A LOW-COMPLEXITY MULTIUSER DETECTOR FOR ASYNCHRONOUS CDMA QPSK SYSTEMS WITH ADAPTIVE ANTENNA ARRAYS

E. Del Re, R. Fantacci, S. Morosi, S. Marapodi.

Dipartimento di Ingegneria Elettronica
Università di Firenze, Via di S.Marta 3, I-50139 Firenze, Italy

ABSTRACT

This paper deals with a multiuser detector for DS-CDMA wireless communication systems. The proposed detector's main feature lies in the joint utilization of the space and time processing techniques since adaptive antenna arrays and decorrelating multiuser receiver are supposed to be used together.

Complexity growth is lowered by implementing a multiuser detection technique based on the Sliding Window Algorithm. The DS-CDMA communication system considered resorts to QPSK modulated wideband signals so that a Sliding Window Algorithm generalization is necessary.

The simulation results shown here confirm that the proposed structure is near-far resistant even in the worst fading cases. As the sensor number increases a remarkable performance improvement takes place. Besides we show that the proposed receiver allows systems to exploit completely the array introduction while maintaining an acceptable computational complexity.

I. INTRODUCTION

Since many researchers have demonstrated that CDMA might be a candidate for the future wireless communications developments, efforts of the scientific community have been concentrated on identifying feasible implementations where the complexity-performance trade off is shown satisfactory. In particular, multiuser detection theory described in [1-2] makes possible to obtain excellent performance and near-far resistance but the multiuser detectors complexity is too heavy to allow a real time working. The introduction of the Sliding Window Algorithm, proposed by Wijayasuria *et al.* in [3], and modified by Yoon *et al.* in [4] seems to suggest a solution to these drawbacks with only slight reduction of system capacity: as is well known, this approach is quite suitable for communications systems with high number of users and where propagation channel is time varying. The considered algorithm takes advantage of a zero-energy bit periodic insertion: this solution allows the sequence detection approach to be maintained without the negative effects of the finite length sequences utilization.

Since in wireless cellular environments the users are randomly located around the base station, it is possible to utilize the information about direction of arrival of the signals to improve the multiuser detector performance: this goal becomes possible with the introduction of the adaptive antenna arrays [5]. Antenna arrays have been used, so far, to reduce interference from particular directions or to increase signal from another: in these schemes space processing is used independently from the demodulation technique.

As the multiuser detection allows us to consider cochannel interference as a additional source of information, the space processing technique deriving from the adaptive antenna arrays introduction makes the maximum exploitation of the information at the receiver input possible. In the following we focus on a receiver scheme which uses both techniques aiming to obtain a near-far resistant sequence detector. This solution is quite suitable for communication systems whose users are placed so that their signals arrive at the receiver from different directions and with random delays between users; therefore the proposed receiver finds a natural application at the end of the wireless communication up-link channel (from mobile user to base station).

Spread-spectrum technique utilization allows the receiver to discriminate each path, to consider them as independent users and, after space and time processing, to combine every contribution of the same signal, as in the classical rake receiv-

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ers.

The suburban wireless communication channel as described in GSM Recommendations has been considered as the propagation environment: six paths are described through their distinctive features, specifically delay, phase and attenuation; phase and amplitude have uniform and Rayleigh distribution respectively. The channel should be slowly fading frequency selective and, as the channel main features are equal for some bits, it is possible to consider windows (i.e. the distance between a zero energy bit and the following) whose length is not so short as to be harmful for the system total capacity.

In the paper different configuration of the detector are considered depending on the number of antennas at the receiver front end. The knowledge of each path phase, direction of arrival and delay, introduced by the channel is assumed for the system while no hypothesis is made about amplitude. In the receiver we propose the decorrelating detector uses additional information deriving from antenna array introduction: it is necessary to incorporate space processing inside the detector as it is defined in [4] and to generalize this structure to the QPSK modulated signals that are used for a better bandwidth occupation.

The paper is organized as follows: the proposed scheme is derived with the definition of the working hypothesis; than some simulation results are reported and compared with the classical rake receiver's performance in the same antenna array configuration.

II. SYSTEM MODEL

In this paragraph a communication system with K simultaneous asynchronous users is considered. It is assumed that each user transmits a packet of N bits. It is also been assumed that the receiver employs a multi-element detector composed of p identical and omnidirectional sensor.

Direction vector $\mathbf{v}_k = \left[1 \; e^{-j\theta_{k1}} \; e^{-j\theta_{k2}} \ldots e^{-j\theta_{kp}}\right]^T$ represents the relative sensor phases with respect to the direction of user k wavefront and they depend on spatial position of user k, array geometry, and carrier frequency.

In [5] multi-sensor antenna optimum multiuser detector has been derived as single sensor extension and suboptimum decorrelating detector, described in Fig. 1, has been defined; moreover user k matched filter output has been demonstrated to be dependent on vector $\mathbf{v}_k$ and, for a multi-element antenna decorrelating detector, cross-correlation fundamental matrices $\mathbf{R}(i)$ have been seen to be transformed by array effects: in fact each element of these matrices is multiplied for a spatial correlation coefficient $\xi_{im} = \mathbf{v}_i^H \mathbf{v}_m$ where ^{H} means transpose complex conjugate. Let $\mathbf{A}$ be the $K \times K$ matrix formed by these coefficients: $A_{im} = \xi_{im} = \mathbf{v}_i^H \mathbf{v}_m$ and $\mathbf{M}(i)$ the new cross-correlation matrix that is equal to $\mathbf{M}(i) = \mathbf{R}(i) \circ (\mathbf{A}^H \mathbf{A})$ where operator $\circ$ means element by element product.

As can be seen in Fig. 1, the sufficient statistics $\mathbf{y}$ is obtained by an optimum beamformer that is a linear operator described by matrix $\mathbf{A}^H$: the signal received by each array element is processed by the beamformer so that all the contributions from the same direction are combined coherently while the others are combined in a non coherent manner.

The decorrelator treats the matched filter outputs so that mutual interference is suppressed from each replica through another linear operation.

Even if the complexity of this receiver is lower than that of an optimum receiver, it keeps on being too large to allow an effective implementation. In particular, a $NKL \times NKL$ complex matrix inversion is necessary and in practical applications this operation is too heavy.

Even the interesting solution proposed by Lupas and Verdú [2] based on the implementation of an LTI filter becomes too complex for large KL values and cannot be performed in real time by the receiver.

In this paper we propose a low complexity implementation with regard to parameter N.

We use a QPSK modulation scheme and the same spreading sequence for the phase and quadrature components. The matched filter output for the k^{th} bit of all users can be written by:

$$\begin{aligned}\mathbf{y}(k) = \mathbf{M}(-1)\mathbf{C}(k+1)\mathbf{b}(k+1) + \mathbf{M}(0)\mathbf{C}(k)\mathbf{b}(k) +& \\ + \mathbf{M}(1)\mathbf{C}(k-1)\mathbf{b}(k-1) + \mathbf{n}(k)& \qquad (1)\end{aligned}$$

where $\mathbf{b}(k) = \mathbf{b}_I(k) + j\mathbf{b}_Q(k)$ is the complex vector composed of the transmitted data. For example $\mathbf{b}_I(k) = \left[b_{I,1}(k) \; \ldots \; b_{I,KL}(k)\right]^T$, where $b_{I,i}(k) \in [\pm 1]$ for $i = 1, \ldots, KL$. Each vector is comprised of KL elements, where L is the number of replicas of each user signal which can be discriminated. Each replica is considered as an individual user, so that it is still possible to exploit multiuser detection and take advantage of both spatial and temporal (rake) processing.

The complex vector $\mathbf{y}(k) = \mathbf{y}_I(k) + j\mathbf{y}_Q(k)$ is composed of the matched filter outputs. $\mathbf{C}(k)$ are the diagonal matrices whose components are the complex channel fading gains of average energy E_b: $c_i(k) = \sqrt{w_i(k)} \cdot e^{j\theta_i(k)}$. The complex vector $\mathbf{N}(k)$ is the additive Gaussian noise vector, with a zero mean and covariance matrix given by $E[\mathbf{N}^H\mathbf{N}] = \sigma^2\mathbf{M}$. We considered a sequence formed by $\hat{N}$ bits (a "window") for each user. For simplicity we define

$$\tilde{\mathbf{b}}(k) = \mathbf{C}(k) \cdot \mathbf{b}(k) \qquad (2)$$

From (1), through algebraic manipulations, we have:

$$\begin{bmatrix} \mathbf{y}(U+1) \\ \mathbf{y}(U+2) \\ \mathbf{y}(U+3) \\ \vdots \\ \mathbf{y}(U+\hat{N}) \end{bmatrix} = \begin{bmatrix} \mathbf{M}(0) & \mathbf{M}(-1) & 0 & \cdots & 0 \\ \mathbf{M}(1) & \mathbf{M}(0) & \mathbf{M}(-1) & \cdots & 0 \\ 0 & \mathbf{M}(1) & \mathbf{M}(0) & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & \cdots & \mathbf{M}(1) & \mathbf{M}(0) \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{b}}(U+1) \\ \tilde{\mathbf{b}}(U+2) \\ \tilde{\mathbf{b}}(U+3) \\ \vdots \\ \tilde{\mathbf{b}}(U+\hat{N}) \end{bmatrix}$$

$$+ \begin{bmatrix} \mathbf{M}(1)\tilde{\mathbf{b}}(U) \\ 0 \\ \vdots \\ 0 \\ \mathbf{M}(-1)\tilde{\mathbf{b}}(U+\hat{N}+1) \end{bmatrix} + \begin{bmatrix} \mathbf{n}(U+1) \\ \mathbf{n}(U+2) \\ \mathbf{n}(U+3) \\ \vdots \\ \mathbf{n}(U+\hat{N}) \end{bmatrix} \qquad (3)$$

where U is an offset from the start of the transmission and $\hat{N} < N$ is the data temporal window length within the complete received sequence. The linear system (3) is composed of $\hat{N}$ equations with $\hat{N}+2$ unknown values: in particular, $y(U+1)$ is dependent on $\tilde{\mathbf{b}}(U)$ and, likewise, $y(U+\hat{N})$ on $\tilde{\mathbf{b}}(U+\hat{N}+1)$. Our strategy is to assume terms $\tilde{\mathbf{b}}(U)$ and $\tilde{\mathbf{b}}(U+\hat{N}+1)$ in (3) equal to zero. This condition is fulfilled by periodically inserting a zero-energy bit in the informative bit sequence. Therefore, the interference due to the cross-correlation of the actual symbols with the past and future symbols in the asynchronous channels can be eliminated (see Fig. 2). Then, parameter $\hat{N}$ is chosen in order to obtain a feasible solution of (3).

The transmission is arranged so that the relative differences in arrival times of the zero-energy bits at the base-station are smaller than the single-bit duration T_b, i.e., $|\tau_k - \tau_l| \leq T_b$, $\forall\, k,l$. It is important to note that the overhead needed to fulfill the synchronization constraints is not too heavy [4]. Now, by exploiting the block tridiagonal structure of **M**, by means of the algorithm that can be found in [4], we can solve the linear system (3).

Thus, all the values of vectors $\tilde{\mathbf{b}}(k)$ are determined. The mutual interference among users has been eliminated, but the decorrelation block outputs are dependent on the random phase offset introduced by the multipath fading channel.

QPSK modulation requires coherent reception and, therefore, random phase compensation is needed. Since each operation on the received signals is linear, it is possible to compensate after decorrelation. For notation simplicity, consider the i^{th} element of (2):

$$\tilde{b}_i(k) = \sqrt{w_i(k)}e^{j\vartheta_i(k)} \cdot b_i(k) \quad \forall\, i = 1,\ldots,KL \qquad (4)$$

where $w_i(k)$ is the received power from the i^{th} bit of the k^{th} user and $\vartheta_i(k)$ is the random phase introduced by the multipath fading channel. The perfect knowledge of $\vartheta_i(k)$ is assumed, while $w_i(k)$ has an unknown value.

In order to obtain the decision variables D, both members of (4) are to be multiplied for $e^{-j\vartheta_i(k)}$. If k is omitted and real and imaginary components are considered separately, we obtain:

$$\begin{aligned} D_{I,i} &= \tilde{b}_{I,i}\cos\vartheta_i + \tilde{b}_{Q,i}\sin\vartheta_i \\ D_{Q,i} &= \tilde{b}_{Q,i}\cos\vartheta_i - \tilde{b}_{I,i}\sin\vartheta_i \end{aligned} \quad \forall\, i = 1,\ldots,\hat{N} \qquad (5)$$

Finally, the values of the decision variables are obtained. These values are affected only by the AWGN and the attenuation due to the multipath fading, but they are completely free from the interference caused by other users and the random phase deviation introduced by the multipath fading channel.

III. SIMULATIONS RESULTS

In this section the performance of the conventional rake detector and that of the proposed receiver are compared in different interference environments. The dependence of the BER performance on the frame length is also investigated. In performing our simulations the following conditions have been assumed:

- Symbol rate for the QPSK modulation equal to 31.496 Ksymbols/sec;
- One spreading sequence assigned to each QPSK user;

- Spreading obtained through Gold sequences with processing gain equal to 127.

We have considered 4 users up-link communication system and a Rayleigh multipath fading channel, as described in [6], with six resolvable paths and a Doppler spread equal to 100 Hz. We consider one zero-energy symbol every four information bits ($\hat{N} = 4$). This leads to an efficiency equal to 80 per cent. This value is clearly too low for practical applications. However, it can be demonstrated that the BER performance is not dependent on the frame length.

Fig. 3 shows the BER performance of the proposed detector compared to a single sensor multiuser detector as a function of the ratio between the energy per bit at the receiving end (E_b) and N_0: a two element uniform linear array is considered in the proposed receiver. Figs. 4-5 show the BER performance of the proposed multiuser detector for different values of the power unbalance (0 dB and 20 dB respectively) between the desired user signal and the interfering signals. The BER performance obtained for a beamformer-rake receiver with the same array structure and the same number of interfering users is also shown in the figures for comparative purposes. In all these figures the BER performance of a single user rake receiver, employing the full array gain, is shown as the lower bound limit. The good behavior of the array multiuser detector is apparent in Figs. 3-5. The fact that the BER performance of the proposed array multiuser detector is independent of the near-far effects particularly interesting. We can deduce that the asymptotic efficiency is very close to unitary value.

The results shown in Fig. 6 have been derived by using a four-element array. This figure proves that the BER performance is dependent on the array dimension: it's possible to obtain better performance by increasing the number of array elements. In this figure single user beamformer-rake receiver performance (in the case of four elements array) is shown as the lower bound limit. For comparison a single sensor multiuser detector performance is also shown.

IV. CONCLUSIONS

In this paper a multiuser receiver using a multi-element antenna for DS/CDMA up-link communications has been presented. The near-far resistance of our receiver and its good behavior with respect to the classical rake receiver have been verified by means of computer simulations in the case of a slowly frequency-selective Rayleigh fading channel.

By means of time and space processing and decorrelating techniques used, this receiver has been shown to be near-far resistant. It achieves excellent performance in multipath fading environment and demonstrates sensible improvement in comparison with single-antenna receiver. Finally, at increasing numbers of antenna sensors, the performance of the proposed receiver improves significantly with only a slight increase in complexity.

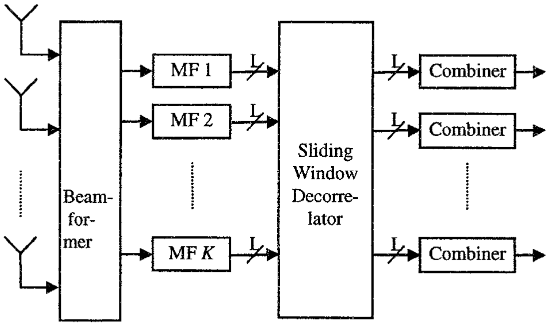

Fig. 1 : Receiver block diagram.

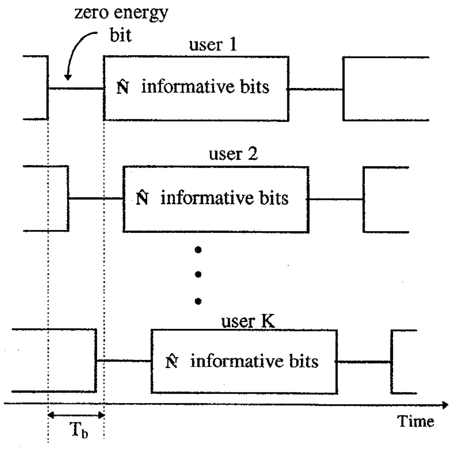

Fig. 2: Transmitted data frame structure.

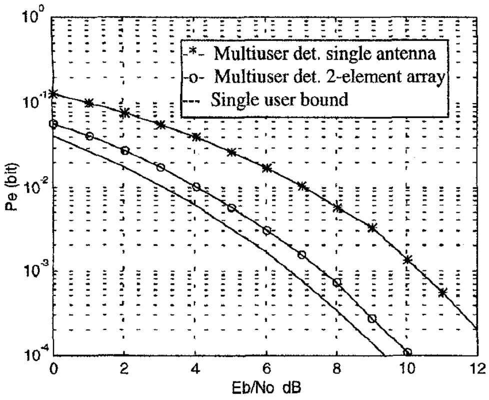

Fig. 3: BER comparison.

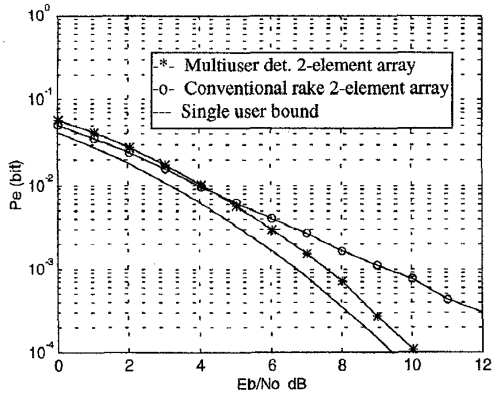

Fig. 4: BER comparison.

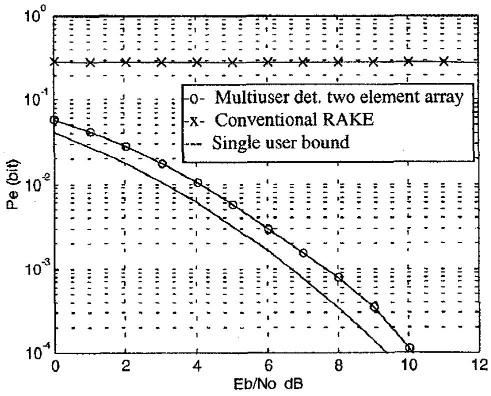

Fig. 5: BER comparison.

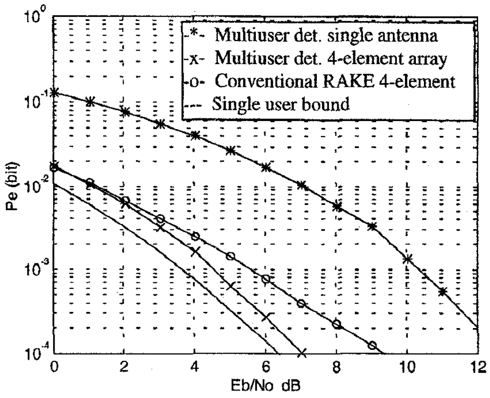

Fig. 6: BER comparison.

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