Spatial-Temporal Processing with Restriction of Degrees of Freedom for CDMA-Multiuser Detection[*]

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ABSTRACT

Multipath distortion and multiple access interference are major limitations for the performance of wireless CDMA systems. In order to overcome both problems, a base-station antenna array RAKE receiver is proposed in this paper. Each one of the main propagation paths is assigned to one of the branches of the RAKE receiver. After removing the spreading sequence from the selected paths, the de-spread signals are used to estimate the spatial signature of the paths and the received power at each one of them. No training signal nor any a priori spatial information is required for the estimation. After estimating the path spatial signatures, an specific weight vector can be computed for each user. In addition to the multipath combination, this weight vector is able to cancel the interference from other users, achieving substantial robustness against fading and near-far effect at the same time.

1 INTRODUCTION

Multipath distortion presents a major limitation for the performance of wireless CDMA systems. The common approach to combat multipath interference is to employ an independent, single-user RAKE receiver for each user. The RAKE receiver combines the different multipath arrivals of the desired user. So, instead of multipath being a source of performance degradation, the multiple paths are used to provide the benefit of diversity [1]. The problem of the RAKE receiver, which is optimal in the absence of multiple access interference (MAI), is that suffers from near-far effect in the presence of these interfering signals. Moreover, if the self interference due to multipath is not low enough after the despreading, the RAKE can perform even worse than the conventional receiver (that is one filter matched to the first path).

A different approach to eliminate the distortion due to multipath is the use of antenna arrays at the base-station. Antenna arrays can combat multipath isolating the signal from a single propagation path based on its different spatial signature from undesired multipath. Furthermore, the antenna array can suppress interfering signals (overcoming the near-far problem) and provide also spatial diversity to combat fading in the single isolated path [2]. Nevertheless, the use of a pure spatial processing does not take advantage of the temporal diversity offered by multipath propagation, exploited by the RAKE receiver.

In order to combine the advantages of both temporal and spatial processing, a base-station antenna array-RAKE receiver is proposed in this paper. The proposed receiver exploits the spatial structure in the multipath received signal in addition to the time diversity to provide a more efficient combining of the different propagation paths.

2 SIGNAL MODEL

The system under consideration is a K-user asynchronous DS-CDMA system using BPSK modulation and operating over a frequency selective channel. The baseband signal for the k-th user is

$$s_k(t) = \sum_m d_k[m]\, b_k(t - mT) \tag{1}$$

the data stream $d_k[m] \in \{+1, -1\}$ is pulse amplitude modulated by a spreading sequence $b_k(t)$, with $b_k(t) = 0$ for $t \notin \{0, T\}$ and T the bit time. The received baseband signal vector corresponding to user k is

$$\mathbf{x}(t) = \sum_{k=1}^{K}\sum_{r=1}^{R} \sqrt{p_{k,r}}\, s_k(t - \tau_{k,r})\mathbf{a}_{k,r}(t) + \mathbf{n}(t) \tag{2}$$

$\mathbf{n}(t)$ is the noise vector at the array input. The noise is considered white Gaussian, uncorrelated among different sensors and with the same power spectral density $N_0\ W/Hz$ for all of them. On the other hand $p_{k,r}$, $\tau_{k,r}$ and $\mathbf{a}_{k,r}$ are respectively the received power, the propagation delay and the steering vector with dimension equal the number of sensors M, all for the r-th path of the k-th user. The R paths model stems from the fact that spread spectrum signaling with a transmitted signal bandwidth wider than the coherence bandwidth

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of the channel allows the multipath components to be resolved. The number of paths R may be assumed to be either fixed or randomly changing. For the sake of clarity in the formulation, a fixed value for R is assumed in this paper for all the users. The resolvable multipath components can be themselves a linear combination of several unresolvable paths. Then, we call $\mathbf{a}_{k,r}(t)$ the spatial signature for the r-th path of the k-th signal. This vector may be time-varying due to the combined effect of multipath and Doppler. Here, $\mathbf{a}_{k,r}$ is assumed to be slowly varying compared to the symbol time, so that it is constant over several symbol durations.

3 PROPOSED APPROACH

The proposed receiver, shown in figure 1, consists of an antenna array followed by a bank of multipath processing blocks, one for each user. Every block contains R branches. Each one of the R main paths of the corresponding user is assigned to one of the branches. The first operation in each branch is to remove the spreading code signal, by means of a matched filter or a correlator synchronized to the corresponding path (see figure 2). In a typical RAKE receiver the de-spread signals corresponding to the desired user are added after cancelling delay spread among them and adjusting the phases and levels of each branch. One major difference between a typical single user RAKE receiver and the ones in figure 1 is that here the signals to combine are vectors with dimension M, the number of array sensors. Another difference is the fact that the combination of the signals corresponding to an specific user is carried out by means of a weight vector $\mathbf{w}_k$ (beamforming), which, in addition to the multipath combination, cancels the interference from other users. The suitable weight vector for each beamforming is computed using just the information at the output of the matched filters. Thus, no training signal nor a priori spatial information is required.

Similar schemes have been proposed in the literature [3], [5]. Nevertheless, these approaches work in a different way as the one presented here, since the aforementioned methods do not consider MAI and they need to compute the spatial autocorrelation matrix for each path before the despreading. The receiver proposed in this paper can be seen as the wideband version of the one proposed in [4] for frequency non-selective channels, with the addition of the multipath processing blocks and further signal combinations. Nevertheless, despite of the philosophy of both approaches is similar, the problem now considered presents some new important aspects which will be pointed later on.

After the despreading operation, we dispose of KR separated signal vectors. Each one of them contains information about the multipath signals of the K users. From now on, we will assume that these vectors are ordered as indicated in figure 1. The first R signal vectors correspond to the first user, the next R ones correspond to the second user and so on. Then, the l-th signal vector is

$$\mathbf{z}_l\,[n] = \frac{1}{T}\int_{nT+\tau_l}^{(n+1)T+\tau_l} \mathbf{x}(t) b_l(t-nT-\tau_l)dt \qquad (3)$$

where $b_l = b_k$ and $\tau_l = \tau_{k,r}$ for $l = (k-1)R + r$, with $k = 1...K$ and $r = 1...R$.

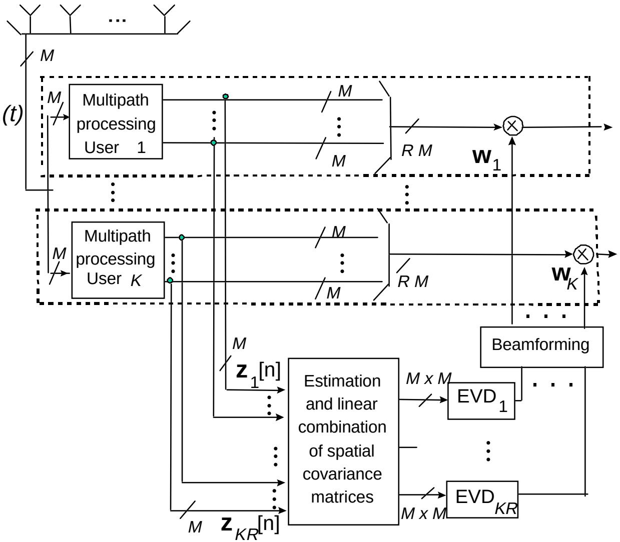

Figure 1: Multiuser-Multisensor proposed scheme

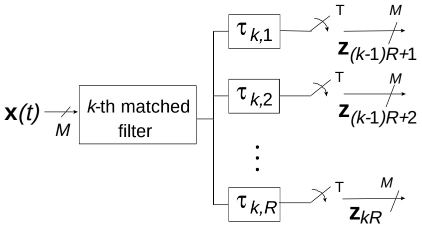

Figure 2: Multipath processing block for each user

As for frequency non-selective channels [4], a $M \times M$ spatial correlation matrix is computed at each branch:

$$\mathbf{R}_{\mathbf{z}_l\mathbf{z}_l} = E\left\{\mathbf{z}_l[n]\mathbf{z}_l^H[n]\right\} \qquad l = 1\ldots KR \qquad (4)$$

Stacking all these covariances matrices, the $KRM \times M$ multiuser covariance matrix is generated:

$$\mathbf{R}_{\mathbf{z}} = \left[\begin{array}{cccc} \mathbf{R}^T_{\mathbf{z}_1\mathbf{z}_1} & \mathbf{R}^T_{\mathbf{z}_2\mathbf{z}_2} & \ldots & \mathbf{R}^T_{\mathbf{z}_{KR}\mathbf{z}_{KR}} \end{array}\right]^T \qquad (5)$$

After some algebraic manipulation the above matrix can be written in a very compact way

$$\mathbf{R}_{\mathbf{z}} = \left(\left[\begin{array}{cc} \mathbf{B} & \mathbf{C} \end{array}\right] \otimes \mathbf{I}_M\right) \left[\begin{array}{c} \mathbf{S} \\ \mathbf{T} \end{array}\right] + \mathbf{N} \qquad (6)$$

$\mathbf{N} = \left[\begin{array}{ccc} \frac{N_0}{T}\mathbf{I}_M & \ldots & \frac{N_0}{T}\mathbf{I}_M \end{array}\right]^T$ is a noise matrix, $\mathbf{I}_M$ is the identity matrix with dimension $M \times M$. Matrix $\mathbf{S}$ can be partitioned into KR rank one matrices with dimension $M \times M$. Each one of these matrices is the outer product of the spatial signature of one propagation path. The partition corresponding to the r-th path of the k-th user is:

$$\mathbf{S}_{k,r} = p_{k,r}\mathbf{a}_{k,r}\mathbf{a}_{k,r}^H \qquad k = 1\ldots K, \quad r = 1\ldots R \quad (7)$$

The position of the above submatrix in $\mathbf{S}$ is $i = (k-1)R + r$.

On the other hand, matrix $\mathbf{T}$ can be partitioned into $(R-1)\,R/2$ matrices per user. Each one contains the outer product of two paths corresponding to a same user. The partition for the paths r and $r^{'}$ of the k−th user is:

$$\begin{array}{l}\mathbf{T}_i = \sqrt{p_{k,r}p_{k,r'}}\left(\mathbf{a}_{k,r}\mathbf{a}_{k,r'}^H + \mathbf{a}_{k,r'}\mathbf{a}_{k,r}^H\right) \\ k = 1...K, \quad r = 1...R-1, \quad r' = r+1...R\end{array} \tag{8}$$

where the position i increases by one with each value of k, r and r'. The contribution of $\mathbf{S}$ and $\mathbf{T}$ to $\mathbf{R_z}$ depends on the autocorrelations and cross-correlations of the codes. This information is contained in matrix $\mathbf{B}$ and $\mathbf{C}$, whose elements are perfectly known provided than the codes are synchronized. Due to the lack of space, the explicit expression for these elements is not depicted here, but it can be derived from the covariance matrices $\mathbf{R}_{\mathbf{z}_l\mathbf{z}_l}$ [4]. There is an extra term in eq. (6) when compared with the similar equation in the frequency non-selective case [4]. This term is $(\mathbf{C}\otimes\mathbf{I}_M)\,\mathbf{T}$ and stems from the cross-correlations between the paths corresponding to a same user. Furthermore, matrix $\begin{bmatrix}\mathbf{B} & \mathbf{C}\end{bmatrix}$ is not a square matrix. Thus, the non-selective frequency procedure of [4] can not be straight used. It is necessary to make use of $K(R-1)R/2$ additional degrees of freedom. The computation of these new equations is possible thanks to the great amount of information available at the receiver due to the highly structured multiuser signal. It can be shown that using the cross-covariance matrix of the signal vectors at the output of the filter matched to an specific user and computing the matrix $\left(\mathbf{R}_{\mathbf{z}_l\mathbf{z}_m} + \mathbf{R}_{\mathbf{z}_l\mathbf{z}_m}^H\right)/2$ for $l = (k-1)R+1\ldots kR-1$, $m = l+1\ldots kR$, the necessary equations can be formulated. Stacking again the new matrices corresponding to each one of the K users, a complete equation system can be written

$$\widetilde{\mathbf{R}_\mathbf{z}} = \begin{bmatrix}\mathbf{R_z} \\ \mathbf{R_c}\end{bmatrix} = \left(\underbrace{\begin{bmatrix}\mathbf{B} & \mathbf{C} \\ \mathbf{F} & \mathbf{G}\end{bmatrix}}_{\widetilde{\mathbf{B}}}\otimes\mathbf{I}_M\right)\begin{bmatrix}\mathbf{S} \\ \mathbf{T}\end{bmatrix} + \widetilde{\mathbf{N}} \tag{9}$$

where the elements of matrices $\mathbf{F}$ and $\mathbf{G}$ are, as the elements of matrices $\mathbf{B}$ and $\mathbf{C}$, a function of the autocorrelation and cross-correlation of the codes.

It can be shown that matrix $\widetilde{\mathbf{B}}$ is a symmetrical and a square matrix. Thus multiplying $\widetilde{\mathbf{R}_\mathbf{z}}$ by the inverse of this matrix it is obtained:

$$\left(\widetilde{\mathbf{B}}^{-1}\otimes\mathbf{I}_M\right)\widetilde{\mathbf{R}_\mathbf{z}} = \begin{bmatrix}\mathbf{S} \\ \mathbf{T}\end{bmatrix} + \left(\widetilde{\mathbf{B}}^{-1}\otimes\mathbf{I}_M\right)\widetilde{\mathbf{N}} \tag{10}$$

The resulting matrix can be decomposed into $KR + KR(R-1)/2$ matrices of dimension $M\times M$, denoted as $\mathbf{M}_l$. We are interested only in the first KR ones $(\mathbf{M}_1\ldots\mathbf{M}_{KR})$. Each one of them has only one signal eigenvector which is the spatial signature of one of the paths. With this information, the linear constrained beamformer [2] nulls those undesired paths and set unitary gain for the desired path.

The number of spatial signatures than can be estimated with the above method is independent of the number of sensors. Nevertheless, the number of signals than the array can cancel is not. Having a number of sensors smaller than the number of undesired signals will be a common situation in practice. This is what we call a restricted number of degrees of freedom. To take into account only those interference paths with greater power, we can use the maximum SNIR beamformer for each path, which is calculated as the eigenvector associated to the main generalized eigenvalue of the pair of matrices $(\mathbf{R}_{\mathbf{z}_l\mathbf{z}_l}, \mathbf{R}_{in,l})$. To prevent the cancellation of the desired signal due to the cross-terms in $\mathbf{R}_{in,l}$ we need to reestimate matrix $\mathbf{R}_{\mathbf{z}_l\mathbf{z}_l}$ as the l-th partition of the following matrix:

$$\widehat{\mathbf{R}}_z = (\mathbf{B}\otimes\mathbf{I}_M)\begin{bmatrix}\mathbf{M}_1 \\ \vdots \\ \mathbf{M}_{KR}\end{bmatrix} \tag{11}$$

which differs from the actual $\mathbf{R}_z$ in the cross-terms and also introduces an slight error in the noise level. Then matrix $\mathbf{R}_{in,l}$ can be calculated as the l-th partition of:

$$\mathbf{R}_{in} = \widehat{\mathbf{R}}_z - \begin{bmatrix}\mathbf{M}_1 - \lambda_{\min}\{\mathbf{M}_1\}\mathbf{I}_M \\ \vdots \\ \mathbf{M}_{KR} - \lambda_{\min}\{\mathbf{M}_{KR}\}\mathbf{I}_M\end{bmatrix} \tag{12}$$

where $\lambda_{\min}\{\mathbf{M}_l\}$ denotes the minimum eigenvalue of matrix $\mathbf{M}_l$.

4 SIMULATION RESULTS

In order to investigate the performance of the proposed detector an asynchronous CDMA system was simulated. The modulating signals in this system are Gold sequences with length 31 (number of chips per symbol). As an example we illustrate the separation of two users $(K=2)$ that are received through three different propagation paths $(R=3)$ by an array of M $\lambda/2$ linearly spaced sensors . The angles of arrival, delays and power relative to the noise level for each path are respectively: $\begin{bmatrix}50^o & 40^o & 30^o \\ 70^o & 80^o & 85^o\end{bmatrix}$, $\begin{bmatrix}0 & T_c & 2T_c \\ 3T_c & 4T_c & 5T_c\end{bmatrix}$ and $\begin{bmatrix}0dB & -7dB & -10 \\ 15dB & 10dB & 5dB\end{bmatrix}$(each row corresponds to an user, each column corresponds to a path). The proposed receiver is able to estimate the six spatial signatures with independence of the number of sensors $(M=8)$. With this information the linear constrained beamformer is able to null all the paths but the one of interest in each case (see figure 3), since the array has enough degrees of freedom to accomplish that $(M = 8 > KR = 6)$. After that, all the resulting signals corresponding to a same user are coherently combined. In order to present a meaningful radiation pattern we have considered an scenario where the resolvable paths correspond to a single direction of arrival. However, since no model is assumed for the steering vector, the same procedure can be used when the resolvable paths are a combination of several unresolvable directions of arrival.

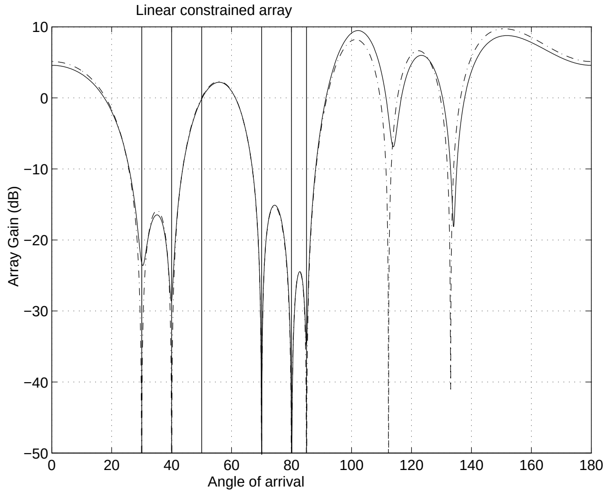

Figure 3: Cancellation of the remaining interference in the first path of the first user. Exact covariance matrices (-.-.). Estimated covariance matrices (———) from 150 symbols.

The reported experiment has been useful to show the potential of the proposed approach as a DOA estimation method. Nevertheless, if the number of sensors is smaller than the total number of paths the array cannot null every undesired signal. The maximum SNIR beamformer selects implicitly those undesired paths with greater power. Figure 4 depicts the output SNIR for the first user, achieved combining its paths after the beamforming approach described in last section.

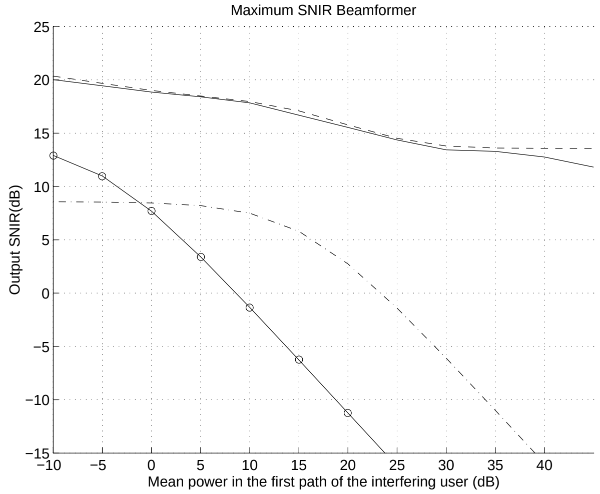

Figure 4: Output SNIR for the first user versus the power at the first path of the second user. RAKE receiver (-.-.), conventional (-o-), proposed approach with exact (- - -) and estimated (—) covariance matrices.

Four sensors ($M = 4$) are considered in this case. The resulting SNIR is depicted as a function of the power in the 1st path of the 2nd user, P. The power in the other two paths is $P-5$ and $P-10$dB respectively. Each path is assumed to be an independent Rayleigh channel except for the RAKE and conventional receiver (Gaussian channels are considered for them). As it can be seen from figure 4, the RAKE receiver (-.-.) outperforms the conventional CDMA receiver (-o-). The RAKE is able to take advantage of the inherent temporal diversity of the CDMA system but it is not able to overcome MAI. The proposed scheme clearly outperforms both conventional techniques. In the same figure results corresponding to the proposed method are shown, using the exact (- - -) and estimated (——) spatial covariance matrices. 150 symbols at the output of the matched filters has been used to estimate these matrices. The figure shows that, for a wide margin of near-far ratio, the performance of the proposed receiver is practically the same with exact or estimated covariance matrices. Only for very high near-far ratios, both cases start to slightly differ.

5 CONCLUSIONS

A new base-station antenna array RAKE receiver has been proposed in this paper. The spatial-temporal processing carried out by the receiver provides substantial robustness against fading an near-far effect in frequency-selective CDMA channels. The results demonstrate significant performance improvement over the RAKE technique. This performance improvement is achieved with no additional knowledge about the desired signals greater than the one required by the RAKE receiver. As no model is assumed for the spatial signatures, the receiver is robust to array calibration errors. For the same reason, it can be used when the resolvable paths correspond to only one direction of arrival or when they are a combination of several unresolvable directions of arrival.

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