Block Modulus Precoding for Blind Multiuser Detection of DS-CDMA Signals

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Abstract—In this letter, we propose a blind multiuser detector based on a new data precoding technique for direct-sequence code-division multiple-access signals. In this technique, the modulus of all users' data is block encoded, using a sequence that is unique for each user. This precoding method, together with the analytical constant modulus algorithm for detection, enables a closed-form, one-shot detection of the desired user's signal in a multipath channel using one or more antennas. The detection process does not involve or require a channel estimation step. The proposed detector is shown to be extremely near-far resistant, and can operate properly in the presence of severe carrier frequency offset.

Index Terms—Blind algorithms, constant-modulus (CM) algorithms, direct-sequence code-division multiple access (DS-CDMA), multipath channels, multiuser detection, precoding.

I. INTRODUCTION

MULTIUSER (MU) detection in direct-sequence code-division multiple-access (DS-CDMA) systems has attracted a lot of interest in the past few years, aiming at capacity and performance improvement of these systems. Blind detection techniques [1], [2], in particular, have been the focus of many researchers in this field, due to the well-known advantages (see [1]) of blind schemes compared to training-based nonblind ones. Blind methods for signal separation and MU detection are based on some known property of the desired signal. Use of higher order statistics (HOS), like the fourth-order cumulants [3], cyclostationarity, [4] or the constant modulus (CM) property of some digital signals, are typical examples of such techniques. In particular, use of the CM property for signal separation and equalization has been widely studied [5]. It has also been recently investigated in the context of MU detection [6], [7]. The CM techniques, however, employ nonlinear cost functions and exhibit local minima causing some problems in convergence of the gradient-based methods generally used to arrive at the solution. In [8], a reformulation of the problem of signal separation based on the CM property was introduced and termed the analytical CM algorithm (ACMA), which provides a closed-form, algebraic solution. However, the method involves a complex procedure of joint diagonalization of a number of matrices, and hence, its implementation in MU detection, such as in CDMA systems, becomes too complex for practical purposes.

In this letter, we propose a blind MU detector based on a new data precoding technique for DS-CDMA signals. In this technique, the modulus of all users' data is block encoded (hence, the term "block modulus precoding") to help in separation and detection of a desired user's signal and rejection of MU interference. In the detection process, we make use of the closed-form solution of the ACMA [8], which when used with our precoding method, leads to a simple, one-shot detection procedure. The resulting method is shown to have many good features. Besides being blind and extremely near-far resistant, it is applicable to multiple receive antennas with an improved performance. Furthermore, being a code-independent detector, it can operate reliably even in cases of severe carrier frequency offsets for various users. While the proposed method compares favorably with respect to other methods that make use of the knowledge of the desired user's code, a small performance loss in terms of signal-to-noise ratio (SNR) results due to its nonconstant modulus. This is, however, amply compensated for by its tolerance to frequency offset, even as it avoids the need for channel knowledge or estimation, in a multipath environment.

II. SIGNAL MODEL

We consider here a scenario of $K$ users in a quasi-synchronous DS-CDMA system using quadrature phase-shift keying (QPSK) modulation, and a linear antenna array of $M$ elements for signal detection. A short spreading code is used, i.e., the code period $P'$ is taken to be one bit or symbol period. Without loss of generality, it is assumed that each user signal arrives from $L$ paths. The assumption of quasi-synchronicity is meant here to imply that all the multipath signals arrive within a few chip durations (i.e., a maximum of $q$ chips with $q < C P'$). Thus, all the user signals are synchronized within the tolerance of a few chips. Hence, it will be possible (with negligible loss in performance) to carry out symbol detection using only those code chips that are free of intersymbol interference (ISI). The number of ISI-free chips shall be denoted by $P$. After downconversion, the received signal at the $m$th antenna is chip-matched filtered and sampled at the chip rate to give (in the absence of noise)

$$x_m(n,p) = \sum_{k=1}^{K} s_k(n) \sum_{i=1}^{L} a_{i,k,m} c_{k,i}(p)$$

where $a_{i,m} c_{k,i}(p)$ denotes the complex gain of the Mi path of the fcth user symbol arriving through the $Zk$th path, taking into consideration the array response at that element. $c_{k,i}(p)$ denotes the $i$th chip of the fcth user's code arriving through the $Zk$th path, taking into consideration the code delay in that path, and the chip pulse shape used. $s_k(n)$ denotes the $k$th user symbol at time instant $n$, and finally, $P$ denotes the process gain considering ISI-free
precoding, will be replaced by $S'$ which is given by

$$
\begin{align*}
\text{transmitted by user} \quad \text{Hence, the matrix } S \text{ in (3), with modulus } k.
\end{align*}
$$

$$
\begin{align*}
(4) \quad \text{fc}
\end{align*}
$$

$$
\begin{align*}
(5) \quad \text{fe}
\end{align*}
$$

$$
\begin{align*}
(6) \quad \text{k}
\end{align*}
$$

III. MODULUS PRECODING AND MU DETECTION

The CM property has been shown to be useful for signal separation and detection in DS-CDMA systems. However, the presence of multiple CM signals from different users generally complicates the detection process and requires methods that ensure detection/separation along with user association for all users.

The method proposed here is based on the same principle, and uses the data modulus, as in the previous CM algorithm (CMA) methods. However, unlike the CM methods, the modulus is not fixed for all the symbols, but is made variable in a predefined fashion over a block of data (we assume block symbol synchronization, which can be achieved in the quasi-synchronous system by using one pilot channel for all users). The resulting modulus is periodic with a period equal to the block length used, and this block modulus pattern is unique for each user. This pre-}

$$
\begin{align*}
(3) \quad \text{S}
\end{align*}
$$

Now, if the diagonal matrices \{M_j, i = 1, \ldots, K\} are selected such that $M^{-1} M_j$, $V^* \wedge j$, deviates considerably from I (identity matrix), then the columns of $X_{\nu}^*$ will be spanned by only one CM vector (viz., si), and $(K - 1)$ non-CM vectors. Hence, applying a CMA detector to $X_{\nu}^*$ should be an easy task now, since, after decoding, only one CM signal is present. Hence, signal detection and user association can be done simultaneously. As mentioned earlier, most CM methods are generally iterative in nature. However, we prefer here to study this precoding method together with a noniterative CMA procedure. More specifically, we use the ACMA [8], which now, using the proposed precoding technique, would have a unique solution corresponding to the desired user. This would enable detection and data association in a single step with a closed-form solution.

In the following, we describe the procedure for blind detection of the data of the desired user (say, user 1), without repeating the theoretical details of the ACMA, for which the reader is referred to [8]. The number of users is assumed to satisfy $K < P$, and only one receive antenna is assumed to be used.

1) Construct the matrix $X^*$ from the samples of the received signal, and construct $X_{\nu}^*$ as $M_{I}^T X_{\nu}^*$. It is easy to see that $X_{\nu}$ and $X_{\nu}^*$ each have a rank equal to $K$.

2) Perform the singular value decomposition on $X_{\nu}^*$ (i.e., $X_{\nu}^* = U \Sigma V^*$) and collect the left singular vectors corresponding to the $K$ most significant singular values, and stack them as rows of a new matrix $F$ of size $(K \times TV)$. Next, we must find $w$ (a row vector of size $K$), the combining vector that operates on $F$ to extract the desired unique CM signal spanned by the rows of $F$. Let $f_j$ denote the $j$th column of $F$.

3) Using the ACMA approach, form the matrix $P$ (corresponding to $P$ of (9) in [8]) of size $(N \times K^2)$, whose $j$th row is defined as $(f_j \otimes f_j)$, where $(\otimes)$ denotes the Kronecker product, and $(*)$ denotes the complex conjugate. The desired combining vector $w$ is obtained by solving

$$
\begin{align*}
(7) \quad \text{y}
\end{align*}
$$

$$
\begin{align*}
(8) \quad \text{y}
\end{align*}
$$

1) In the ACMA [8], the extraction of the desired CM signal is achieved by attempting to solve the set of quadratic equations $(w^T f_j)^2 = 1$ (j = 1, . . . , $N$), viz., forcing the CM property on the extracted output. To enable a closed-form solution, this set of equations is converted into a linear system of equations by expanding the quadratic equations into a sum of terms, rearranging, and finally rewriting in terms of a modified parameter set, which are the vector $y$ [$y = \text{vec}(w^* w)$] and the matrix $P$ (defined above).

2) Practically, in the presence of noise, $N$ should be of the order of 2-3 times $K$.
where \(+\) denotes the pseudoinverse. This uniqueness will also allow \(w^H\) to be estimated directly (without further operations), as
\[
w^H = \text{dominant eigenvector of } (\text{vec}^{-1}(y)) \tag{9}
\]
where the \(\text{vec}^{-1}\) operator is defined for a \((K^2 \times 1)\) vector as
\[
\text{vec}^{-1}(y) = \begin{bmatrix}
  V_2 & \cdots & V_K \\
  V_K+1 & \cdots & V_K+2 \\
  \vdots & \ddots & \vdots \\
  Y_{K^2-K+1} & \cdots & Y_{K^2}
\end{bmatrix}.
\]

5) The desired user’s data vector \(s_i\) (for user 1) is now recovered, up to a complex scaling ambiguity, as
\[
s_i^1 = wF. \tag{10}
\]

6) Differential detection is used to recover the differentially encoded data.

Finally, we note that the above detection procedure can be easily extended to the case where \(M\) antennas are used at the receiver for detection. This can be achieved by replacing the matrix \(X_f\) by the stacked data matrix \([X_1 X_2 \ldots X_M]\). It is not difficult to see that this stacked matrix has a similar structure to (5) and can be expressed as
\[
[X_1 X_2 \ldots X_M] = S' [H_1 \cdots H_M]. \tag{11}
\]

Hence, the above detection procedure is directly applicable. Obviously, performance is expected to improve here as a result of the additional diversity available at the receiver. Furthermore, detection of \(K\) users (where \(K > P\)) becomes possible. This can be explained by the fact that stacking data matrices from multiple antennas [as in (11)] would help restore the rank of the resulting data matrix to \(K\), as compared to the rank of \(X'M\), which is limited to \(P\) in the case of \(K > P\). Hence, the column range of the matrix \([X_1 X_2 \ldots X_M]\) will again span all users’ symbol vectors, viz., \(s'_k\) for \(k = 1, \ldots, K\). Therefore, by using the matrix in (11), the ACMA procedure can be implemented for detecting \(K\) users where \(K > P\).

IV EFFECT OF CARRIER FREQUENCY OFFSETS

The effect of the carrier offset on the signal model in (5), with the symbol matrix given by (4b), will be to modify both the symbol and the effective code matrices. Each symbol vector in (4b) will be premultiplied by an exponential diagonal matrix \(E_k = \text{diag}(1 e^{j\theta_k}, e^{j\theta_k}, \ldots, e^{j\theta_k})\), where \(\theta_k = 2\pi f_c T/\lambda\), with \(f_c/\lambda\) denoting the carrier frequency offset for user \(k\), and \(1/T_c\) denoting the system’s symbol rate. Hence, the modified symbol matrix, to be denoted by \(S''\) in the presence of carrier offsets, can be written as
\[
S'' = [E_{s1} M_{s1} s_1 E_{s2} M_{s2} s_2 \cdots E_{sk} M_{sk} s_k]. \tag{12}
\]

A similar transformation occurs on the effective code matrix \(H_m\), and it can be rewritten as
\[
H^T = [E_{h1} M_{h1} h_{m1} \cdots E'_{kh} h_{mK}]. \tag{13}
\]

It is clear from (13) that the carrier offset will cause distortion in the received effective codes. For small offsets, the distortion is small, but as the offset increases, these effective codes will be significantly modified. As a result, detection methods such as those in [10] and [11] which rely on using the knowledge of the original (nondistorted) codes are rendered ineffective. Since the method proposed here does not use the desired user’s code in the detection process, and since the modulus of the transmitted symbols is not altered due to the carrier offset [see (12)], it remains tolerant to this frequency offset, regardless of its severity. However, it should be noted from (12) that the symbols detected by the proposed method would be \(E_s s_k\) rather than \(s_k\), i.e., it will detect the desired symbol vector along with the phase change arising from the carrier offset. Nevertheless, as long as \(\theta_k\) is small, differential phase detection of the vector \(E_s s_k\) would result in recovering the differentially encoded data in \(s_k\) with negligible error. However, as \(4\theta_k\) exceeds \(TT/4\) (in the context of a QPSK constellation) the symbol error rate would approach 100%. Hence, without correcting this phase error, the proposed detector can tolerate a maximum offset of \(A/I_c T/4 = 1/8\). Alternatively, we can assume knowledge of a few symbols in each symbol block, to estimate \(\theta_k\), and hence, \(E_{s_k}\) which can then be used to cancel the effect of \(E_s\). This would enable retrieving the desired symbol vector \(s_k\) properly, regardless of the amount of carrier offset. Simulations show that the associated bandwidth overhead is insignificant.

V COMPUTER SIMULATIONS

In order to verify the performance of the proposed precoding and detection method, we have carried out a number of simulation experiments. For benchmarking, we have compared the performance of our method with that of several recently proposed methods [2], [10], [11] to ascertain its merits and demerits. For implementing the proposed precoding method, the values of the diagonal elements in the matrices \(M_i\) \((i = 1, \ldots, K)\) were selected randomly to be either 1 or \(\sqrt{2}\), with equal probability (yielding a peak-to-average ratio of 1.25 dB). However, further optimization may be possible for selecting suitable precoding matrices.

We assume a scenario of a quasi-synchronous, uplink, DS-CDMA system using Gold codes with a raised cosine pulse shape (with a rolloff factor of 0.5), and employing QPSK modulation, in a multipath channel providing three paths for each user. The path delays are randomly generated in the range of 0-3 chips. In our experiments, detection is performed over blocks of 200 symbols, and results were averaged over 5000 blocks. For each data block, all the channel parameters, viz., the path gains, delays, and directions of arrival (DOAs) are randomly generated and kept fixed for the block, and varied from block to block. In all the experiments, detection performance is ascertained for the weakest user in a severe near-far situation, where the power of every other user’s signal is 20-dB higher than the desired user’s signal.

Experiment 1: We first take up comparison of the proposed method with the well-known D-RAKE receiver, which generalizes the minimum output energy (MOE) method for the multipath case. Unlike the proposed method, D-RAKE uses knowledge of
the desired user code for blind MU detection. For comparison, we consider a system with a process gain $P$ of 16 and 8 users. Fig. 1 shows the performance of the two methods in terms of symbol error rate (SER) versus SNR of the desired user, for the cases of a single antenna and two antennas. For the two-antenna case, D-RAKE is implemented for each antenna separately, followed by maximal ratio combining of the two outputs. The results clearly show that the proposed detector is superior in performance for both cases. This shows that the proposed precoding and detection scheme is more effective in suppressing MU interference than the D-RAKE, in the tested scenario.

Experiment 2: In this experiment, we compare the performance of the proposed method with the minimum mean-square error (MMSE) detector of [10], and with the zero-forcing (ZF) detector of [11], using single-antenna receivers. Both of these methods are subspace-based blind techniques, with the latter method exploiting the knowledge of all user codes in the detection of each user. The parameters of the experiment are taken to be $P = 23$, $K = 10$.

Fig. 2 shows the SER performance of the three methods versus SNR of the desired user. The proposed method is seen to perform better than the MMSE detector of [10] in the moderate-to-high SNR range, while it becomes slightly worse in the low SNR region. This may be expected in view of the deterministic nature of the proposed method. The second benchmark method, viz., the ZF detector of [11], outperforms the proposed method by 3-4 dB. This can be explained by the fact that this ZF detector uses knowledge of all users’ codes in the detection process, in contrast to the method proposed here or to the MMSE method of [10].

However, it should be noted that such a ZF procedure is unable to cancel intercell interference, while the proposed method and the MMSE of [10] should have no difficulty in that. Furthermore, the MMSE [10] and the ZF [11] detectors, being code dependent, would be highly sensitive to carrier frequency offset, like any method of this class may be expected to do.

Experiment 3: This experiment shows the tolerance of the proposed method to the carrier offset, regardless of the amount of this offset. Simultaneously, by taking an example from code-dependent detection methods, the experiment demonstrates that such methods fail to operate in severe offset cases. In this experiment, we assume $P = 20$, $K = 10$, $M = 2$, and we fix the SNR of the desired user to 15 dB. The ten users are assigned the relative carrier offsets of $[1, 0.23, 0.92, 0.35, 0.77, 0.45, 0.62, 0.13, 0.55, 0.04]$. Performance (SER) is plotted against $A/i\bar{T}_s$, where $T_s$ is the symbol period, which is the carrier frequency offset of user 1 normalized to the symbol rate.

Fig. 3 clearly shows that the D-RAKE, which is a code-dependent detection method, is able to withstand only a small amount of offset, after which its performance is severely degraded. On the other hand, the results confirm the ability of the proposed detector to withstand a large carrier frequency offset. Without phase error compensation for the detected symbol vector, the proposed detector is seen to tolerate up to an offset of nearly $A/i\bar{T}_s = 1/10$, which is close to the ideal value of $1/8$ discussed earlier. However, with the use of only six known symbols, for offset estimation and compensation, embedded in each 200-symbol block, the proposed detector is shown to be almost completely tolerant to carrier offsets, regardless of its magnitude.
VI. CONCLUSIONS

In this letter, we have introduced a new blind MU detector for DS-CDMA signals based on a new data precoding method. In contrast to some previous blind MU detection methods, which have been based on using the constant modulus property, we have exploited here a predefined periodic modulus over a block of symbols. Detection is performed using the ACMA [8] method so as to achieve a simple noniterative closed-form solution. The resulting blind detector is shown to have many good features: it is extremely near-far resistant, and its code-independent detection enables proper operation in the presence of severe carrier frequency offset and does not require channel estimation even in a severe, but slowly varying, multipath environment. The method is easily extendable to multiple antennas either for improved performance, or to deal with the case when we have more users than processing gain. Currently, we are investigating several other aspects of this precoding method, such as detection in asynchronous systems; its modification to enable operation in fast fading channels, possibly by implementing the ACMA by equating the modulus of successive symbols rather than solving $Py = 1$ for the entire block; and finally, investigation of the possibility of using reduced-complexity adaptive implementations such as gradient CMAs, to take over after a start up with the ACMA.

REFERENCES