Cancellation of external and multiple access interference in CDMA systems using antenna arrays

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Abstract

This paper deals with the problem of multisensor-multiuser detection in CDMA systems in the presence of interferences external to the system. The paper presents a new method able to estimate the spatial signature of all active users projected onto the subspace orthogonal to the external interference. With this information a specific beamformer can be designed for each user in order to combat the external and multiple access interference. The method performs in frequency non-selective multipath scenarios as they arise from some CDMA satellite and indoor communications systems. The estimation process does not require any training signal nor any a priori spatial information. It exploits the temporal structure of CDMA signals and extract the required information directly from the received signals. In addition, the method is independent of the nature of the external interference and it can cope with narrow-band and wide-band interfering signals. © 1997 Elsevier Science B.V.

Zusammenfassung

Dieser Artikel behandelt das Problem der Multisensor/Multibenutzer-Detektion in CDMA Systemen bei externen Störeinflüssen. Es wird eine neue Methode vorgestellt, die in der Lage ist, die räumliche Signatur aller aktiven Benutzer zu schätzen. Dabei werden die Nutzsignale in denjenigen Raum projiziert, der orthogonal zum Raum der externen Störungen liegt. Mit Hilfe dieser Information kann ein spezieller Beamformer für jeden Benutzer entworfen werden, um die externen, und diejenigen Störungen zu unterdrücken, die durch multiplen Zugriff der verbleibenden Benutzer entstehen. Die Methode eignet sich zur Anwendung in nichtfrequenzselektiven Mehrwege-Szenarien, die z.B. bei einigen CDMA Satellitensystemen und Kommunikationssystemen in Gebäuden vorliegen. Der Schätzprozess benötigt weder ein Trainingssignal, noch irgendwelche räumlichen a priori Informationen. Er nutzt lediglich die Struktur der CDMA Signale im Zeitbereich aus und extrahiert die notwendigen Informationen direkt aus den empfangenen Signalen. Außerdem ist die Methode von der Art der externen Störungen unabhängig und kann sowohl bei schmalbandigen als auch bei breitbandigen Störsignalen angewandt werden. © 1997 Elsevier Science B.V.

Résumé

Cet article traite du problème de la détection multi-capteurs et multi-utilisateurs dans les systèmes CDMA en présence d’interférences externes au système. Cet article présente une méthode nouvelle capable d’estimer la signature spatiale de tous les utilisateurs actifs projetée sur le sous-espace orthogonal aux interférences extérieures. Avec cette information un formateur de voie spécifique peut être conçu pour chaque utilisateur pour combattre les interférences externes et d’accès

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1. Introduction

Direct-sequence code division multiple access (DS-CDMA) is an accepted technique for future high capacity digital wireless communications systems. In order to successfully extract the users in a CDMA system, two major troubles need to be overcome: channel distortion and interferences. There are two types of interferences: multiple access interference and interferences external to the system.

In mobile environments, channel distortion may be multiplicative (fading) and/or dispersive. The dispersive distortion holds any time the spread bandwidth exceeds the coherence bandwidth of the channel. The use of spread spectrum can be useful in combating this kind of degradation: direct sequence (DS) waveforms can either reject multipath returns that fall outside of the correlation interval of the spreading waveform, or enhance overall performance by diversity combining multipath returns in a RAKE receiver [3, 10]. The temporal diversity introduced by the RAKE receiver may be useful in the presence of deep fades. Nevertheless, when there is a single fading path (frequency non-selective channels), it is not longer possible to apply temporal diversity to combat fading. This is the case of most of mobile-satellite systems (see Refs. [2, 13]) which employ CDMA and some indoor communications systems. In this situation, an important countermeasure is the use of spatial diversity. The discussion herein focuses on the use of antenna arrays to improve the performance of CDMA systems in frequency non-selective channels.

Regarding multiple access interference, CDMA systems are strongly affected by the near–far problem. This problem arises when users are received with very dissimilar powers on account of the distance and/or the presence of deep fades. If their code sequences are not perfectly orthogonal, the higher power sources overwhelm the lower power ones and, in consequence, the system capacity drops spectacularly. The orthogonality cannot in general be guaranteed in asynchronous systems. This lack of orthogonality among the modulating signals makes the standard receiver for DS-CDMA (that is a bank of filters with each filter matched to a particular user code) fails even for similar powers of the users. For this reason an accurate adaptive power control is critical for a good system performance.

Another possibility is the use of near–far resistant receivers. Since multiple-access-interference is a highly structured interference and the signature waveforms of all users are available at the central receiver, this additional knowledge may be exploited in the decision process. Multiuser detection has the capability of mitigating the near–far problem and providing a capacity increase in CDMA systems [4, 12]. On the other hand, since spatial diversity reception combats the fading effects of the channel, some multiuser receivers incorporating explicit antenna diversity have been also contemplated in the literature [5, 14]. The use of an antenna array has been also considered to cancel those users with higher power, avoiding the requirement of perfect power control [5].

However, most of the multiuser receivers developed so far do not consider the possibility of having interferences external to the system. We must take into account that most existing users in any given frequency band are narrow-band. A certain level of out-of-band spurious emission is unavoidable and, in fact, is legally permitted. In the limit when the interference gets very close to a base site, it can significantly degrade the capacity of the entire cell. Such interference from existing services to new mobile systems should be considered in the design of a high performance receiver.

Over the past two decades a significant body of research has been concerned with the development of
techniques for narrow-band interference supression in spread spectrum systems. Despite of much of this work has been motivated by the application of spread spectrum as an anti-jamming signaling method for military use, the developed anti-jamming techniques are equally applicable to the problem of narrow-band interference supression in cellular CDMA. An overview of these techniques for single sensor detection can be found in [8, 9]. Another possible kind of external interference is that one provoked by other-cell user, about which the centralized receiver has no information. This kind of interference would be a broadband one and should be also taken into account.

In this paper a new multisensor–multiuser scheme able to overcome the near–far problem, multipath fading and external interferences is presented. To make the presentation as clear as possible, the method is firstly presented for scenarios free of external interferences. Later on, the procedure is extended to cope with external interferences with independence of the nature of these interferences (narrow-band or broad-band).

The proposed method for the former scenario conceptually consists in the following: the received signal vector at the antenna array is fed to a bank of matched filters, each one matched to one of the \( K \) active users. The outputs are sampled every \( T \) seconds, each one synchronized to the corresponding source emission. From the corresponding filter output, a specific array covariance matrix is computed for each user. In absence of noise, each one of the \( K \) matrices is a linear combination of \( K \) rank-one matrices, each one of them formed by the outer product of the corresponding user spatial signature and weighted by the received user power. The coefficients of the linear combination are the autocorrelations and cross-correlations of the \( K \) codes. These coefficients are perfectly known in the multiuser receiver provided that the codes are perfectly synchronized. Thus, inverting the matrix of coefficients, the \( K \) rank-one matrices can be determined. Each spatial signature is exactly the eigenvector corresponding to the largest eigenvalue of the corresponding rank-one matrix.

The problem is further complicated in the presence of noise. In this case the inversion of the matrix of coefficients permits to obtain a noisy estimation of the rank-one matrices, but, again, the eigenvector associated to the largest eigenvalue of each matrix is the corresponding user spatial signature.

With the above information about the spatial signature a specific array weight vector can be computed for each user. A shorter version of the above method was presented in a previous publication [6]. It is enlarged herein and extended in order to cope with external interferences.

In the presence of external interference the user covariance matrices contain a supplementary term due to the interference which prevent from computing the rank-one matrices. The extension of the above method consists in utilizing an extra unused code and computing an additional covariance matrix. This matrix provides a new degree of freedom that permits to estimate the interference subspace. Then, the rest of matrices can be projected onto the subspace orthogonal to the interference subspace. This operation removes the supplementary terms associated to the external interference. The price paid for this operation is that it is no longer possible to estimate the true spatial signatures but its projection onto the subspace orthogonal to the external interferences. Nevertheless, the multiple access interference can be cancelled using the projected spatial signatures, at the expense of increasing the noise in each user output. In addition to the spatial processing, further improvements can be achieved using also some temporal processing [5].

The rest of the paper is organized as follows. The next section introduces some considerations about the channel and describes the signal model. In Section 3 the basic ideas of the proposed detector to extract multiple users in absence of external interferences are formulated. In Section 4 the method of Section 3 is extended to the case of having interferences external to the system. Even though both sections could be jointly derived, they are herein separated for the sake of clarity in the exposition. Section 5 presents some simulation results and, finally, in Section 6 some general conclusions are drawn.

2. Channel considerations and signal model

Radio propagation in mobile environments presents a time-varying multipath caused by reflections and scattering. The mobile channel is basically described by the fading amplitude statistics and the channel coherence bandwidth, which is roughly the inverse of the multipath delay spread. Both features are very
relevant to CDMA performance. The first one because it is responsible for variations of power among different users. The second one because it determines whether temporal diversity is feasible for a specific system or if another kind of diversity is necessary.

The fading amplitude statistics are typically described as Rician or Rayleigh. When a dominant line-of-sight path exists between the transmitter and the receiver, the global received envelope is a Rician stochastic process. If the direct path is obstructed (shadowing) the statistic of the received envelope is said to be Rayleigh.

From now on, it will be considered that the spread bandwidth is smaller than the channel bandwidth, or equivalently that the channel appears frequency non-selective to the spread spectrum signal. Thus, the transmitted signal is simply multiplied by the channel response \([11]\). The array signal vector (a column vector of \(N\) elements, with \(N\) the number of sensors) can be written as follows:

\[
x(t) = [x_1(t), x_2(t), \ldots, x_N(t)]^T = s(t)h(t),
\]

where \(h(t)\) is the transfer function vector whose components are the time-varying channel responses for each sensor. The superindex \(^T\) denotes transposition.

\(h(t)\) is the sum of the line-of-sight steering vector and the multipath component \([11]\). The multipath component is summed to the direct path with an amplitude depending on the value of the Rician parameter \(R\) (the ratio of the power in the dominant path to the power in the scattered paths). If \(R\) is expressed in linear units,

\[
h(t) = \sqrt{\frac{R}{R + 1}}h_d(t) + \frac{1}{\sqrt{R + 1}}h_m(t).
\]

In the above expression, \(h(t), h_d(t)\) and \(h_m(t)\) are normalized so that all of them have mean power equals 0 dB.

A general channel model which will be used in the simulations is the one that assumes a motion with uniform velocity \(\mathbf{v}\) for the array. In this case, the channel vector can be written as

\[
h_d(t) = s_d e^{j2\pi f_d t},
\]

where \(s_d\) is the direction of arrival DOA vector for the direct path (an \(N\)-dimension column vector) and \(f_d\) the Doppler frequency shift:

\[
s_d,i = e^{j2\pi f_d k_d r_i/c}, \quad i = 1, \ldots, N,
\]

\[
f_d = \frac{f_0 k_d v}{c},
\]

with \(k_d\) the unitary wave propagation vector for the line of sight, \(r_i\) the position vector of sensor \(i\) related to the first sensor and \(c\) the propagation speed.

The expression for \(h_m(t)\) is

\[
h_m(t) = \sum_{p=1}^{P} a_p s_p e^{j2\pi f_p t}.
\]

The complex amplitudes \(a_p\) for each path are independent complex valued random variables. Each path has a DOA vector \(s_p\) and Doppler shift \(f_p\) depending on its angle of arrival.

Let us consider a \(K\)-user asynchronous DS-CDMA system using BPSK modulation and operating over the described frequency non-selective channel. The baseband signal for the \(k\)th user is given by

\[
s_k = \sum_m d_k[m]b_k(t - mT).
\]

The data stream \(d_k[m] \in \{+1, -1\}\) is pulse amplitude modulated by the code waveform \(b_k(t)\), with \(b_k(t) = 0\) for \(t \notin \{0, T\}\) and \(T\) the bit time.

\[
b_k(t) = \sum_{l=0}^{L-1} g_{kl} P_{T_c} (t - lT_c),
\]

\(g_{kl}\) is the \(l\)th chip in the \(k\)th code and \(P_{T_c}\) is a rectangular pulse of duration \(T_c = T/L\).

For the rest of the paper the channel response \(h(t)\) for user \(k\) will be denoted as \(a_k(t)\). Note that the channel response \(a_k\), also known as the generalized steering vector or spatial signature of the \(k\)th signal, coincides with the direction of arrival DOA vector for non-multipath channels, that is, with \(R = \infty\). From now on, in order to clarify the notation, the explicit indication of the temporal dependence of the spatial signatures will be dropped. It should be, however, considered implicitly, since the usual situation in mobile channels is to have time-varying spatial signatures.

The variation with time of \(a_k\) depends on the coherence time of the mobile channel. By the moment, the only assumption taken about the time-varying nature
of the spatial signature \( a_k \) is that it is slowly varying compared to the symbol time: \( a_k(t) \cong a_k(t + T) \). Later on, a more restrictive assumption about the time-varying nature of \( a_k \) will be specified.

Thus, the received baseband signal for the multi-channel case is

\[
x(t) = \sum_{k=1}^{K} \sqrt{p_k} s_k(t - \tau_k) a_k + n(t),
\]

(9)

\( p_k \) and \( \tau_k \in [0, T) \) are, respectively, the power and the propagation delay for the \( k \)th user and \( n(t) \) is the complex 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. \( (N_0/2) \) is the bandpass noise power spectral density.

In the presence of external interference, the received baseband signal vector becomes

\[
x(t) = \sum_{k=1}^{K} \sqrt{p_k} s_k(t - \tau_k) a_k + A_I i(t) + n(t).
\]

(10)

Matrix \( A_I \) contains the spatial signatures of the external interfering signals and vector \( i(t) \) contains the interfering signals at time \( t \):

\[
A_I = [a_{K+1} \ldots a_{K+I}],
\]

(11)

\[
i(t) = [i_1(t) \ldots i_I(t)]^T,
\]

(12)

with \( I \) the number of external interferences. In this work, no assumption about the temporal structure of the interferences is made.

\[11\]

3. Multiuser separation

In this section a robust method to successfully extract the signals of multiple users in an asynchronous CDMA system is presented.

The basic scheme of the receiver is shown in Fig. 1. In what follows, mathematical details of the method are given. The received signal vector at the antenna array is fed to a bank of matched filters, each one matched to one of the \( K \) active users. The outputs are sampled every \( T \) seconds, each one synchronized to the corresponding source emission.

The sampled output of the \( l \)th matched filter is

\[
z_l[n] = \frac{1}{T} \int_{nT + \tau_l}^{(n+1)T + \tau_l} x(t) b_l(t - nT - \tau_l) \, dt,
\]

\[l = 1, 2, \ldots, K\]

(13)

Let

\[
c_{kl}[n] = \frac{1}{T} \int_{nT + \tau_l}^{(n+1)T + \tau_l} s_k(t - \tau_k) b_l(t - nT - \tau_l) \, dt
\]

\[
= \frac{1}{T} \int_{0}^{T} s_k(u + nT + \tau_l - \tau_k) b_l(u) \, du.
\]

(14)

After some mathematical manipulation we arrive at

\[
c_{kl}[n] = \beta_{kl} d_k[n] + \gamma_{kl} d_k[n + \text{sgn}(\tau_l - \tau_k)],
\]

(15)

where

\[
\text{sgn}(\tau) = \begin{cases} 1, & \tau \geq 0, \\ -1, & \tau < 0. \end{cases}
\]

(16)

and

\[
\beta_{kl} = \frac{1}{T} R_{b_l b_l}(\tau_l - \tau_k),
\]

(17)

\[
\gamma_{kl} = \frac{1}{T} R_{b_l b_l}(\tau_l - \tau_k - \text{sgn}(\tau_l - \tau_k)T),
\]

(18)

\( R_{b_l b_l}(\tau) \) denotes cross correlation function between the \( k \)th and \( l \)th codes at lag \( \tau \), that is

\[
R_{b_l b_l}(\tau) = \int_{0}^{T} b_l(t + \tau) b_l(t) \, dt.
\]

(19)

Note that \( \beta_{lk} = \beta_{kl}, \gamma_{lk} = \gamma_{kl} \) and for the \( k \)th user

\[
\beta_{kk} = \frac{1}{T} R_{b_k b_k}(0) = 1,
\]

(20)

\[\gamma_{kk} = 0.\]

(21)

Finally, Eq. (13) may be written as

\[
z_l[n] = \sum_{k=1}^{K} \sqrt{p_k} c_{kl}[n] a_k + n_l[n],
\]

(22)

where \( n_l \) is the noise vector filtered by the \( l \)th filter.

From the corresponding filter output, a specific array covariance matrix is computed for each user. Consider the spatial covariance matrix for the \( l \)th
user:

\[ R_{z,l} = E\{ z_l[n] z_l^H[n] \} \]

\[ = \sum_{k=1}^{K} \sum_{r=1}^{K} \sqrt{p_k p_r} E\{ c_{kl}[n] c_{lr}^*[n]\} a_k a_r^H \]

\[ + E\{ n_l[n] n_l^H[n] \}, \]

(23)

\( E\{ \cdot \} \) and \( \{ \cdot \}^H \) denote expectation and complex conjugate transpose, respectively.

Assuming that the symbols are uncorrelated,

\[ E\{ c_{kl}[n] c_{lr}^*[n] \} \]

\[ = E\{ (\beta_{kl} d_k[n] + \gamma_{kl} d_k[n + \text{sign}(\tau_l - \tau_k)]) \times (\beta_{lr} d_r[n] + \gamma_{lr} d_r[n + \text{sign}(\tau_l - \tau_r)]) \} \]

\[ = (\beta_{kl}^2 + \gamma_{kl}^2) \delta_{kl}, \]

(24)

where \( \delta_{kl} \) is the Kronecker delta.

The spatial covariance matrix of the filtered noise is

\[ E\{ n_l[n] n_l^H[n] \} = \sigma_l^2 I_N = \frac{N_0}{T} I_N. \]

(25)

\( I_N \) is the identity matrix with dimension \( N \times N \).

Then, it can be concluded

\[ R_{z,l} = \sum_{k=1}^{K} p_k (\beta_{kl}^2 + \gamma_{kl}^2) a_k a_k^H + \sigma_l^2 I_N, \]

\( l = 1, \ldots, K. \)

(26)

Note that regardless of the noise term, the \( l \)th user spatial covariance matrix is a linear combination of \( K \) rank-one matrices \( p_k a_k a_k^H \), where \( a_k \) is the spatial signature of the \( k \)th user. The coefficients of the linear combination are very well known provided that the codes are perfectly synchronized. These coefficients can be grouped into a \( K \times K \) matrix \( B \). The element at the \( k \)th row and \( l \)th column of matrix \( B \) is

\[ [B]_{kl} = \beta_{kl}^2 + \gamma_{kl}^2. \]

(27)

Note that from Eqs. (20) and (21) the elements in the main diagonal are the unity.

Defining now the following \( KN \times N \) matrices:

\[ S = \begin{bmatrix} p_1 a_1 a_1^H \\ p_2 a_2 a_2^H \\ \vdots \\ p_K a_K a_K^H \end{bmatrix}, \quad R_z = \begin{bmatrix} R_{z,1} \\ R_{z,2} \\ \vdots \\ R_{z,K} \end{bmatrix}, \]

(28)

\[ N = [\sigma_1^2 \quad \sigma_2^2 \quad \ldots \quad \sigma_K^2]^T \otimes I_N = \frac{N_0}{T} I \otimes I_N, \]

where the symbol \( \otimes \) denotes the Kronecker or tensor product and \( I \) is an all ones column vector with dimension \( K \), the expression (26) can be written in a more compact form as

\[ R_z = (B \otimes I_N) S + \frac{N_0}{T} I \otimes I_N. \]

(29)

Matrix \( R_z \) groups all the user spatial covariance matrices and so it will be referred from now on as the multiuser spatial covariance matrix. For similar reasons, matrix \( S \) will be called multiuser noise-and-interference-free spatial covariance matrix.
A noisy estimation of the latter matrix can be obtained by simply multiplying the matrix $R_z$ by the inverse of the Kronecker product of matrices $B$ and $I_N$:

$M = (B^{-1} \otimes I_N)R_z = S + \frac{N_0}{T}u \otimes I_N,$

(30)

where

$u = B^{-1}1.$

(31)

Matrix $M$ can be seen as a linear combination of the user spatial covariance matrices $R_{z,1} \ldots R_{z,K}$. Considering now $M$ partitioned into $K$ blocks with dimension $N \times N$ as follows:

$M = \begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_K \end{bmatrix}$.

(32)

The part of the matrix $M$ corresponding to the $k$th user is

$M_k = p_k a_k a_k^H + u_k \frac{N_0}{T} I_N,$

(33)

where $u_k$ is the $k$th element of vector $u$.

Matrix $M_k$ have $N - 1$ eigenvalues equal to $u_k N_0 / T$ and one different eigenvalue equal to $p_k |a_k|^2 + u_k N_0 / T$. The key issue to remark is that the eigenvector associated with this eigenvalue is exactly the spatial signature of the $k$th user.

In practical situations, the multiuser spatial covariance matrix is not known and must be estimated from measurements. The standard estimate is the ML estimate. So the $l$th user spatial covariance matrix can be estimated as

$\hat{R}_{z,l} = \frac{1}{M} \sum_{n=1}^{M} z_l[n] z_l^H[n],

(34)$

with $M$ the number of measured snapshots. To do so, the spatial signatures have to remain constant for the block size in which $R_{z,l}$ is estimated. This condition is a reasonable one, since the required number of symbols for proper operation of the algorithm is relatively small as it will be seen in Section 5.

In this case the spatial signature of the corresponding user is not exactly the main eigenvector of the associated matrix $M_k$. Nevertheless, this eigenvector represents an accurate spatial signature estimate. The estimation improves with the increase of the number of samples used to estimate the user spatial covariances matrices.

Thus, the problem of estimating the user spatial signatures has been reduced to compute the eigenvector associated to the largest eigenvalue of each one of the $K$ matrices $M_k$. There are several efficient algorithms to solve this problem. An adaptive version of one of these algorithms was developed in [7] in order to make the receiver robust to channel variations and to reduce the computational load required by the $K$ direct eigenvalue decompositions. In the adaptive version, the covariance matrices and so the main eigenvectors are iteratively estimated. Thus, the condition of having constant spatial signatures for several symbols is not necessary.

Once the spatial signatures for all the users have been estimated, a specific beamformer for each of them can be designed. A simple design which will be used further on in the simulations is the linear-constrained minimum noise power beamformer. It is defined as the weight vector that minimize the noise power at the output, subject to the constraints of having unit gain for the desired user and nulling the other users. Such a beamformer appears, e.g., as an estimator of the signals given their directions [1] and it can be seen as the spatial domain linear MMSE multiuser detector. The well-known solutions for all the users can be compacted in the weight matrix $W$ whose columns are the weight vectors for the $K$ users,

$W = \hat{A} (\hat{A}^H \hat{A})^{-1} I_K,$

(35)

where $\hat{A}$ is the matrix which columns are the estimated spatial signatures,

$\hat{A} = [\hat{a}_1 \ldots \hat{a}_l \ldots \hat{a}_K],

(36)$

and $I_K$ the identity matrix with dimension $K \times K$.

Note that for the computation of the array weight vectors only the estimated spatial signatures are required. Nevertheless, the algorithm herein proposed provides also an accurate received power estimate for different users. The power estimates could be used, if it was necessary, for power control purposes.
4. Multiuser separation and external interference suppression

The multiuser detector described in the above section, as other multiuser detectors, has been developed under the assumption of having no external interferences to the system. Thus, despite of being robust to multiple-access interference, in the presence of external interferences, this method fails, as those multiuser detectors which do not take into account this problem.

In this section, some modifications into the previous algorithm are introduced, in order to cope also with external interferences. The new algorithm increases the degree of freedom number, in order to estimate the interference subspace. This is achieved by means of an extra equation, which can be obtained using an additional filter matched to an unused code. Thus, the spatial signatures of the users and the interference subspace are estimated from the augmented multiuser spatial covariance matrix. This augmented matrix is composed by \( K + 1 \) user spatial covariance matrices, one matrix for each user plus the additional matrix from the unused code.

Let us see now step by step the required modifications of the algorithm. The received snapshot vector now is fed to a bank of \( K + 1 \) filters (see Fig. 2). Each one of the first \( K \) filters is matched to one of the \( K \) active users of the system. The last one is matched to an unused code.

Using now the expression (10) for the received baseband signal vector and following the same steps as in the previous section, the spatial correlation matrix at the output of the \( l \)th filter is now

\[
R_{z,l} = \sum_{k=1}^{K} p_k \left( \beta_{kl}^2 + \gamma_{kl}^2 \right) a_k a_k^H + A_l Q_l A_l^H + \sigma_l^2 I_N,
\]

\( l = 1, \ldots, K + 1, \)  \hspace{1cm}  (37)

where \( A_l \) is the interference spatial signature matrix as defined in Eq. (11), and

\[
Q_l = E\{i_l[n]i_l^H[n]\}
\]

(38)

being

\[
i_l[n] = \frac{1}{T} \int_{nT+\tau_l}^{(n+1)T+\tau_l} i(t)b_l(t-nT-\tau_l) \, dt,
\]

\( l = 1, 2, \ldots, K + 1, \) \hspace{1cm}  (39)

the sampled response of the \( l \)th filter to the interference vector \( i(t) \).

The expression (37) is the same as equation (26) in the precedent section with an extra term which is the spatial covariance matrix part corresponding to the external interference. The number of available spatial covariance matrices is now \( K + 1 \).

Substituting (39) into (38), \( Q_l \) can be written as

\[
Q_l = \frac{1}{T^2} \int_0^T \int_0^T \Gamma_l(u-v) b_l(u)b_l(v) \, du \, dv
\]

\[
= \frac{1}{T^2} \int_{-T}^T \Gamma_l(\lambda) R_{b_l b_l}(\lambda) \, d\lambda,
\]

(40)

where \( \Gamma_l(\tau) \) is the interference covariance matrix defined as

\[
\Gamma_l(\tau) = E\{i_l(t+\tau)i_l^H(t)\}.
\]

(41)

Let us define now matrices \( S' \) and \( R_l \) as follows:

\[
S' = \begin{bmatrix}
p_{1} a_1 a_1^H \\
p_{2} a_2 a_2^H \\
\vdots \\
p_{K} a_K a_K^H
\end{bmatrix}, \quad R_l = \begin{bmatrix}
A_l Q_l A_l^H \\
\vdots \\
A_l Q_{K+1} A_l^H
\end{bmatrix}.
\]

(42)

\( \mathbf{0} \) is an all zeros matrix with dimension \( N \times N \).

In these conditions, the augmented multiuser spatial covariance matrix as defined in (28) can be written as

\[
R_z = (B \otimes I_N) S' + R_l + \frac{N_0}{T} \mathbf{1} \otimes I_N.
\]

(43)

Regardless of the interference spatial covariance matrix \( R_l \), expression (43) looks like Eq. (29). Note, however, that now the dimension of matrix \( R_z \) and \( S' \) are \( (K + 1)N \times N \). Matrix \( S' \), which is the augmented multiuser noise-and-interference-free spatial covariance matrix, could be defined as in Eq. (28) with \( p_{K+1} = 0 \). Matrix \( B \) is also defined as in Eq. (27), but now it has dimension \( (K + 1) \times (K + 1) \). Finally, the vector \( \mathbf{1} \) is also \( (K + 1) \) dimensional.

Operating now upon matrix \( R_z \), as in the previous section, a new matrix \( M \) is obtained. This new matrix can be partitioned into \( K + 1 \) blocks with
Fig. 2. Multisensor–multiuser receiver resistant to external interferences.

\[
M = (B^{-1} \otimes I_N) R_z = \begin{bmatrix}
M_1 \\
\vdots \\
M_{K+1}
\end{bmatrix}, \tag{44}
\]

The part of \( M \) corresponding to the \( k \)th user is

\[
M_k = p_k a_k a_k^H + A_I \bar{Q}_k A_I^H + u_k \frac{N_0}{T} I_N, \quad k = 1, \ldots, K, \tag{45}
\]

\( u_k \) is the \( k \)th element of vector \( u = B^{-1} 1 \) and \( \bar{Q}_k \) is calculated as the \( k \)th part of matrix:

\[
\bar{Q} = \begin{bmatrix}
\bar{Q}_1 \\
\vdots \\
\bar{Q}_{K+1}
\end{bmatrix} = (B^{-1} \otimes I_I) \begin{bmatrix}
Q_1 \\
\vdots \\
Q_{K+1}
\end{bmatrix}, \tag{46}
\]

\( I_I \) is the identity matrix with dimension \( I \times I \), with \( I \) the number of external interferences.

The last part of \( M \), corresponding to the \( K + 1 \) filter, is

\[
M_{K+1} = A_I \bar{Q}_{K+1} A_I^H + u_{K+1} \frac{N_0}{T} I_N, \tag{47}
\]

\( u_{K+1} \) is the \((K + 1)\)th element of vector \( u \). The signal subspace component in matrix \( M_{K+1} \) contains only information about the external interferences. The other \( K \) matrices have information about the external interferences and the signal of the corresponding user. The main eigenvector in this case, depending on the signal power balances, may be quite different from the spatial signature of any of the involved users. Nevertheless, it is possible to eliminate the information relative to the external interferences in each \( M_k \) with \( k \neq K + 1 \). For this purpose, from the signal subspace of \( M_{K+1} \), the projection matrix onto the interference orthogonal subspace is computed. This projection matrix is

\[
P_\perp \equiv I_N - A_I (A_I A_I^H)^{-1} A_I^H E_n, K+1 \tag{48}
\]

\( E_{n,K+1} \) is the noise subspace of matrix \( M_{K+1} \). Its columns are the noise subspace eigenvectors. \( E_{s,K+1} \) is the signal subspace of matrix \( M_{K+1} \). Its columns are the signal subspace eigenvectors. Note that it is not necessary to calculate the spatial signatures of the interferences individually (matrix \( A_I \)). \( P_\perp \) can be computed from the whole signal subspace or noise subspace.

Next step is the projection of each submatrix \( M_k \) \((k = 1, \ldots, K)\) onto the subspace orthogonal to the interference subspace. As a result of the projection, each matrix \( P_\perp M_k \) \((k = 1, \ldots, K)\) has only one signal eigenvector: \( a_{p,k} \). This eigenvector is the spatial signature of the corresponding user projected onto the subspace orthogonal to the external interference. The associated eigenvalue in this case is equal to \( p_k |a_{p,k}|^2 + u_k \sigma^2 / T \). Note that it is not necessary the
knowledge of the $\tilde{Q}_i$ matrices. In fact, they cannot be computed, but fortunately they are removed in the projection operations.

Again, with this information a specific beamformer for each user may be computed, able to null external and multiple access interference. From the estimated spatial signatures, the weight vector for the $k$th user is the $k$th column of matrix $W$:

$$W = \hat{A}_P \left( \hat{A}_P^H \hat{A}_P \right)^{-1} I_K,$$

(49)

with $\hat{A}_P = [\hat{a}_P,1 \ldots \hat{a}_P,k \ldots \hat{a}_P,K]$ the estimated projected spatial signatures matrix and $I_K$ the identity matrix with dimension $K \times K$.

If the user spatial covariance matrices were perfectly known, it would be possible to obtain the exact projected spatial signatures of all the active users with independence of their respective powers and the power of the external interferences. Thus, the proposed detector would be perfectly near–far resistant provided that an enough number of degrees of freedom was available (number of antenna elements). The use of estimated matrices instead of actual ones degrades the performance of the system. The degradation depends on the near–far ratio and the number of samples used to estimate the spatial covariance matrices. However, the extensive simulations carried out by the authors have shown that the performance of the proposed approach is excellent for a large near–far dynamic range (40–50 dB) even using a small number of samples to estimate the spatial autocorrelation matrices.

4.1. Summary of the proposed algorithm

The practical use of the proposed spatial decorrelator can be summarized into the following steps:

Step 1. Filtering of the received signal vector $x(t)$ by a bank of $K + 1$ filters ($K$ filters matched to the $K$ active users plus one filter matched to an unused code). The outputs, sampled every $T$ seconds, are the $K + 1$ filtered snapshots:

$$z_i[n] = \frac{1}{T} \int_{nT+\tau_i}^{(n+1)T+\tau_i} x(t) b_i(t - nT - \tau_i) \, dt,$$

$l = 1, 2, \ldots, K + 1$.

Step 2. Estimation of the $K + 1$ user spatial covariance matrices from $M$ measured snapshots:

$$\hat{R}_{z, l} = \frac{1}{M} \sum_{n=1}^{M} z_i[n] z_i^H[n], \quad l = 1, 2, \ldots, K + 1.$$

Step 3. Computation of the multiuser spatial covariance matrix:

$$R_z = [\hat{R}_{z, 1}^T \hat{R}_{z, 2}^T \ldots \hat{R}_{z, K+1}^T]^T.$$

Step 4. Linear combination of the user spatial covariance matrices:

$$M = (B^{-1} \otimes I_N) R_z,$$

where matrix $B$ contains the partial cross-correlations among the $K + 1$ codes and $I_N$ is the identity matrix with dimension $N \times N$.

Step 5. Partitioning matrix $M$ into $K + 1$ blocks of dimension $N \times N$:

$$M = [M_1^T \ M_2^T \ldots \ M_{K+1}^T]^T.$$

Step 6. Computation of $P_\perp$ (the projection matrix onto the orthogonal subspace to the external interference) from the signal subspace or noise subspace of matrix $M_{K+1}$ (which contains only information about the external interference):

$$P_\perp = I_N - E_{s,K+1} E_{s,K+1}^H.$$

Step 7. Projection of the rest of matrices $M_1 \ldots M_K$, to eliminate the information relative to the external interferences:

$$P_\perp M_k, \quad k = 1, \ldots, K.$$

Step 8. Computation of the main eigenvector of the projected matrices, which is the spatial signature of the corresponding user projected onto the orthogonal subspace to the external interference:

$$\hat{a}_{P,k} = \text{main\_eigenvector}(P_\perp M_k), \quad k = 1, \ldots, K.$$

Step 9. Computation of the matrix whose columns are the weight vectors for the $K$ active users, able to null external and multiple access interference:

$$W = \hat{A}_P (\hat{A}_P^H \hat{A}_P)^{-1} I_K,$$

with $\hat{A}_P = [\hat{a}_P,1 \ldots \hat{a}_P,k \ldots \hat{a}_P,K]$ the estimated projected spatial signatures matrix and $I_K$ the identity matrix with dimension $K \times K$. 

5. Simulation results

Many simulations have been conducted by the authors exploring the performance of the spatial signature separation algorithm in both cases with and without external interferences. For the former, some results were presented in previous publication [6]. Therefore, the results presented in this paper are concentrated in showing the performance of the algorithm when external interferences are presented in the scenario.

For this purpose, an asynchronous CDMA system was simulated. The modulating signals were Gold sequences with length \( L = 31 \). Four active system users (\( K = 4 \)) were considered and an array of eight \( \lambda/2 \) linearly spaced sensors (\( N = 8 \)) was used. Two types of interference external to the system were studied: a BPSK signal with random chips and the same chip rate as the CDMA system signals (broad-band interference) and a sinusoid at the carrier frequency (narrow-band interference).

We considered firstly the case of point sources, that is, each source arriving from one single direction. The angles of arrival were \( 20^\circ, 38^\circ, 45^\circ \) and \( 70^\circ \) from broadside for the cell users and \( 80^\circ \) for the external interfering signal. The relative propagation delays for the known users were \( \tau_1 = 0, \tau_2 = 2T_c, \tau_3 = 5T_c \) and \( \tau_4 = 7T_c \). At the receiver five matched filters were used. They were matched to the users from first to fourth one, and synchronized with the corresponding one. The fifth filter was matched to an unused Gold code. The correlation matrix at the output of the matched filters bank was estimated by temporal averaging of the despreaded signal vectors, using a block size of 30 symbols. The signal-to-noise ratios (SNR) at every sensor were \(-5, 0, 5, 0 \) and \( 10 \text{ dB} \), respectively, before the despreading.

In the above scenario and for the codes and time delays considered, the signal-to-noise-plus-interference ratios after the despreading (SNIR\(_d\)) were \(-3.18, 3.95, 8.64 \) and \( 2.82 \text{ dB} \), respectively, for the four system users. These values correspond to the performance in terms of output SNIR of the conventional CDMA receiver, that is, a single matched filter for each user. Under the above conditions and using the signals at the output of the bank of matched filters in the way described in the paper, the beamformers designed for the 1st (solid line) and 2nd user (dashed-dotted line, \( \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \) ) are shown in Fig. 3. For the sake of clarity the beamformers corresponding to the third and fourth system user are not depicted in this figure.

It can be observed how every beamformer nulls the multiple-access interference due to the other users as well as the external interference.

Fig. 4 compares the performance of the conventional detector (a single matched filter for each user) with the performance of the method proposed in this paper, as a function of the external interference power. Regardless of the power variation for the external interference, the rest of the signal scenario is the same that in previous simulation. (It is worth remarking that the lowest signal-to-noise-plus-interference ratio after the despreading SNIR\(_d\) correspond to the first user.) The figure plots the output signal-to-noise-plus-interference ratio for the first user (SNIR\(_1\) ) versus the interference to signal ratio before the despreading, also for the first user (ISR\(_1\) ). The dashed and solid with sign plus lines correspond to the proposed method when exact and estimated user spatial covariance matrices are used, respectively. The performance of the conventional receiver is illustrated by the dashed-dotted line. Two other curves have been included in the same figure in order to obtain a clearer interpretation of the results. Their meanings will be explained further on.

For the conventional detector two regions can be distinguished. In the first region, approximately until \( 0 \text{ dB} \) of ISR\(_1\) (before the despreading), the receiver performance is basically limited by noise and multiple-access interference. Thus, it is independent of the power of the external interference. In the second region, where the interference power is greater than the power of the signal of the first user, the performance of the detector is mainly limited by the power of the interference. Anyway, the performance of this detector is very poor for this signal scenario, and it is clearly outperformed by the proposed detector.

Assuming that the user spatial correlation matrices at the output of the matched filters bank are perfectly known, the performance of the proposed detector is independent of the power of the interference (dashed line in Fig. 4).

In reality, the \( K + 1 \) spatial correlation matrices may only be estimated from a finite number of snapshots. The solid line with plus sign in Fig. 4 corresponds to this case, where the matrices are estimated from 30 snapshots after the despreading. Even though
some degradation occurs because of the matrix estimation, the performance is still very good and clearly much better than that from the classical receiver. In this curve there are also two well delimited regions and a transition zone between them. In the left region, the dominant effect stems from the multiple access interference as in the classical receiver. However, in this case the proposed detector practically nulls this interference. Paradoxically, the performance in this region is degraded with respect to the right region because of the low power of the external interference. This feature is inherent to the method. In effect, when the interference power is low, the interference subspace is poorly estimated. Then, when the corresponding matrix $M_1$ is projected onto the orthogonal subspace, the noise increases. On the contrary, when the external interference power is high enough, as in the right region, the interference subspace is better estimated and in consequence the performance improves.

In order to compare the proposed method with and without projection, two more curves were plotted in the same figure. The dotted curve shows the output SNIR achieved by the first user when the beamformer is computed from the exact non-projected spatial signatures of the system users. The solid line curve without plus sign depicts the performance of the beamforming computed from the estimated non-projected spatial signatures, that is, from the main eigenvector of each matrix $M_k$ ($k = 1, \ldots, K$) in Eq. (45). In the left region, the output SNIR in both cases is practically the same and even better than that obtained with the beamformer computed from the exact projected spatial signatures. Even though the interferences are completely nulled with the latter beamformer, the output noise level is higher than the noise plus interference obtained with the non-projected beamformers. The performance improvement obtained in the left region by the non-projected beamformer is even more significant with respect to the estimated projected beamformer. In this case the two previously mentioned effects occur: projection noise and noise from the poor estimation of the interference subspace. In the right region, on the contrary, the performance
of the non-projected beamformers degrades strongly with the interfering power increase.

Because of the degradation caused by the projection operation for low values of the interfering power, some refinement could be introduced in the proposed method in order to improve the performance for the whole dynamic range of interfering powers. It would consist in blocking the projection whenever the interference did not reach a certain threshold level. This would be equivalent to use the method of Section 3 as if the interference were not present. Above the threshold, the complete method of Section 4, which projects the matrices $M_k$ ($k = 1, \ldots, K$) onto the orthogonal subspace to the interference, would be used.

The optimal threshold is theoretically given by the interfering power which provides the same output SNIR for both cases: with and without projection. Unfortunately, both SNIRs are not known a priori. Their estimations require a high computational burden and it is not clear that they provide the most suitable criterion to decide if the projection should be avoided.

Simpler criteria are currently being investigated based on the interference to noise ratio at the filter outputs. This information could be directly extracted from the eigenvalues of matrix $M_{K+1}$. Note, however, that this further refinement is not essential for the proper operation of the method proposed in this paper since, actually, the performance loss due to the projection for low values of the interference power is small.

The curve obtained using the main eigenvectors of non-projected matrices $M_1$, $M_2$, $M_3$ and $M_4$ (solid line) also presents an anomalous behavior in the right region when compared with the curve achieved using the exact spatial signatures of the four system users. Seemingly, the performance is quite good even for extremely high interference powers. What occurs in fact is that the main eigenvector of the non-projected matrices $M_k$ ($k = 1, \ldots, K$) in Eq. (45) is practically the spatial signature of the interference. Thus, every user beamformer tries to set nulls and unit gain in spatial signatures which are very close. In addition, the estimated spatial signature for each user if far away from
the corresponding true spatial signature. This behavior is absolutely unpredictable and strongly depending on the involved scenario. The method without projection is not recommendable when an interference with an appreciable power level is present. Fig. 5 illustrates this effect. Note that the external interference signal is cancelled as it is the only spatial signature detected. The radiation pattern is very distorted, which results in a high output noise power. Finally, the gain for all the users is completely random.

The performance of the method for the narrow-band interference is shown in Fig. 6. The signal scenario is the same that in the above simulations except for the interference which now consists of one sinusoid of frequency equal to that of the carrier frequency of the CDMA signals. The results are very similar to those obtained for the broad-band interference case. The only difference is that the bend of all the curves are shifted to the right region more than 15 dB. The explanation is that the code gain of a CDMA system is higher for a narrow-band interference than for a broad-band one.

The code gain with respect multiple access interference in all of the presented cases is smaller than that achieved in a synchronous system. Specifically, for the four users the gain with respect to each other is reduced from almost 30 dB to a lower value which is given by matrix $B$. For the codes and time delays herein considered the corresponding matrix $B$ is

$$B \text{(dB)} = \begin{bmatrix}
29.83 & 19.08 & 18.13 & 6.99 \\
18.13 & 6.99 & 29.83 & 16.90 \\
\end{bmatrix}$$

The off-diagonal (cross-correlations) entries would be 0 dB (note that matrix $B$ is expressed in dB) for a perfect synchronism among users.

The results presented so far correspond to the case of point sources, that is, the sources arrive at the receiver from one single direction of arrival. In this case, the spatial signature corresponds to the direction of arrival DOA vector. Nevertheless, since there is no model assumption for the spatial signature, the same procedure can be applied to estimate the
spatial signature when the signals arrive from multiple reflections, while other classical DOA estimation methods as MUSIC fail in this situation. To illustrate this assertion, Fig. 7 depicts the same output SNIR curves that in previous simulations for the same multiple access interference scenario with a broad-band external interference, but considering a Rayleigh channel. (Only for the classical detector the channel was not assumed to be Rayleigh but Gaussian with unit gain.) The Rayleigh channel, according to the model presented in Section 2, corresponds to the case of having a Rician factor equal 0 (linear units). On the other hand, the velocity parameter in the model was chosen low enough for all the signals, so that it was possible to assume that the channel was stationary during the 30 symbols where the user covariance matrices were estimated.

As it can be observed in Fig. 7, the same general behaviors obtained in the case of point sources (Fig. 4) are obtained in this case.

All the results presented herein corresponding to the output SNIR were computed by averaging 100 independent runs.

6. Conclusions

This paper has introduced a new array processing method for spatial signature estimation in CDMA systems, in the presence of interferences external to the system. The estimated spatial signatures can be used in the design of specific beamformers for all the active users able to cope with multiple access and external interferences. Simulation results have verified the efficacy of this innovative method in severe scenarios with strong near–far effect and very high external interference power.

An important feature of this array signal processing method is that the number of user spatial signatures that can be estimated is independent of the number of array sensors N. The former can be much more
higher than the latter. Of course, the total number of signals that can be cancelled is $N - 1$. Nevertheless, the method can work with more interferences in a least-squares sense (over constrained-problem). In this case, the array cannot form nulls toward each interference direction but the performance can be still acceptable for many situations. This issue is currently under study.

The proposed method is very robust to array calibration errors, since no model is assumed for the steering vectors/spatial signatures in its formulation. The spatial signatures can be simply a source direction of arrival or be composed by several multipath reflections as expressed in Section 2. The spatial signatures are estimated working at the symbol rate, instead of the chip rate, and without any temporal reference or any a priori spatial information. The required information is the code waveforms and timing of active users, just the information required by the classical receiver.

Finally, the authors are devoting many efforts to extend this multiple-user separation method to cope with frequency-selective scenarios.

References


