace{\sum_{k=2}^{K} (\mathbf{w}_1^H \mathbf{a}_k) e_k b_k \rho_{1k} + \sigma(\mathbf{w}_1^H \mathbf{N}_1 \mathbf{s}_1)}_{i_1}, \end{aligned}$$

where $\mathbf{X}_1$ is the received signal at the first stage. It is also useful to find the output energy of the beamformer and the

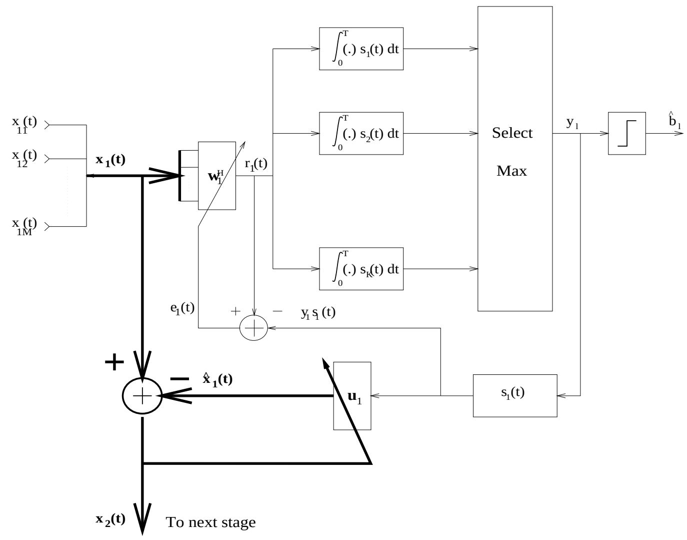

Figure 1. Block diagram of one stage of a Multielement interference canceller

matched filter for every stage. For the first stage, they are found to be, respectively,

$$E\left[\mathbf{r}_1^H \mathbf{r}_1\right] = \mathbf{w}_1^H \mathbf{R}_1 \mathbf{w}_1 \quad , \quad E\left[|y_1|^2\right] = \mathbf{w}_1^H \mathbf{R}_{y_1} \mathbf{w}_1 \tag{4}$$

where

$$\begin{aligned} \mathbf{R}_1 &= \mathbf{A}_1 \mathbf{E}_1^2 \mathbf{A}_1^H + N\sigma^2 \mathbf{I}_M, \\ \mathbf{R}_{y_1} &= \mathbf{A}_1 (\mathbf{E}_1 \mathbf{P}_1)^2 \mathbf{A}_1^H + \sigma^2 \mathbf{I}_M, \\ \mathbf{A}_1 &= [\mathbf{a}_1, \cdots, \mathbf{a}_K], \\ \mathbf{P}_1 &= \mathrm{diag}(\rho_{11}, \cdots, \rho 1K). \end{aligned}$$

Cancelling the effect of user 1, we get

$$\begin{aligned} \mathbf{X}_2 &= \mathbf{X}_1 - y_1 \mathbf{u}_1 \mathbf{s}_1^T = \sum_{k=2}^{K} \mathbf{a}_k e_k b_k \mathbf{s}_k \qquad (5) \\ &+ \underbrace{\mathbf{a}_1 e_1 b_1 \mathbf{s}_1 - (\mathbf{w}_1^H \mathbf{a}_1) e_1 b_1 \mathbf{u}_1 \mathbf{s}_1^T}_{\approx 0} + \sigma \underbrace{(\mathbf{N}_1 - \frac{1}{\sigma} i_1 \mathbf{u}_1 \mathbf{s}_1^T)}_{\mathbf{N}_2}. \end{aligned}$$

Similarly, for the j^{th} stage, the input signal is

$$\mathbf{X}_j = \sum_{k=j+1}^{K} \mathbf{a}_k e_k b_k \mathbf{s}_k + \sigma \underbrace{(\mathbf{N}_1 - \frac{1}{\sigma} \sum_{l=1}^{j-1} i_l \mathbf{u}_l \mathbf{s}_l^T)}_{\mathbf{N}_j}, \tag{6}$$

and y_j is given by

$$y_j = (\mathbf{w}_j^H \mathbf{a}_j) e_j b_j + \underbrace{\sum_{k=j+1}^{K} (\mathbf{w}_j^H \mathbf{a}_k) e_k b_k \rho_{jk} + \sigma(\mathbf{w}_j^H \mathbf{N}_j \mathbf{s}_j)}_{i_j}. \tag{7}$$

The output energy of the beamformer and the matched filter for j^{th} are, respectively,

$$E\left[\mathbf{r}_j^H \mathbf{r}_j\right] = \mathbf{w}_j^H \mathbf{R}_j \mathbf{w}_j \quad , \quad E\left[|y_j|^2\right] = \mathbf{w}_j^H \mathbf{R}_{y_j} \mathbf{w}_j \tag{8}$$

where

$$\mathbf{R}_j = \mathbf{A}_j \mathbf{E}_j^2 \mathbf{A}_j^H + N\sigma^2 \mathbf{I}_M + \sum_{i=1}^{j-1} \eta_i \mathbf{u}_i \mathbf{u}_i^H,$$

$$\mathbf{R}_{y_j} = \mathbf{A}_j (\mathbf{E}_j \mathbf{P}_j)^2 \mathbf{A}_j^H + \sigma^2 \mathbf{I}_M + \sum_{i=1}^{j-1} \eta_i \rho_{ji} \mathbf{u}_i \mathbf{u}_i^H,$$

$$\mathbf{A}_j = [\mathbf{a}_j, \cdots, \mathbf{a}_K],$$

$$\mathbf{P}_j = \mathrm{diag}(\rho_{jj}, \cdots, \rho j K).$$

The transmitted bit by the j^{th} user is detected using the decision variable in (7),

$$\hat{b}_j = \mathrm{sgn}[\mathrm{Re}(y_j)].$$

To analyze the error performance of this receiver, it is assumed that the residual interference plus noise at each stage has a Gaussian distribution. If the propagation between the transmitters and the receiver antenna is assumed to be a plane wave, and if the users are uniformly distributed around the receiver, the variance of the interference term i_j, conditioned on $\{e_k\}$, is found to be [4],

$$\eta_j = \frac{M}{N} v(M) \sum_{k=j+1}^{K} e_k^2 + \sigma^2 + \frac{1}{N} v(M) \sum_{i=1}^{j-1} \eta_i, \qquad (9)$$

where

$$v(M) = \frac{1}{M^2} \sum_{m=0}^{M-1} \sum_{m\prime=0}^{M-1} J_0^2(\omega(m - m\prime)),$$

J_0 is the zeroth order Bessel function of the first kind and $\omega = \frac{2\pi d}{\lambda}$, where d is the spacing between antenna elements and λ is the wavelength. The Probability of error is then found to be:

$$\mathcal{P}_e^j = Q(\sqrt{\frac{M e_j^2}{\eta_j}}) \qquad (10)$$

4. ADAPTIVE BLIND ARRAY

In this section we discuss two different methods to adaptively form beams towards the desired user at each stage and to cancel that user from the signal going into next stage.

Method I This method, which was originally suggested in [1] for a multi-element conventional detector, is extended here for an interference cancelling receiver. From Fig. 1, the error signal that is used to adapt $\mathbf{w}_j$ can be written as:

$$\mathbf{e}_j = \mathbf{w}_j \mathbf{X}_j - (\mathbf{w}_j \mathbf{X}_j \mathbf{s}_j)\mathbf{s}_j^T = \mathbf{w}_j \mathbf{X}_j (\mathbf{I} - \mathbf{s}_j \mathbf{s}_j^T) \qquad (11)$$

which is the orthogonal projection of the beamformer output on the space spanned by the signature sequence of the desired user. If the weights of the beamformer are chosen to minimize the error signal energy, the beamformer will steer nulls in the direction of some interfering users, depending on the relative number of users and antenna elements (which basically determines the degrees of freedom for the array). To avoid the trivial solution, an additional constraint is required. If the array response of the desired user is known, the optimal solution would be achieved with a constant gain in the direction of the desired user(linear constraint). Here we use the output energy of the decision variable for the desired user as the (quadratic)constraint. Since the users are detected and cancelled based on the order of their strength, the decision variable at each stage does not suffer from near-far problem, so it approximately represents the transmitted signal by the desired user. The optimization rule can be written as follows:

$$\min_{\mathbf{w}_j} E\left[\mathbf{e}_j^H \mathbf{e}_j\right] \qquad \text{subject to} \quad E\left[|y_j|^2\right] = 1, \qquad (12)$$

where $E\left[\mathbf{e}_j^H \mathbf{e}_j\right] = \mathbf{w}_j^H (\mathbf{R}_j - \mathbf{R}_{y_j})\mathbf{w}_j$. The solution to this problem is given by the generalized eigenvector corresponding to the minimum eigenvalue of the matrix pencil $(\mathbf{R}_j, \mathbf{R}_{y_j})$.

Method II The idea here is to maximize the output power of the matched filter subject to a unit norm constraint for the beamformer weight vector. The optimization rule is as follows:

$$\min_{\mathbf{w}_j} E\left[|y_j|^2\right] = \mathbf{w}_j^H \mathbf{R}_{y_j} \mathbf{w}_j \quad \text{subject to} \quad \mathbf{w}_j^H \mathbf{w}_j = 1, \quad (13)$$

Since the desired user at each stage is the strongest user, and assuming the interference plus noise at the matched filter output has Gaussian distribution, this method approximates the conventional(or Bartlett) beamformer. The solution, which is the eigenvector corresponding to the maximum eigenvalue of $\mathbf{R}_{y_j}$ is approximately the array response vector of the desired user.

For both methods, at each stage, the output of the filter matched to the strongest user is respread by its signature sequence and multiplied by vector $\mathbf{u}_j$ to form an estimate of that user's component in the received signal. The vector $\mathbf{u}_j$ is adaptively updated using the following rule:

$$\min_{\mathbf{u}_j} E\left[\mathbf{X}_{j+1} \mathbf{X}_{j+1}^H\right] = E\left[(\mathbf{X}_j - y_j \mathbf{u}_j \mathbf{s}_j^T)(\mathbf{X}_j - y_j \mathbf{u}_j \mathbf{s}_j^T)^H\right]. \qquad (14)$$

The closed form solution for $\mathbf{u}_j$ is found to be:

$$\mathbf{u}_j = \frac{\mathbf{R}_{y_j} \mathbf{w}_j}{\mathbf{w}_j^H \mathbf{R}_{y_j} \mathbf{w}_j}. \qquad (15)$$

5. SIMULATIONS AND RESULTS

In simulations, a system with $K = 6$ users, codes of length $N = 7$ and a receiver with $M = 3$ antennas was considered. Table 1 lists the angles of arrival and the SNRs for all the users. The following receivers were considered in the simulations:

1. Single-element conventional detector(Conv), 2. Single-element interference cancelling receiver(IC), 3. Multi-element conventional detector with the knowledge of array response vectors(Conv-M), 4. Multi-element interference cancelling receiver with the knowledge of array response vectors(IC-M), 5. Multi-element adaptive interference cancelling receiver using method I(IC-M I), 6. Multi-element adaptive interference cancelling receiver using method II(IC-M II).

Probability of error was used as the performance measure and was calculated over 10,000 runs. The results for all the

User	1	2	3	4	5	6
AOA	87°	40°	46°	27°	−77°	24°
SNR(dB)	14	13	9	8	4	3

Table 1. Angle of arrivals and SNRs

User	1	2	3	4	5	6
Conv	0	3	274	411	1510	1908
IC	0	0	105	122	824	1057
Conv-M	0	0	0	0	158	180
IC-M	0	3	0	0	0	9
IC-M I	0	2	6	3	5	20
IC-M II	0	0	2	6	1	18

Table 2. Probability of error($\times 10^{-4}$) for users 1-6

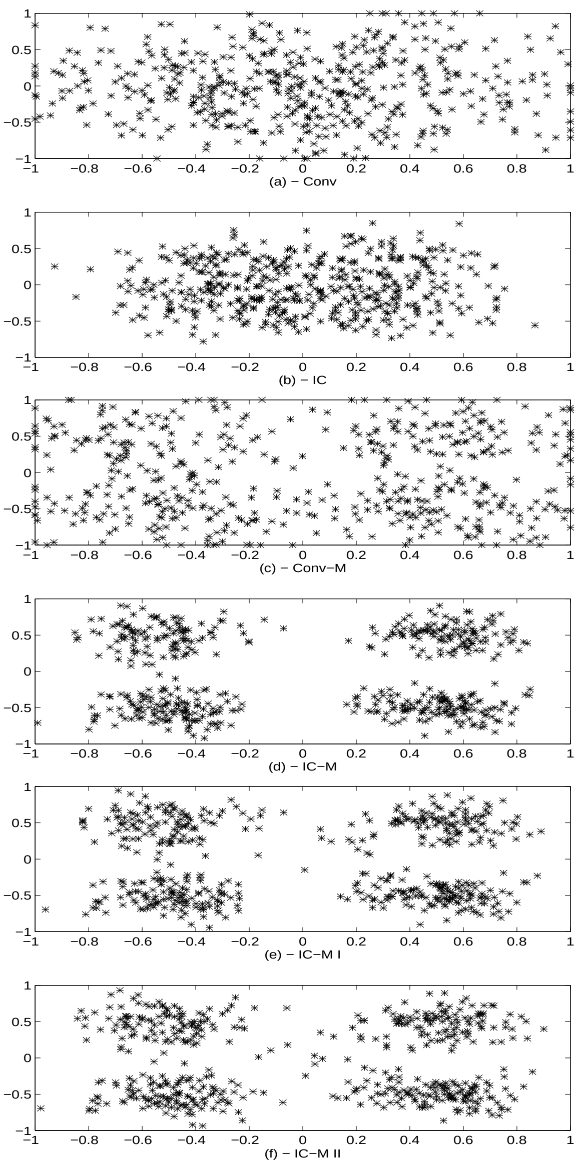

Figure 2. Constellations of the received signal for user 6

6 users are listed in Table 2. The QPSK constellations of the detected signal for the weakest user(i.e. user 6) corresponding to the detectors mentioned above are shown in Fig. 2 (a-f), respectively.

As the results indicate, the adaptive multi-element interference cancellers outperform the single-element conventional detector, the interference canceller and the multi-element conventional detector. Because both adaptive methods find the beamformer weight vector as the solution to an eigenvalue problem, the calculated eigenvectors are unique within a complex factor. Thus, the only additional information required is the carrier phase at the receiver input, which can be estimated by transmission of known pilot symbols. The relative performance of the two adaptive methods is not immediately obvious from the results presented. Since method I minimizes the interference energy at each stage, the beamformer has the ability of placing nulls in the direction of the interferers, if there are enough degrees of freedom. In favorable conditions, when the users are well separated, the receiver with adaptive method I will outperform the one using method II. But in general, we have found method II to be more robust than method I, with its performance degrading more gradually, as the spacing between the users decrease.

6. CONCLUSION

In this paper we proposed a simple detector for a synchronous multiuser CDMA system. The detector is an interference canceller with a blind adaptive array 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, even though no extra information about the spatial distribution of the users is needed by the receiver. Two methods for adapting the beamformer weights were suggested. While method I is capable of nulling some interfering users spatially, it is less robust than method II. In future work, we will try to combine these two methods to formulate a more robust receiver with nulling capability. We will also consider asynchronous CDMA with multipath fading.

Acknowledgment The authors appreciate discussions with Dr. Chandra Vaidyanathan and Prof. Kevin Buckley.

REFERENCES

[1] C. Vaidyanathan, K. Buckley, and S. Hosur, "A blind adaptive antenna array for CDMA systems," *Proc. of the Asilomar Conf.*, Nov. 1995.

[2] V. Ghazi-Moghadam, L. Nelson and M. Kaveh, "A multi-element blind adaptive multiuser detector," *Proc. of the 8th IEEE Workshop on Statistical Signal & Array Processing*, Corfu, Greece, June 1996.

[3] P. Patel and J. Holtzman, "Analysis of a DS/CDMA successive interference cancellation scheme using correlations," *Proc. GLOBECOM* Houston, TX, 1993.

[4] V. Ghazi-Moghadam and M. Kaveh, "Interference cancellation using antenna arrays," *Proc. Sixth IEEE Int. Symp. on Personal, Indoor and Mobile Radio Communications*, Toronto, Canada, Sep. 1995.