BLIND ADAPTATION ALGORITHMS FOR DIRECT-SEQUENCE SPREAD-SPECTRUM CDMA SINGLE-USER DETECTION

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Abstract — Single-user detection techniques mitigate multiple access interference and the near-far problem in direct-sequence spread-spectrum CDMA systems. Trained adaptation algorithms are commonly used to adapt the receivers. Two blind adaptation algorithms, the Griffiths’ algorithm and the linearly constrained constant modulus algorithm (LCCMA), are proposed for this application. Simulation results show a performance greatly superior to that of the conventional receiver and close to the case of trained adaptive receivers. Blind adaptation allows for a much more flexible network design by eliminating the need for a training sequence.

I. INTRODUCTION

The capacity of a direct-sequence spread-spectrum code division multiple access (DSSS-CDMA) system is limited by multiple access interference (MAI) and the near-far problem. There are two approaches to mitigating these problems: multiuser detection and single-user detection techniques. Multiuser detection techniques cancel the interference and enhance system capacity, but have large computational requirements and require the knowledge of MAI parameters [1]. Single-user detection techniques, surveyed in [2], require only the knowledge of the desired user’s spreading code and timing, and have a significantly lower complexity. Single-user detectors perform interference rejection, provide near-far resistance and achieve better bit error rates (BER) and larger capacity than the conventional receiver.

Single-user detectors are adaptive receivers, whose performance greatly depends on the choice of the adaptation algorithm. Algorithms commonly proposed have been trained sequence directed and employed the least mean-square (LMS), the normalized least-mean-square (NLMS) and the recursive least-squares (RLS) algorithms [3]-[7]. This paper proposes two blind adaptation algorithms, the Griffiths’ algorithm and the linearly constrained constant modulus algorithm (LCCMA), both novel in the area of DSSS-CDMA single-user detection. The single-user detector considered is the complex-weight fractionally-spaced linear adaptive receiver (CW-FS-LAR) [4], [5], which is derived from the conventional receiver and has a structure similar to that of a fractionally-spaced equalizer. The experimental results show that this receiver adapted using the two blind algorithms greatly outperforms the conventional receiver in terms of BER performance, that it performs almost as well as in the case of trained adaptation, and that it is near-far resistant.

II. SYSTEM DESCRIPTION

We consider an asynchronous DSSS-CDMA system with \( K \) users. Each user’s data signal is spread and binary-phase-shift keying (BPSK) modulated, and all the resulting signals are simultaneously transmitted over an AWGN channel. The complex bandpass representation of the \( k \)th user’s transmitted signal is given by

\[
x_k(t) = \sqrt{P_{tk}} \cdot \sum_{m=-\infty}^{\infty} d_k(m) s_k(t - mT - \tau_k) e^{j [\omega_k(t - \tau_k) + \theta_k]}
\]

where \( P_{tk} \) is the \( k \)th user’s transmitted signal power; \( d_k(m) \) is the \( k \)th user’s data symbol at the \( m \)th symbol interval, \( d_k(m) \in \{-1, +1\}; s_k(t) \) is the \( k \)th users’ spreading waveform; \( T \) is the symbol period; and \( k = 1, 2, \ldots, K \). The \( k \)th user’s delay, \( \tau_k \in [0, T] \), is chosen to be an integer multiple of the sampling period \( T_s \), which is in turn equal to a fraction of the chip period, \( T_c \). The processing gain is \( N \). Therefore, \( \tau_k = l_k T_s \), \( l_k \) is a uniformly distributed discrete random variable, \( l_k \in \{0, 1, \ldots, pN - 1\} \), \( T_s = T_c/p \), where \( p \) is an integer, and \( T_c = T/N \). The \( k \)th user’s carrier frequency is \( \omega_k = \omega_c + \Delta \omega_k \), where \( \omega_c \) is the nominal carrier frequency, and \( \Delta \omega_k \) is the carrier frequency offset for user \( k \). The carrier phase is denoted as \( \theta_k \), and is uniformly distributed over the interval \([0, 2\pi]\).

The \( k \)th user’s spreading waveform is given by

\[
s_k(t) = \sum_{n=0}^{N-1} s_{kn} \Pi_{T_c}(t - n T_c), \quad 0 \leq t \leq T
\]

where \( s_k(t) = 0 \) for \( t \notin [0, T] \). The \( n \)th chip of the \( k \)th user’s spreading code is denoted as \( s_{kn} \), and \( \Pi_{T_c}(t) \) is a rectangular pulse of duration \( T_c \). For a spreading waveform defined by (2), code-on-pulse modulation is employed, i.e., the spreading code of each user repeats with a period equal to the symbol interval \( T_s \).

It is assumed that for the desired user \( k = 1 \), \( \tau_1 = 0 \), \( \Delta \omega_1 = 0 \), and \( \theta_1 = 0 \), i.e., the receiver is perfectly synchronized with the desired user’s signal. After downconversion to baseband, the received signal can be written as

\[
r(t) = r_1(t) + \sum_{k=2}^{K} r_k(t) + n(t)
\]
where $r_k(t)$ is the $k$th user's received and downconverted signal,
\[ r_k(t) = \sqrt{P_{r_k}} \sum_{m=-\infty}^{\infty} d_k(m) s_k(t-mT-T_k) e^{j[\Delta \omega_k(t-T_k) - \omega_c T_k + \theta_k]} \]
its received power denoted as $P_{r_k}$ ($P_{r_1} = 1$ is assumed), and $n(t)$ is complex white Gaussian noise.

III. SINGLE-USER DETECTION AND THE ANALOGY WITH BEAMFORMING

The complex-weight fractionally-spaced linear adaptive receiver (CW-FS-LAR) can be derived from the conventional receiver, implemented as a fixed transversal filter matched to the desired user's spreading waveform $s_1(t)$. The CW-FS-LAR is obtained by making the transversal filter adaptive, and employing the minimum mean-squared error (MMSE) adaptation criterion. Such a structure was proposed by Monogioudis et al. in [4], where it was referred to as the linear fractionally-spaced equalizer, and Rapajić and Vučetić in [5], where it was referred to as the adaptive linear receiver.

The receiver is shown in Figure 1. The received signal $r(t)$ is sampled $p$ times per chip, the sampling interval being $T_s = T_c/p$. When the AWGN channel is assumed, it is enough for the adaptive filter to be $N_p$ taps long (i.e., one whole sampled spread data symbol is contained in the filter). The samples corresponding to the $m$th data symbol form a fractionally-spaced received signal vector given by
\[ r(m) = [r_0(m) \ r_1(m) \ \cdots \ r_{N_p-1}(m)]^T \]
while the filter weights form a weight vector given by
\[ w = [w_0 \ w_1 \ \cdots \ w_{N_p-1}]^T \]
The filter output is sampled at the data rate $1/T$ to obtain the estimate for the desired user's $m$th data symbol $y_1(m)$, given by
\[ y_1(m) = w^T r(m) \]
where $[.]^T$ denotes the matrix transpose operation. The adaptation algorithm is chosen to minimize the mean squared error (MSE), given by
\[ MSE = E[|e(m)|^2] \]

During initial adaptation, the algorithm operates in the training adaptation mode, and after initial convergence in the decision-directed adaptation mode.

Mathematically speaking, a DSSS-CDMA single-user detector works similarly to a narrowband linear equi-spaced adaptive antenna array, provided that the number of receiver filter taps equals the number of antenna elements. In the first case the received signal is sampled in time, and in the other case it is sampled in space. The temporal or spacial samples form the received signal vector $r$ of (5),

Figure 1: Complex-weight fractionally-spaced linear adaptive receiver (CW-FS-LAR)

which can be split into a desired term $r_1$, an interference term $r_i$, and a background noise term $n$, i.e.,
\[ r = r_1 + r_i + n \]

In case of code-on-pulse modulation, the desired DSSS signal vector can be written as
\[ r_1 = d_1 \cdot s_1 \]
where $d_1$ is the data symbol being detected, and $s_1$ is formed by the desired user's spreading waveform samples. In case of beamforming, $r_1$ has the same form as given in (10), where $d_1$ contains the amplitude and time dependence of the desired signal, and $s_1$ is the steering vector corresponding to the desired signal's direction of arrival [8].

The presented analogy is of great importance, because it allows us to apply the beamforming concepts, ideas and techniques to the problem of DSSS-CDMA single-user detection, one of which is blind adaptation.

IV. BLIND ADAPTATION ALGORITHMS

The choice of the adaptation algorithm can greatly influence the performance of a single-user detector. It is preferred that the algorithm has low computational requirements, a fast convergence rate and that it is blind. Fast convergence is important so that the algorithm can successfully track the quickly varying channel characteristics. Blind adaptation algorithms that can converge even if the receiver starts with a "closed eye" are preferred to the trained ones. Such algorithms don’t require a training sequence and the transmission needn’t be interrupted for retraining when there is a sudden and large change in the system. Two blind adaptation algorithms novel in the area of DSSS-CDMA single-user detection are derived to suit this application. They are the Griffiths' algorithm and the LCCMA, both commonly used to adapt antenna arrays for beamforming.
A. Griffith's Algorithm

The derivation of the Griffith's algorithm is similar to that of the LMS algorithm [9]. Both are approximate implementations of the method of steepest descent that follows the MMSE criterion, given by

\[
\mathbf{w}(m + 1) = \mathbf{w}(m) + \mu(\mathbf{p} - \mathbf{R}\mathbf{w}(m))
\]

(11)

where \(\mathbf{R}\) is the correlation matrix of the input signal vector,

\[
\mathbf{R} = \mathbb{E}[\mathbf{r}^*(m)\mathbf{r}(m)^T]
\]

(12)

and \(\mathbf{p}\) is the cross-correlation between the input vector and the desired output,

\[
\mathbf{p} = \mathbb{E}[\mathbf{r}^*(m)d_1(m)]
\]

(13)

While the LMS algorithm uses the instantaneous estimates for \(\mathbf{R}\) and \(\mathbf{p}\), the Griffiths' algorithm assumes that the cross-correlation vector \(\mathbf{p}\) is known. The result is that no training sequence is required for the adaptation, i.e., the algorithm is blind.

In case of beamforming, the cross-correlation vector \(\mathbf{p}\) is equal to the conjugated steering vector for the desired user, and in case of DSSS-CDMA single-user detection it is equal to the conjugated desired user's spreading code, as derived by

\[
\mathbf{p} = \mathbb{E}[\mathbf{r}^*(m)d_1(m)]
\]

(14)

The derivation is based on the fact that the detected data symbol \(d_1(m)\) is uncorrelated with the interference, or the background noise.

Assuming the instantaneous estimate for the correlation matrix \(\mathbf{R}\),

\[
\hat{\mathbf{R}} = \mathbf{r}^*(m)\mathbf{r}(m)^T
\]

(15)

and the derived value for \(\mathbf{p}\), the Griffiths' algorithm applied to DSSS-CDMA single-user detection is

\[
\begin{align*}
\mathbf{w}(m + 1) &= \mathbf{w}(m) + \mu(\mathbf{p} - \mathbf{R}\mathbf{w}(m)) \\
\mathbf{w}(0) &= \mathbf{s}_1
\end{align*}
\]

(16)

(17)

B. Linearly Constrained Constant Modulus Algorithm

The LCCMA is derived from the constant modulus algorithm (CMA). The CMA minimizes a cost function which exploits the constant envelope of the modulated signal. Instead of a training sequence, the algorithm uses the constant modulus property and adapts the filter in order to restore/maintain this property [10]. The constant modulus (CM) cost function is given by

\[
CM = \frac{1}{4}\mathbb{E}[(|y_1(m)|^2 - \delta)^2]
\]

(18)

where \(\delta\) is the expected or estimated value for the desired user's received signal power, assumed to be \(\delta = 1\). The CMA weight update is given by

\[
\mathbf{w}(m + 1) = \mathbf{w}(m) - \mu(|y_1(m)|^2 - 1)r^*(m)y_1(m)
\]

(19)

The disadvantage of the CMA is that it may capture a constant modulus signal other than the desired one [11]. The problem stems from the fact that the CM cost function doesn't have a unique minimum, and that it will be minimized for any constant modulus filter output. Since all the MAI signals in a CDMA system are BPSK modulated and have a constant modulus, a single-user detector adapted using the CMA might fail in detecting the desired user's signal and capture an interferer instead. The LCCMA was proposed as a method for controlling the behavior of the CMA in case of adaptive antenna arrays performing beamforming [11]. By using the analogy with beamforming, it can be applied to DSSS-CDMA single-user detection.

In case of LCCMA adaptation, the weight vector is under a set of linear constraints,

\[
\mathbf{C}^H\mathbf{w} = \mathbf{f}
\]

(20)

where \(\mathbf{C}\) is a constant matrix of dimensions \(Np \times L\), \(\mathbf{f}\) is a constant column vector of length \(L\), and \(L\) is the number of linear constraints, \(L < Np\).

The constrained problem of minimizing the CM cost function can be converted to an unconstrained minimization problem by using a preprocessor known as the generalized sidelobe canceller (GSC) [11], shown in Figure 2. The preprocessor splits the weight vector into a constrained component and an unconstrained one, such that

\[
\mathbf{w} = \mathbf{w}_q - \mathbf{Ww}_a
\]

(21)

where \(\mathbf{w}_q\) is the constrained fixed portion of the weight vector, given by

\[
\mathbf{w}_q = \mathbf{C}(\mathbf{C}^H\mathbf{C})^{-1}\mathbf{f}
\]

(22)

and \(\mathbf{w}_a\) is the portion that is adapted, of length \(Np - L\). The reduction matrix \(\mathbf{W}\) is chosen so that its columns span the left nullspace of \(\mathbf{C}\), i.e.,

\[
\mathbf{C}^H\mathbf{W} = \mathbf{0}
\]

(23)
and its dimensions are \( Np \times (Np - L) \). It is shown in [11] that \( \mathbf{w}_q \) and \( \mathbf{W} \) given by (22) and (23) satisfy the linear constraints of (20). It is also shown that (20) is satisfied for any choice of \( \mathbf{w}_a \), which means that the adaptive portion of the weight vector is unconstrained.

For DS-SS-CDMA single-user detection a proper choice for the linear constraints would be to pass the desired user’s signal with unity gain and to null the interfering signals. The number of constraints \( L \) would be equal to the number of users \( K \). Since the interferers’ spreading codes are unknown, only the first constraint can be used, given by

\[
\mathbf{s}_1^* \cdot \mathbf{w} = \| \mathbf{s}_1 \|^2 = 1
\]  

(24)

It is assumed that the desired user’s spreading waveform is normalized to have unit energy. The constraint given by (24) is equivalent to the constraint

\[
\mathbf{w} = \mathbf{s}_1 + \mathbf{w}_{\text{adapt}}, \quad \text{where} \quad \mathbf{s}_1 \cdot \mathbf{w}_{\text{adapt}} = 0
\]  

(25)

which was used in [12] for linearly-constrained minimum output-energy adaptation. It is seen that the chosen constraint forces the weight vector to have a component responsible for the detection of the desired user’s signal, and a component orthogonal to it, responsible for rejecting the interferers. This makes it impossible for the filter to capture an interferer instead of the desired signal.

The constraint (24) can be written in matrix form (20), where \( \mathbf{C} = \mathbf{s}_1 \), \( \mathbf{f} = 1 \) and \( L = 1 \). Based on (22), the constrained portion of the weight vector is \( \mathbf{w}_q = \mathbf{s}_1 \), i.e., \( \mathbf{w}_q \) is equal to the desired user’s spreading code, which is consistent with (25). The reduction matrix \( \mathbf{W} \) is chosen to be

\[
\mathbf{W} = \left[ \begin{array}{cccc} \mathbf{e}_1 & \mathbf{e}_2 & \cdots & \mathbf{e}_{Np-1} \end{array} \right]
\]  

(26)

where \( \mathbf{e}_j \) is the \( j \)th eigenvector corresponding to the zero eigenvalue of matrix \( \mathbf{A} \), of dimensions \( Np \times Np \) and given by

\[
\mathbf{A} = \left[ \begin{array}{c} \mathbf{s}_1^H \\
0 \\
\vdots \\
0 \end{array} \right]
\]  

(27)

Such a choice for the reduction matrix \( \mathbf{W} \) satisfies the condition (23).

The LCCMA is then given by

\[
\mathbf{w}_a(0) = \left[ \begin{array}{ccc} 0 & 0 & \cdots & 0 \end{array} \right]
\]  

(28)

\[
\mathbf{w}(m) = \mathbf{s}_1 - \mathbf{Ww}_a(m)
\]  

(29)

\[
y_1(m) = \mathbf{w}^T \mathbf{r}(m)
\]  

(30)

\[
\mathbf{r}_a(m) = \mathbf{W} \mathbf{r}(m)
\]  

(31)

\[
\mathbf{w}_a(m + 1) = \mu(y_1(m) - r_a^*(m)y_1(m))
\]  

(32)

\[
\mathbf{w}_a(m) + \mu(b_1(\mathbf{y}_2(m)))
\]  

(33)

V. SIMULATION RESULTS

The performance of the CW-FS-LAR adapted using the discussed blind adaptation algorithms is investigated through Monte Carlo simulations. The processing gain is \( N = 15 \), and the spreading is performed using randomly generated spreading codes. The receiver samples the received signal \( p = 3 \) times per chip, and the length of its transversal filter is \( Np = 45 \).

One application for single-user detection is for the mobile unit in a cellular radio system. Assuming that the base station uses a single transmitter for the downlink, all users’ signals are synchronous, of equal powers, and with no frequency or phase drifts relative to the desired user’s signal. For such a case, the performance of the CW-FS-LAR adapted using the Griffiths’ algorithm and the LCCMA is compared with the fixed-weights case (i.e., the conventional detector) and the case when decision-directed (DD) NLMS adaptation is used after initial adaptation with a training sequence. Figure 3 shows the BER performance as a function of the number of users for a pre-despread SNR of –6 dB. It is seen that decision-directed adaptation after training gives the best performance, but that the Griffiths’ algorithm and the LCCMA are quite close. In case of both blind adaptation algorithms the CW-FS-LAR performs much better than the conventional detector, yielding up to two orders of magnitude of difference in BER.

Another application for single-user detection is in ad-hoc wireless networks, where a user receives signals directly from other users instead of a base station. The signals arrive asynchronously, there is little or no power control and a training sequence is not likely. In order to investigate the possibility of using the two blind adaptive receivers in such a network, an asynchronous system with 1 dB and 12 dB power variance and SNR of –6 dB and –9 dB is simulated (Figures 4 and 5). It is seen that there is little difference in the performance in the two cases of relaxed and strict power control, which shows that the two adaptive receivers are near-far resistant.
VI. CONCLUSIONS

Based on the analogy with beamforming, two blind adaptation algorithms can be applied to single-user detection in DSSS-CDMA systems. The CW-FS-LAR adapted using the Griffiths’ algorithm and the LCCMA greatly outperforms the conventional receiver in terms of BER performance, performs almost as well as in the case of trained adaptation, and is near-far resistant. The performance of the two algorithms is similar, but they differ in terms of complexity. The complexity of the Griffiths’ algorithm is smaller than that of the LCCMA, and only slightly larger than that of the trained LMS algorithm. Both blind algorithms have a great advantage over the commonly used LMS algorithm, because they don’t require a training sequence for the adaptation, thus allowing greater flexibility in a network design.

V. REFERENCES


