 Blind Adaptive Linear Parallel Interference Canceller for DS-CDMA in Frequency Selective Fading Channels

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Abstract—In this work we propose an adaptive blind linear parallel interference canceller (PIC) for direct-sequence code division multiple access (DS-CDMA) systems in frequency selective fading channels. A code-constrained constant modulus (CCM) design criterion based on constrained optimization techniques is proposed for PIC detectors in scenarios subject to multipath, and computationally efficient blind adaptive stochastic gradient (SG) and recursive least squares (RLS) algorithms are described for estimating both the receiver and channel parameters. Simulation results for an uplink scenario assess the algorithms, the proposed blind adaptive PIC detectors against existing receivers and evaluate the effects of error propagation of the new cancellation techniques.

I. INTRODUCTION

Multiuser detection is a vibrant and important research field that deals with the mitigation of multiaccess interference (MAI), increasing the capacity and the performance of CDMA systems [1]. The optimal multiuser detector has been proposed by Verdu in [2], however, the exponential complexity required for its deployment has motivated the development of several suboptimal schemes that are amenable to implementation: the linear [3] and decision feedback [4] receivers, the successive interference canceller (SIC) [5] and the multistage detector or parallel interference canceller (PIC) [6]. These suboptimal receivers require the estimation of various parameters in order to carry out interference suppression.

In most practical scenarios, such as those subject to multipath fading channels, the parameter estimation of the receiver has to be computed adaptively in order to track the time-varying channel conditions. Amongst the existing adaptive parameter estimation techniques, one can broadly divide them into two classes: supervised and unsupervised (blind) methods. In this context, blind adaptive parameter estimation methods have been reported in [7]–[9] along with linear detectors and have proven to be very valuable techniques that can alleviate the need for training sequences, increasing the throughput and efficiency of wireless networks.

Parallel interference cancellation (PIC) [6] has become a widely deployed structure for uplink scenarios due to its good performance and relative simplicity. Several variations of PIC have been investigated in the last years [10]–[16]. These receivers were examined in [10] for relatively fast fading channels, while the problem of error propagation encountered in these structures was investigated in [11]. A simple solution for the error propagation phenomenon was attempted in [12], where the authors describe a partial interference cancellation for enhancing PIC performance, and then a more general and powerful adaptive weighted PIC algorithm was described in [13]. Recently, combinations of adaptive PIC structures with linear detectors were reported in [14] for trained algorithms and in [15] and [16] for blind techniques in single-path and multipath channels, respectively. In this regard and to the best of our knowledge, the work on PIC detectors is quite limited with respect to blind parameter estimation in multipath. The work in [16] assumes ideal channel estimation, employs the constrained minimum variance approach [7] for parameter estimation but neither considers the role of adaptive algorithms and their trade-offs between performance and complexity.

In this paper we introduce blind adaptive linear PIC detectors that employ algorithms based on the code-constrained constant modulus (CCM) criterion. Firstly, we describe a CCM design criterion for the PIC receiver that jointly estimates the channel and the receiver parameters, using a decoupled blind channel estimation algorithm and computationally efficient SG and RLS type for parameter estimation, respectively. Secondly, we present an adaptive blind PIC receiver that employs a linear receiver front-end and multiple cancellation stages, that can significantly enhance the performance of the receiver as well as the convergence performance of the adaptive algorithms, and evaluate the receiver performance in several scenarios of practical interest.

This paper is structured as follows. Section II briefly describes the DS-CDMA communication system model. Section III focuses on the proposed PIC detector, the linearly constrained CCM receiver front-end, and the blind channel estimator. Section IV is dedicated to the derivation of adaptive SG algorithms and RLS-type algorithms for the receiver and channel estimation. Section V presents and discusses simulation results, while Section VI gives the conclusions.
II. DS-CDMA SIGNAL MODEL

Consider the uplink connection of a BPSK DS-CDMA system with \( K \) users, \( N \) chips per symbol, and \( L_p \) paths. Assuming that the channel is constant during each symbol interval, the received signal after coherent demodulation and filtering by a chip-pulse matched filter and sampled at chip rate yields the \((M = N + L_p - 1) \times 1\) received vector

\[
\mathbf{r}(i) = \sum_{k=1}^{K} A_k \mathbf{b}_k(i) \mathbf{C}_k \mathbf{h}_k(i) + \eta(i) + \mathbf{n}(i)
\]
subject to \( \mathbf{C}_k^H \mathbf{w}_k(i) = \nu \mathbf{h}_k(i) \), where \( \| \mathbf{h}_k(i) \|^2 = 1 \) and \( \nu \) is a constant to ensure the convexity of the CM-based receiver [9], [17]. Assuming that the channel vector \( \mathbf{h}_k \) is known, the expression for the CCM receiver can be written as:

\[
\mathbf{w}_k(i) = \mathbf{R}_k^{-1}(i) \left[ \mathbf{d}_k(i) - \mathbf{C}_k \left( \mathbf{C}_k^H \mathbf{R}_k^{-1}(i) \mathbf{C}_k \right)^{-1} \right]
\]

where \( \mathbf{z}_k(i) = \mathbf{w}_k^H(i) \mathbf{r}(i), \mathbf{R}_k(i) = E[\|\mathbf{z}_k(i)\|^2 \mathbf{r}(i) \mathbf{r}^H(i)], \mathbf{d}_k(i) = E[\mathbf{z}_k(i) \mathbf{r}(i)] \), the asterisk denotes complex conjugation. Note that the right-hand side of (5) is still a function of \( \mathbf{w}_k(i) \) and the channel \( \mathbf{h}_k(i) \). The channel estimation procedure adopted here [18] is equivalent to the following optimization:

\[
\hat{\mathbf{h}}_k(i) = \arg \min_{\mathbf{h}_k} \left\| \mathbf{h}_k^H \mathbf{C}_k^H \mathbf{R}_k^{-1}(i) \mathbf{C}_k \mathbf{h}_k \right\|_2
\]
subject to \( \| \mathbf{h}_k \| = 1 \) and whose solution is the eigenvector corresponding to the minimum eigenvalue of the \( L_p \times L_p \) matrix \( \mathbf{C}_k^H \mathbf{R}_k^{-1}(i) \mathbf{C}_k \). The use of \( \mathbf{R}_k \) instead of \( \mathbf{R} \), as in [18], avoids the estimation of both \( \mathbf{R} \) and \( \mathbf{R}_k \), and shows no performance loss as verified in our studies. In the next section we present iterative solutions via SG and RLS-like algorithms to find the receiver parameter vector \( \mathbf{w}_k(i) \) and the channel estimate \( \hat{\mathbf{h}}_k(i) \).

Once the CCM receiver parameter vectors and channel estimates are obtained, we focus on the interference cancellation stage. The filter output \( \mathbf{y}_k(i) = \mathbf{w}_k^H(i) \mathbf{r}(i) \) represents a noisy estimate of \( A_k \mathbf{b}_k(i) \). After \( m \) stages we define

\[
\mathbf{y}_k^{(m)}(i) = \mathbf{w}_k^H(i) \mathbf{r}_k^{(m)}(i)
\]
as the refined estimate of \( A_k \mathbf{b}_k(i) \) where \( \mathbf{r}_k^{(m)}(i) \) is the residual observation vector for user \( k \) at the \( m \)th stage \( \mathbf{r}_k^{(1)}(i) = \mathbf{r}(i) \). By defining the outputs of the detected users as \( \mathbf{y}^{(m)}(i) = [\mathbf{y}_1^{(m)}(i), \ldots, \mathbf{y}_K^{(m)}(i)]^T \), the residual signal for the proposed adaptive blind PIC receiver at the \((m + 1)\)th stage for user \( k \) can be written as:

\[
\mathbf{r}_k^{(m+1)}(i) = \mathbf{r}(i) - \mathbf{S}(i) \mathbf{y}^{(m)}(i) + \mathbf{c}_k(i) \mathbf{y}_k^{(m)}(i)
\]

where \( \mathbf{S}(i) = [\mathbf{c}_1(i) \ldots \mathbf{c}_K(i)] \) is a matrix that contains the effective signatures of the users in their columns. It should be remarked that the channel estimates for each user are employed to construct the effective signature sequence and thus we have for user \( k \) that

\[
\mathbf{c}_k(i) = \frac{\mathbf{C}_k \hat{\mathbf{h}}_k(i)}{\nu}
\]

where \( \hat{\mathbf{h}}_k \) is the normalized channel estimate for the \( k \)th user. It follows from (8) that the PIC receiver attempts to preserve the signal of interest, while cancelling the remaining signals. It should also be noticed that due to the use of soft outputs, amplitude estimation is not required for interference reconstruction. From (7) and (8) the output of the \((m + 1)\)th stage for the \( k \)th user of the adaptive PIC detector is given by:

\[
J_{CM} = E \left[ (|\mathbf{w}_k^H(i)\mathbf{r}(i)|^2 - 1)^2 \right]
\]
function and estimation of the channel and the parameter vector \( w_k \) generated by: SIC receivers using the CCM criterion.

Note that the final equality in (14) is valid only if the matrix product is nonsingular.

A. Code-Constrained Constant Modulus (CCM) SG Algorithm

To derive an CCM-SG algorithm [8] let us consider the cost function

\[
J_{CM} = (|z_k|^2 - 1)^2 + 2R [\mathbf{C}_L w_k(i) - \nu h_k(i)]^H \lambda
\]

where \( z_k = \mathbf{w}_k H (i) \mathbf{r}_k(i) \) and \( \lambda \) is a vector of Lagrange multipliers. An SG solution to (4) can be obtained by taking the gradient terms with respect to \( \mathbf{w}_k(i) \) which yields the following parameter estimator:

\[
\mathbf{w}_k(i+1) = \Pi_k (\mathbf{w}_k(i) - \mu_w e_k(i) z_k^* (i)) + \nu \mathbf{C}_L \mathbf{C}_L^{-1} \mathbf{h}_k(i)
\]

where \( e_k(i) = (|z_k(i)|^2 - 1) \). \( \Pi_k = \mathbf{I} - \mathbf{C}_L \mathbf{C}_L^{-1} \mathbf{C}_L^H \). A normalized version of this algorithm [19] is adopted here in order to make easier the choice of the step size, also guaranteeing stability. The algorithm utilizes \( \mu_w = \frac{\mu_w (|z_k(i)|^2 + 1)}{(1 + |e_k(i)|^2) \Pi_k r_k(i) \nu} \), where \( \mu_w \) is the convergence factor. To estimate the channel and avoid the SVD on \( \mathbf{C}_L^{-1} \mathbf{R}_k^{-1} \), we compute the estimates \( \hat{\mathbf{V}}_k(i) = \mathbf{C}_L^{-1} \hat{\mathbf{V}}_k(i) \), where \( \hat{\mathbf{V}}_k(i) \) is an estimate of the matrix \( \mathbf{R}_k^{-1} \mathbf{C}_L \); and then the following recursion:

\[
\hat{\mathbf{V}}_k(i) = \mathbf{r}_k(i+1) - \mathbf{r}(i) \mathbf{r}_k(i) \hat{\mathbf{V}}_k(i-1)
\]

where \( \gamma(i) = 1/\text{tr}(\hat{\mathbf{V}}_k(i)) \), \( \text{tr}[\cdot] \) stands for trace, and we make \( \hat{\mathbf{h}}_k(i) = \hat{\mathbf{h}}_k(i)/||\hat{\mathbf{h}}_k(i)|| \) to normalize the channel.

B. Code-Constrained CM RLS-Type (CCM-RLS) Algorithm

Given the expression for \( \mathbf{w}_k \) in (5) we apply an algorithm [9] that estimates the matrices \( \mathbf{R}_k^{-1} \) and \( \mathbf{C}_L^{-1} \mathbf{R}_k^{-1} \) recursively, reducing the computational complexity. Using the matrix inversion lemma and Kalman RLS recursions we have:

\[
\mathbf{F}_k(i) = \frac{\alpha^{-1} \hat{\mathbf{R}}_k^{-1}(i-1) z_k(i) r_k(i)}{1 + \alpha^{-1} r_k H(i) z_k(i) \hat{\mathbf{R}}_k^{-1}(i-1) z_k^* (i) r_k(i)}
\]

\[
\hat{\mathbf{R}}_k^{-1}(i) = \alpha^{-1} \hat{\mathbf{R}}_k^{-1}(i-1) - \alpha^{-1} \mathbf{F}_k(i) z_k^* (i) \hat{\mathbf{R}}_k^{-1}(i-1) \mathbf{F}_k(i)
\]

where \( \mathbf{F}_k \) is the Kalman gain vector with dimension \( M \times 1 \), \( \hat{\mathbf{R}}_k \) is the estimate of the matrix \( \mathbf{R}_k \) and \( 0 < \alpha < 1 \) is the forgetting factor. At each processed symbol, the matrix \( \hat{\mathbf{R}}_k^{-1}(i) \) is updated and we employ another recursion to estimate \( \mathbf{C}_L^{-1} \mathbf{R}_k^{-1}(i) \mathbf{C}_L^{-1} \) as described by:

\[
\Gamma_k^{-1}(i) = \Gamma_k^{-1}(i-1) - \frac{\Gamma_k^{-1}(i-1) \gamma_k(i) \mathbf{r}_k(i) \Gamma_k^{-1}(i-1)}{\alpha(1 - \alpha)} + (1 - \alpha) \gamma_k(i)
\]

where \( \Gamma_k(i) \) is an estimate of \( \mathbf{C}_L^{-1} \mathbf{R}_k^{-1}(i) \mathbf{C}_L^{-1} \) and \( \gamma_k(i) = \mathbf{C}_L^H \mathbf{r}_k(i) z_k(i) \). To estimate the channel and avoid the SVD on \( \mathbf{C}_L^{-1} \mathbf{R}_k^{-1}(i) \mathbf{C}_L \), we compute an estimate \( \hat{\mathbf{h}}_k(i) \) of \( \mathbf{C}_L^H \mathbf{R}_k^{-1}(i) \mathbf{C}_L \) and employ the variant of the power method introduced in [18]:

\[
\hat{\mathbf{h}}_k(i) = (1 - \gamma(i) \Gamma_k(i)) \hat{\mathbf{h}}_k(i-1)
\]
where $\gamma(i) = 1/\text{tr}[\Gamma_0(i)]$, $\text{tr}[.]$ stands for trace, and we make $h_k(i) - \hat{h}_k(i)/||h_k(i)||$ to normalize the channel. The CCM linear receiver is then designed as described by:

$$\hat{w}_k(i) = \hat{R}^{-1}_k(i) \left[ d_k(i) - C_k \Gamma^{-1}_k(i) \times (C_k^H \hat{R}^{-1}_k(i) d_k(i) - \nu \hat{h}_k(i)) \right]$$

(24)

where $d_k(i+1) = \alpha d_k(i) + (1-\alpha)z_k^H(i) r_k(i)$ corresponds to an estimate of $d_k(i)$. In terms of computational complexity, the CCM-RLS algorithm requires $O(M^2)$ to suppress MAI and ISI and $O(L_p^2)$ to estimate the channel, against and $O(M^3)$ and $O(L_p^k)$ required by (5) and (6) respectively.

V. SIMULATIONS AND RESULTS

The simulation results presented are for a BPSK synchronous DS-CDMA system that employs Gold sequences of length $N = 31$. Because we focus on uplink scenarios, users experience different channel conditions. All channels assume that $L_0 = 3$. It is also assumed here that the channels experienced by different users are statistically independent and identically distributed. For fading channels, the sequence of channel coefficients for each user $k$ ($k = 1,\ldots,K$), $h_{k,l}(i) = p_{k,l} |\alpha_{k,l}(i)|$ ($l = 0,1,2,\ldots,L_0-1$) is obtained with Clarke’s model [20]. This procedure corresponds to the generation of independent sequences of correlated unit power complex Gaussian random variables $[E[|\alpha_{k,l}^2(i)|] = 1]$ with the path weights $p_{k,l}$ normalized so that $\sum_{l=0}^{L_0-1} p_{k,l}^2 = 1$. In this work $p_{k,0} = 0.7581$, $p_{k,1} = 0.5307$ and $p_{k,2} = 0.3790$. The phase ambiguity derived from the blind channel estimation method in [18] is eliminated in our simulations by using the phase of $h_{k,0}$ as a reference, and for fading channels we assume ideal phase tracking and express the results in terms of the normalized Doppler frequency $f_d T$ (cycles/symbol). All experiments are averaged over 150 runs and the parameters of the algorithms are optimized for each scenario.

In the experiments, we compare the normalized version of the constrained constant modulus algorithm from Xu and Liu [8], denoted CCM-SG, the single-stage CCM receiver from [9] denoted CCM-RLS. The proposed receiver with 2 and 3 stages are denoted PIC-2 and PIC-3 respectively. We found in our studies that the increase of the number of stages after $m \geq 3$ does not lead to significant performance improvements.

In Figs. 1 and 2 we assess performance in terms of signal-to-noise-plus-interference ratio (SINR) for SG and RLS-like versions, respectively, in a system with $K = 12$ users under fading ($f_d T = 10^{-3}$). The power transmitted by all users are the same and corresponds to $E_b/N_0 = 15 \text{ dB}$. The results indicate that the use of interference cancellation increases the speed of convergence and yields, for both algorithms, higher values of SINR in steady-state.

In Figs. 3 and 4 we present bit error rate (BER) performance versus $E_b/N_0$ and number of users for SG and RLS-like versions, respectively. For BER versus $E_b/N_0$ results, we assume a $K = 8$ user system under fading ($f_d T = 10^{-3}$) where all users transmit at the same power level. For BER versus number of users, it is also assumed that all users transmit at the same power level, with $E_b/N_0 = 15 \text{ dB}$ and that the system is also subject to fading ($f_d T = 10^{-3}$).

For both algorithms the proposed PIC achieves good performance. The SG version, with $m > 1$, shows a much lower BER floor than the single-stage CCM-SG. The RLS-like version with $m = 2$ yields a $8 \text{ dB}$ gain over the CCM-RLS for BER=$10^{-2}$. It was also noted that if the number of users is small, only one stage of interference cancellation is needed. As the number of users increases so does the performance gain due to the user of a second cancellation stage. In terms of system capacity, the proposed PIC receivers were able to accommodate up to 5 more users.
VI. CONCLUSIONS

In this work we proposed an adaptive blind linear parallel interference canceller (PIC) for direct-sequence code division multiple access (DS-CDMA) systems in frequency selective fading channels. The structure of the proposed PIC receiver consists of multiple stages of blind linear detectors that are designed on the basis of the CCM criterion. Adaptive SG and RLS-type algorithms were derived for the blind estimation of the channel and the parameter vector. Simulation results showed that the proposed receiver achieved gains in terms of BER and SINR performance when compared to the single-stage CCM-SG and CCM-RLS receivers.

REFERENCES