A UNITED APPROACH TO JOINT AND ITERATIVE ADAPTIVE INTERFERENCE CANCELLATION AND PARAMETER ESTIMATION FOR CDMA SYSTEMS IN MULTIPATH CHANNELS

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ABSTRACT

This paper proposes a unified approach to joint adaptive parameter estimation and interference cancellation (IC) for direct sequence code-division-multiple-access (DS-CDMA) systems in multipath channels. A unified framework is presented in which the IC problem is formulated as an optimization problem with extra degrees of freedom of an IC parameter vector for each stage and user. We propose a joint optimization method for estimating the IC parameter vector, the linear receiver filter front-end, and the channel along with minimum mean squared error (MMSE) expressions for the estimators. Based on the proposed joint optimization approach, we derive low-complexity stochastic gradient (SG) algorithms for estimating the desired parameters. Simulation results for the uplink of a synchronous DS-CDMA system show that the proposed methods significantly outperform the best known IC receivers.

1. INTRODUCTION

High data rate applications for future wireless systems require an ever-increasing sophistication and performance of receivers. In multiuser systems such as DS-CDMA, novel signal processing techniques are of crucial importance to enhance the capacity and the performance. The field of interference mitigation techniques has become an important and vibrant field since the pioneering work of Verdú [1]. The optimal multiuser detector has been proposed by Verdú in [2], however, prohibitive complexity makes its deployment infeasible and motivated the development of several suboptimal schemes that are amenable to implementation: The linear [3] and decision feedback [4] receivers, the successive interference canceler (SIC) [5], and the parallel interference canceler (PIC) [6]. These receivers require the estimation of various parameters in order to carry out interference suppression.

In most practical scenarios, the parameter estimation of the receiver has to be computed adaptively in order to track the time-varying multipath channel conditions. Several adaptive receivers have been reported in [7,8,9] and have proven to be very valuable techniques for interference mitigation. Specifically for uplink scenarios, SIC [5,10,11] and PIC [6,12,13,14,15,16] receivers, which are relatively simple and perform interference cancellation (IC) by sequentially or iteratively removing multiple access interference (MAI), are known to provide significant gains over RAKE and linear detectors. The works on SIC and PIC detectors present severe limitations with respect to the amount of interference to be estimated and cancelled in dispersive and dynamic environments. This is because SIC and PIC detectors rely on an amplitude estimate of the parameters to be cancelled which affect the whole IC procedure.

This work proposes a unified approach to joint adaptive IC detectors for DS-CDMA systems in frequency selective channels. A novel framework in which the IC problem is formulated as an optimization problem of an IC parameter vector for each user and a unification of existing IC under the same model is described. A joint optimization method for estimating the IC parameter vector, the linear receiver front-end filter and the channel parameters is proposed with MMSE expressions. Based on the proposed joint optimization approach, we also present low complexity SG algorithms for estimating the desired parameters. Simulations for the uplink of a DS-CDMA system show that the proposed methods significantly outperform the best known IC receivers.

The rest of this article is organized as follows: Section 2 describes a synchronous DS-CDMA system model. In Section 3 we present the novel unified framework for IC. Section 4 details the proposed joint optimization approach and describes the MMSE expressions for channel estimation, receiver filter and IC parameter vector estimation. Section 5 is devoted to the proposed SG adaptive algorithms for joint IC and parameter estimation. Section 6 is dedicated to the simulations and to the discussion of the results, whereas the conclusions are drawn in Section 7.

2. DS-CDMA SYSTEM MODEL

Let us consider the uplink of a symbol synchronous quadrature phase-shift keying (QPSK) DS-CDMA system with \( K \) users, \( N \) chips per symbol and \( L_p \) propagation paths. Note that a synchronous model is assumed for simplicity, although it captures most of the features of asynchronous models with small to moderate delay spreads. The baseband signal transmitted by the \( k \)-th active user to the base station is given by

\[
x_k(t) = A_k \sum_{i=-\infty}^{\infty} b_i[k] s_k(t - iT),
\]

where \( b_i[k] \in \{ \pm 1 \pm j \} \) with \( j^2 = -1 \) denotes the \( i \)-th symbol for user \( k \), the real-valued spreading waveform and the amplitude associated with user \( k \) are \( s_k(t) \) and \( A_k \), respectively. The spreading waveforms are expressed by \( s_k(t) = \sum_{i=1}^{N} a_k[i] \phi(t - iT_c) \), where

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\[ a_k[i] \in \{\pm 1/\sqrt{N}\}, \] 
\( \phi(t) \) is the chip waveform, \( T_c \) is the chip duration and \( N = T/T_c \) is the processing gain. Assuming that the receiver is synchronized with the main path, the complex envelope of the coherently demodulated composite received signal is

\[
r(t) = \sum_{k=1}^{K} \sum_{j=0}^{L_p-1} h_{k,j}(t) x_k(t - \tau_{k,j}) + n(t),
\]

where \( h_{k,j}(t) \) and \( \tau_{k,j} \) are, respectively, the channel coefficient and the delay associated with the \( j \)-th path and the \( k \)-th user. Assuming that \( \tau_{k,j} = IT_c \), the channel is constant during each packet transmission. \( L_p \leq N \) and the spreading codes are repeated from symbol to symbol, the received signal \( r(t) \) after filtering by a chip-pulse matched filter and sampled at chip rate yields the \( M \)-dimensional received vector

\[
r[i] = \sum_{k=1}^{K} A_k \left( b_k[i - 1] C_{k,0}^p + b_k[i] C_{k,1} \right) h_k + n[i],
\]

where \( M = N + L_p - 1 \), \( n[i] = [n_1[i] \ldots n_M[i]]^T \) is the complex Gaussian noise vector with \( \mathbb{E}[n[i]n^H[i]] = \sigma^2 I \), where \(( \cdot )^T \) and \(( \cdot )^H \) denote transpose and Hermitian transpose, respectively, \( \mathbb{E}[\cdot] \) stands for expected value, the amplitude of user \( k \) is \( A_k, s_k = \{a_k(1) \ldots a_k(N)\}^T \) is the signature sequence for the \( k \)-th user, the \( M \times L_p \) constraint matrices \( C_{k,0}^p, C_k, C_k^p \) that contains one-chip shifted versions of the signature sequence for user \( k \) and the \( L_p \times 1 \) vector \( h_k \) with the discrete-time multipath components are described by

\[
C_k = \begin{bmatrix}
  a_k(1) & 0 & \cdots & 0 \\
  \vdots & \ddots & \ddots & \vdots \\
  0 & \cdots & a_k(N) & 0 \\
\end{bmatrix},
\quad h_k = \begin{bmatrix}
  h_{k,0} \\
  \vdots \\
  h_{k,L_p-1} \\
\end{bmatrix}, \tag{4}
\]

\[
C_k^p = \begin{bmatrix}
  C_k, [N+1,M,1:L_p] \\
  0_{N \times L_p} \\
\end{bmatrix}, \quad C_k = \begin{bmatrix}
  C_k, [1,L_p-1,1:L_p] \\
  0_{N \times L_p} \\
\end{bmatrix}, \tag{5}
\]

where the matrices \( C_k^p \) and \( C_k^t \) account for the intersymbol interference from the previous and subsequent symbols, respectively. The subscript \( [m:q,j:p] \) denotes the range of elements of a given matrix used.

3. UNIFIED FRAMEWORK FOR INTERFERENCE CANCELLATION

In this section, we present a unified framework for IC based on the formulation of the problem as the optimization of an IC parameter vector for each user. Prior works on IC are heavily based on the estimation of an amplitude of a user (or an amount of interference) to be reconstructed and cancelled. This approach is very sensitive and tends to be inaccurate in multipath scenarios. Unlike prior works, the proposed approach trades off an amplitude estimate against a parameter vector estimate for each stage, incorporating more degrees of freedom to the problem and which reveals to be significantly more effective than the best known methods. With this new formulation, we provide a unifying treatment of IC schemes in what follows.

Let us first consider a conventional IC approach, where the centralized processor aims to reconstruct the detected data and subtract them from the \( M \times 1 \) received data

\[
r_k^[m] = r[i] - \sum_{j \in \mathcal{G}} \hat{A}_j \left( \hat{b}_j[i - 1] C_j^p + \hat{b}_j[i] C_j \right) + \hat{b}_j[i] C_j \tag{6}
\]

\[
 = r[i] - \sum_{j \in \mathcal{G}} \hat{A}_j F_j[i] \hat{h}_j[i].
\]

where \( F_j[i] = \left( \hat{b}_j[i - 1] C_j^p + \hat{b}_j[i] C_j + \hat{b}_j[i] C_j \right) \) is an \( M \times L_p \) matrix with the signature code and symbol estimates of user \( j \) at the IC stage \( m, \mathcal{G} = \{\mathcal{G}_1, \mathcal{G}_2, \ldots, \mathcal{G}_P\} \) denotes the group of users with \( P \) entries to be reconstructed and subtracted, whereas the subscript denotes the \( m \)-th IC. In the conventional approach outlined in (6), the goal is to compute the estimates \( \hat{A}_m, F_m[i] \) and \( \hat{h}_m[i] \) and this often leads to inaccurate IC for systems in dispersive channels.

The novel approach we detail here corresponds to a mathematical reformulation of (6) and the introduction of an IC parameter vector \( \lambda_k^m = [\lambda_k^m,1 \lambda_k^m,2 \ldots \lambda_k^m,P] \) for each stage \( m \) and user \( k \), as expressed by

\[
r_k^[m] = r[i] - \sum_{j \in \mathcal{G}} \lambda_k^m C_j^p \hat{F}_j[i] \hat{h}_j[i] \tag{7}
\]

\[
r[i] - D_k[i] \lambda_k^m[i],
\]

where the \( M \times P \) matrix with signature codes, symbols and channels estimates of the group of users \( \mathcal{G} \) is given by

\[
D_k[i] = C_k^p H^m B^m[i - 1] + C_k T H^m B^m[i] + C_k T H^m B^m[i + 1], \tag{8}
\]

\[
C_T = \begin{bmatrix}
  C_{\mathcal{G}_1} C_{\mathcal{G}_2} \ldots C_{\mathcal{G}_P} \\
\end{bmatrix}, \quad C_T = \begin{bmatrix}
  C_{\mathcal{G}_1}^p C_{\mathcal{G}_2}^p \ldots C_{\mathcal{G}_P}^p \\
\end{bmatrix}, \tag{9}
\]

\[
B^m[i] = \text{diag}(h_{k,1}^m, h_{k,2}^m, \ldots, h_{k,P}^m). \tag{10}
\]

The matrix \( D_k^m[i] \) corresponds to the reconstructed data of users which belong to group \( \mathcal{G} \) and it is a function of the \( M \times (P \cdot L_p) \) code matrices \( C_k^p, C_k, C_k^t \), the \( P \times P \) user’s symbol matrix \( B^m[i] \) and the \( (P \cdot L_p) \times P \) channel matrix \( H^m \) with a block diagonal structure, with all the parameters of the users to be reconstructed and cancelled.

The mathematical framework detailed in (7) can be actually used to describe IC schemes which perform SIC and PIC as particular cases. For instance, if the designer chooses to detect the users according to a decreasing power ordering, we obtain the following SIC approach

\[
r_k^[m] = r[i] - \sum_{j=1}^{k-1} \lambda_j^m C_j^p \hat{F}_j[i] \hat{h}_j[i] \tag{12}
\]

\[
r[i] - D_{\mathcal{G}_{k-1}}[i] \lambda_k[i], \quad m = 1
\]

where \( \mathcal{G}_{k-1} = \{\mathcal{G}_1, \mathcal{G}_2, \ldots, \mathcal{G}_{k-1}\} \) denotes the group of users to be reconstructed according to the SIC approach (decreasing power order). Note that there is only one detected stage \( (m = 1) \) for SIC, user \( k \) is detected and the previously detected users are regenerated and subtracted from the received data \( r[i] \) and this is repeated for the remaining users.
Another detection strategy which can be carried out as a particular case of the framework in (17) is the multistage detection or PIC. Following the proposed detection scheme users are detected on the basis of the following structure

\[
\begin{align*}
    r_m^k[i] &= r[i] - \sum_{j=1}^K \lambda_{y,j}^m F_{y,j}^m[i] \hat{h}_m^i[i] \\
    &= r[i] - D_{g_{K-1}}^m[i] \lambda_{m}^i, \quad m = 1, 2, \ldots
\end{align*}
\]

where \( k \) represents the desired user to be detected, \( m \) is the stage, and \( G_{K-1} \) contains all but the desired \( k \)th user.

4. JOINT INTERFERENCE CANCELLATION AND PARAMETER ESTIMATION METHOD

In this section, we present a novel strategy for joint interference cancellation and parameters estimation based on the formulation given in the previous section. The idea is to consider the problems of receiver filter, channel, and IC parameter vector estimation jointly and devise MMSE expressions to solve it. Specifically, we consider here that a linear receiver filter is employed at the front-end of the IC detector. The proposed receiver structure is shown in Figure 1. Let us first consider the following cost functions

\[
\begin{align*}
    J_1(w_m^i[i]) &= E \left[ b_k[i] - w_{m,H}^m[i] r_m^m[i] \right]^2, \quad (14) \\
    J_2(\lambda_m^i, \hat{h}_m^i[i]) &= E \left[ \left| F_{m,H}^m[i] \hat{h}_m^i[i] - r[i] + D_g^m[i] \lambda_m^i \right|^2 \right]. \quad (15)
\end{align*}
\]

By minimizing (14) with respect to the receiver linear filter \( w_m^m[i] \) we obtain the Wiener-Hopf-like expressions

\[
w_m^m[i] = R_{y_k}^{-1}[i] p_{b_k}[i], \quad (16)
\]

where \( R_{y_k}^m[i] = E \left[ r_m^m[i] r_{m,H}^m[i] \right] \) is the \( M \times M \) covariance matrix and \( p_{b_k}[i] = E \left[ b_k[i] r_m^m[i] \right] \) is the \( M \times 1 \) cross-correlation vector. By taking the gradient terms of (15) with respect to the IC parameter vector \( \lambda_m^i \) and equating them to zero we get

\[
\lambda_m^i[i] = R_{D_g}^{-1}[i] p_{D_g}[i], \quad (17)
\]

where \( R_{D_g}^m[i] = E \left[ D_g_{m,H}^m[i] D_g^m[i] \right] \) is the \( P \times P \) covariance matrix and \( p_{D_g}[i] = E \left[ \hat{h}_m^i[i] r_{m,H}^m[i] \right] \) is the \( P \times 1 \) cross-correlation vector. By minimizing (15) with regard to the channel estimate \( \hat{h}_m^i[i] \) we obtain the last system of linear equations

\[
\hat{h}_m^i[i] = R_{F_{m,H}^m}[i] p_{D_g}[i], \quad (18)
\]

where \( R_{F_{m,H}^m}[i] = E \left[ F_{m,H}^m[i] F_{m,H}^m[i] \right] \) is the \( L_p \times L_p \) covariance matrix and \( p_{D_g}[i] = E \left[ D_g_{m,H}^m[i] (r[i] - D_g^m[i] \lambda_m^i[i]) \right] \) is the \( P \times 1 \) cross-correlation vector. The expressions in (16)-(18) are not closed-form ones as the interference cancellation and the receiver linear filter parameters depend on the channel and vice-versa. This means that (16)-(18) have to be iterated in order to seek a solution to the optimization problem. The detected symbols are obtained as follows:

\[
\hat{b}_k[i] = \text{sgn} \left[ \text{Re}(x_k[i]) + j \text{Im}(x_k[i]) \right].
\]

5. ADAPTIVE ESTIMATION ALGORITHMS

In this section, we propose adaptive estimation algorithms based on the joint optimization problems stated in (14) and (15). In order to develop SG adaptive algorithms, we compute the instantaneous joint optimization problems stated in (14) and (15) for estimating these parameters and allow amendable implementation.

In what follows, we seek adaptive SG solutions based on the joint optimization of the parameters formulated in (14) and (15) for estimating these parameters and allowing amendable implementation.
where $\mu_w$, $\mu_\lambda$, and $\mu_k$ are the step sizes for the adaptive SG estimators for the receiver filter, the IC parameter vector, and the channel, respectively, and scalar and vector errors are given by

$$e_k^m[i] = b_k[i] - w_k^mH_k[i]r_k^m[i],$$

$$e_k^m[i] = F_k^m[i]h_k^m[i] - r[i] + D_k^m[i]\lambda_k^m[i]$$

The adaptive algorithms described above should be iterated in order to converge to a solution since the parameters estimated by them are inter-dependent. The complexity of the algorithms in [23]-[24] is $O(M)$, $O(PLM)$ and $O(MLp)$ for the estimation of the receiver filter $w_k^m[i]$, the IC parameter vector $\lambda_k^m[i]$, and the channel $h_k^m[i]$, respectively.

### 6. SIMULATIONS

In this section, we evaluate the bit error rate (BER) performance of the proposed joint interference cancellation and parameter estimation algorithms. We compare the proposed algorithms with the best known methods of interference mitigation, namely, the linear, the SIC, and the PIC detectors using SG algorithms as the estimation procedure. The DS-CDMA system employs randomly generated spreading sequences of length $N = 16$. The channels $h_k = [h_{k,0}, h_{k,1}, \ldots, h_{k,L_p-1}]^T$ are modeled by a tapped-delay-line with $L_p = 9$ taps and are normalized such that $\sum_{l=0}^{L_p-1} |h_l|^2 = 1$. Specifically, of the $L_p = 9$ taps, there are only 3 non-zero paths with complex random gains, whose real and imaginary parts are generated in each transmitted packet by a uniform continuous random variables (i.e., $\sim N(0,1)$). The system has a power distribution among the users for each trial that follows a log-normal distribution with associated standard deviation of 3 dB, the performance is shown in terms of average $E_b/N_0$, and all curves are averaged over 100 runs. The packets used in the simulations have 1500 symbols and the training sequences have 150 symbols. After the training sequences, the receivers are switched to decision-directed mode. The receiver filters used in the simulations have $M = N + L_p - 1 = 24$ taps. The step sizes of all algorithms are optimized for each situation to ensure the best BER performance for each packet. All the receivers considered in this part employ a linear receiver as the front-end. When there is no IC after the linear front-end, the structure corresponds to a conventional adaptive linear receiver [7]-[9]. The proposed jointly optimized (JO) algorithms with SIC and PIC receivers are denoted JO-SIC and JO-PIC, respectively. For the PIC receivers we used $m = 3$ stages and the amplitude estimation based on the estimate at the output of linear receiver front-end [15] and for the proposed JO-PIC we also use $m = 3$ stages. For the existing SIC receivers [10] [11] we used the amplitude estimation algorithm reported in [11].

In the first experiment, shown in Figure 2, we assess the BER convergence performance of the proposed adaptive estimation algorithms and receiver structures. The results indicate that the proposed JO-SIC and JO-PIC receivers have the best performance among the compared structures. The JO-SIC slightly outperforms the JO-PIC, which is followed by the SIC, the PIC, and the linear receivers. In particular, we notice that the convergence performance of the JO-SIC and JO-PIC is significantly superior to the remaining approaches. This is because the IC is substantially more accurate than the IC carried out by the existing SIC and PIC approaches.

The second experiment, depicted in Figure 3, evaluates the MSE performance of the channel estimators. The channel estimators of IC schemes clearly benefit by the cancellation process as compared to the linear estimator without IC. The use of IC for improving the performance is particularly relevant for the proposed JO-SIC and JO-PIC, which achieve the best performance.

The BER versus $E_b/N_0$ and number of users is illustrated in Figure 4. The curves indicate that the best performance is obtained by the proposed JO-SIC and JO-PIC receiver and algorithms. The plots show that the proposed JO-SIC and JO-PIC receivers can save up to 4 dB in $E_b/N_0$ for the same BER as compared with the linear receiver, and up to 2.5 dB as compared with existing SIC and PIC detectors. In terms of system capacity, the proposed detectors and algorithms provide a substantial capacity improvement and can accommodate up to 50% more users for this small system.

### 7. CONCLUSIONS

This work proposed a unified framework for IC in DS-CDMA systems, which formulates the IC problem as the optimization of an IC parameter vector. A joint optimization method for estimating the IC parameter vector, the receiver linear front-end filter and the channel parameters along with MMSE expressions was also presented. Low-complexity adaptive estimation algorithms were developed for jointly estimating the desired parameters. The results for the uplink of a synchronous DS-CDMA system show that the proposed methods significantly outperform the best known IC receivers.

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Fig. 3. MSE performance of channel estimator versus number of received symbols.

Fig. 4. BER performance of receivers versus (a) \( E_b/N_0 \) and (b) number of users (K).