Joint Iterative Interference Cancellation and Parameter Estimation for CDMA Systems

Rodrigo C. de Lamare, Raimundo Sampaio-Neto, and Are Hjørungnes

***Abstract*— This letter proposes a unified approach to joint iterative parameter estimation and interference cancellation (IC) for uplink CDMA systems in multipath channels. A unified framework is presented in which the IC problem is formulated as an optimization problem of an IC parameter vector for each stage and user. We also propose detectors based on a least-squares (LS) joint optimization method for estimating the linear receiver filter front-end, the IC, and the channel parameters. Simulations for the uplink of a synchronous DS-CDMA system show that the proposed methods significantly outperform the best known IC schemes.**

***Index Terms*— CDMA systems, interference cancellation, iterative methods.**

I. INTRODUCTION

HIGH data rate applications for future wireless CDMA systems require an ever-increasing sophistication and performance of receivers. Novel detection techniques are fundamental to enhance the capacity and the performance of these systems. The optimal multiuser detector of Verdú [1] is too complex for practical use. This motivated the development of several sub-optimal schemes with affordable complexity: the linear [2], [3], [4] and decision feedback [1], [5] receivers, the successive interference canceller (SIC) [6], [7], [8] and the parallel interference canceller (PIC) [9], [10], [11], [12]. Improvements to the original SIC [6] were reported in [7] with the use of a linear detector front-end in place of a matched filter and in [8] with amplitude estimation algorithms. The original PIC [9] was subsequently enhanced by the inclusion of partial IC [10], adaptive weights for IC [11] and a linear detection front-end [12]. These SIC and PIC receivers are relatively simple, provide significant performance gains over RAKE and linear detectors and are suitable for the uplink. However, they require the estimation of several parameters in order to carry out interference mitigation. Prior work on IC has 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 amplitude estimates of the parameters to be cancelled.

This work proposes a unified approach to joint iterative IC and parameter estimation for CDMA systems in multipath. A novel framework in which the IC is formulated with extra degrees of freedom as an optimization problem of an IC parameter vector for each user and a unification of IC techniques under the same model are presented. We propose detectors which combine linear and IC structures and an LS joint optimization method for estimating the IC parameters, the receiver filter and the channel.

II. DS-CDMA SYSTEM MODEL

Let us consider the uplink of a synchronous DS-CDMA system with K users, N chips per symbol and L_p propagation paths. Assuming that the channel is constant during each symbol, $L_p \leq N$ and the spreading codes are repeated from symbol to symbol, the received signal $r(t)$ after filtering by a chip-pulse matched filter and sampling at chip rate yields the M-dimensional received vector at time instant i

$$\mathbf{r}[i] = \sum_{k=1}^{K} A_k \big(b_k[i-1]\mathbf{C}_k^p + b_k[i]\mathbf{C}_k + b_k[i+1]\mathbf{C}_k^s \big)\mathbf{h}_k[i] + \mathbf{n}[i], \tag{1}$$

where $M = N + L_p - 1$, $\mathbf{n}[i] = [n_1[i] \; \ldots \; n_M[i]]^T$ is the complex Gaussian noise vector with zero mean and $E[\mathbf{n}[i]\mathbf{n}^H[i]] = \sigma^2 \mathbf{I}_M$, $(\cdot)^T$ and $(\cdot)^H$ denote transpose and Hermitian transpose, respectively. $E[\cdot]$ is the expected value, b_k is the data symbol, the amplitude of user k is A_k, $\mathbf{s}_k = [a_k(1) \ldots a_k(N)]^T$ is the signature sequence for the k-th user, the $M \times L_p$ Toeplitz matrices $\mathbf{C}_k^p$, $\mathbf{C}_k$, $\mathbf{C}_k^s$ that contain one-chip shifted versions of $\mathbf{s}_k$ and the $L_p \times 1$ vector $\mathbf{h}_k[i]$ with multipath gains are given by

$$\mathbf{C}_k = \begin{bmatrix} a_k(1) & & \mathbf{0} \\ \vdots & \ddots & a_k(1) \\ a_k(N) & & \vdots \\ \mathbf{0} & \ddots & a_k(N) \end{bmatrix}, \; \mathbf{h}_k[i] = \begin{bmatrix} h_{k,0}[i] \\ \vdots \\ h_{k,L_p-1}[i] \end{bmatrix},$$

$$\mathbf{C}_k^s = \begin{bmatrix} \mathbf{C}_{k,\;[N+1:M,1:L_p]} \\ \mathbf{0}_{N\times L_p} \end{bmatrix}, \; \mathbf{C}_k^p = \begin{bmatrix} \mathbf{0}_{N\times L_p} \\ \mathbf{C}_{k,\;[1:L_p-1,1:L_p]} \end{bmatrix}, \tag{2}$$

where $\mathbf{C}_k^p$ and $\mathbf{C}_k^s$ account for the intersymbol interference (ISI) from previous and subsequent symbols, respectively. The subscript $[m : q, j : p]$ denotes the range of elements of a given matrix. Note that the $\mathbf{r}[i]$ and $\mathbf{r}[i+1]$ are overlapping as $\mathbf{r}[i+1]$ has the first $L_p - 1$ elements that are the same as the last $L_p - 1$ elements of $\mathbf{r}[i]$. In an asynchronous uplink scenario, the model should consider the maximum delay between any two users.

III. UNIFIED FRAMEWORK FOR INTERFERENCE CANCELLATION

Let us consider a conventional IC scheme, where the receiver aims to reconstruct the detected data and subtract them from the $M \times 1$ received vector $\mathbf{r}[i]$, yielding the received data for user k

$$\begin{aligned} \mathbf{r}_k^m[i] &= \mathbf{r}[i] - \sum_{j\in\mathcal{G},\; j\neq k} \hat{A}_j^m[i] \Big(\hat{b}_j^m[i-1]\mathbf{C}_j^p + \hat{b}_j^m[i]\mathbf{C}_j \\ &\qquad + \hat{b}_j^m[i+1]\mathbf{C}_j^s \Big) \hat{\mathbf{h}}_j^m[i] \\ &= \mathbf{r}[i] - \sum_{j\in\mathcal{G},\; j\neq k} \hat{A}_j^m[i]\mathbf{F}_j^m[i]\hat{\mathbf{h}}_j^m[i], \end{aligned} \tag{3}$$

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R. C. de Lamare is with the Department of Electronics, University of York, York Y010 5DD, UK (e-mail: rcdl500@york.ac.uk).

R. Sampaio-Neto is with CETUC/PUC-RIO, 22453-900, Rio de Janeiro, Brazil (e-mail: raimundo@cetuc.puc-rio.br).

A. Hjørungnes is with UniK, University of Oslo, Norway (e-mail: arehj@unik.no).

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where $\mathbf{F}_j^m[i] = \left(\hat{b}_j^m[i-1]\mathbf{C}_j^p + \hat{b}_j^m[i]\mathbf{C}_j + \hat{b}_j^m[i+1]\mathbf{C}_j^s\right)$ is an $M \times L_p$ matrix with the signature and symbol estimates of user j at the IC stage m, $\boldsymbol{\mathcal{G}} = \{\mathcal{G}_1,\ \mathcal{G}_2,\ \ldots,\ \mathcal{G}_P\}$ denotes the group of P users to be reconstructed and subtracted. We use P instead of K since only the P users from the group $\boldsymbol{\mathcal{G}}$ will be used for IC rather than all K users. In the conventional approach, the goal is to compute the estimates $\hat{A}_j^m[i]$, $\mathbf{F}_j^m[i]$ and $\hat{\mathbf{h}}_k^m[i]$ and this often leads to inaccurate IC.

The novel approach corresponds to a mathematical reformulation of (3) and the introduction of a $P \times 1$ IC parameter vector $\boldsymbol{\lambda}_k^m[i] = [\lambda_{k,1}^m[i]\ \lambda_{k,2}^m[i]\ \ldots\ \lambda_{k,P}^m[i]]^T$ for stage m and user k:

$$\begin{aligned}\mathbf{r}_k^m[i] &= \mathbf{r}[i] - \sum_{j \in \boldsymbol{\mathcal{G}},\ j \neq k} \lambda_{k,j}^m[i]\mathbf{F}_j^m[i]\hat{\mathbf{h}}_j^m[i] \\ &= \mathbf{r}[i] - \mathbf{D}_{\boldsymbol{\mathcal{G}}}^m[i]\boldsymbol{\lambda}_k^m[i],\end{aligned} \tag{4}$$

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

$$\mathbf{D}_{\boldsymbol{\mathcal{G}}}^m[i] = \boldsymbol{\mathcal{C}}_{\mathrm{T}}^p\boldsymbol{\mathcal{H}}^m\mathbf{B}^m[i-1] + \boldsymbol{\mathcal{C}}_{\mathrm{T}}\boldsymbol{\mathcal{H}}^m\mathbf{B}^m[i] + \boldsymbol{\mathcal{C}}_{\mathrm{T}}^s\boldsymbol{\mathcal{H}}^m\mathbf{B}^m[i+1], \tag{5}$$

$$\boldsymbol{\mathcal{C}}_{\mathrm{T}} = \left[\mathbf{C}_{\mathcal{G}_1}\ \mathbf{C}_{\mathcal{G}_2}\ \ldots\ \mathbf{C}_{\mathcal{G}_P}\right],\ \boldsymbol{\mathcal{C}}_{\mathrm{T}}^s = \left[\mathbf{C}_{\mathcal{G}_1}^s\ \mathbf{C}_{\mathcal{G}_2}^s\ \ldots\ \mathbf{C}_{\mathcal{G}_P}^s,\right], \tag{6}$$

$$\boldsymbol{\mathcal{C}}_{\mathrm{T}}^p = \left[\mathbf{C}_{\mathcal{G}_1}^p\ \mathbf{C}_{\mathcal{G}_2}^p\ \ldots \mathbf{C}_{\mathcal{G}_P}^p\right],\ \mathbf{B}^m[i] = \mathrm{diag}\big(b_{\mathcal{G}_1}^m[i],\ \ldots,\ b_{\mathcal{G}_P}^m[i]\big). \tag{7}$$

The matrix $\mathbf{D}_{\mathcal{G}}^m[i]$ corresponds to the reconstructed data of users which belong to group $\boldsymbol{\mathcal{G}}$ and it is a function of the $M \times (P \cdot L_p)$ code matrices $\boldsymbol{\mathcal{C}}_{\mathrm{T}}^p$, $\boldsymbol{\mathcal{C}}_{\mathrm{T}}$, $\boldsymbol{\mathcal{C}}_{\mathrm{T}}^s$, the $P \times P$ user's symbol matrix $\mathbf{B}^m[i]$, and $\boldsymbol{\mathcal{H}}^m[i] = \mathrm{diag}(\mathbf{h}_{\mathcal{G}_1}^m[i]\ \mathbf{h}_{\mathcal{G}_2}^m[i]\ \ldots\ \mathbf{h}_{\mathcal{G}_P}^m[i])$ is a block diagonal channel matrix with dimensions $(P \cdot L_p) \times P$, with the parameters of the users to be reconstructed and cancelled. *The key strategy* is to introduce extra degrees of freedom for IC with $\boldsymbol{\lambda}_k^m[i]$. This allows the optimization of $\boldsymbol{\lambda}_k^m[i]$ to address the individual impact of each interferer on the user of interest, leading to more accurate IC and robustness against error propagation.

The mathematical framework detailed in (4) can be used to describe IC schemes which perform SIC and PIC as particular cases. If the designer chooses to detect the users according to a decreasing power ordering, we obtain the proposed SIC

$$\begin{aligned}\mathbf{r}_k^m[i] &= \mathbf{r}[i] - \sum_{j=1}^{k-1} \lambda_{k,j}^m[i]\mathbf{F}_j^m[i]\hat{\mathbf{h}}_j^m[i] \\ &= \mathbf{r}[i] - \mathbf{D}_{\boldsymbol{\mathcal{G}}_{k-1}}^m[i]\boldsymbol{\lambda}_k^m[i], \quad m = 1,\end{aligned} \tag{8}$$

where $\boldsymbol{\mathcal{G}}_{k-1} = \{\mathcal{G}_1,\ \mathcal{G}_2,\ \ldots,\ \mathcal{G}_{k-1}\}$ denotes the group of users to be reconstructed according to the SIC approach (decreasing power order). There is only one stage ($m = 1$) for SIC, user k is detected and the previously detected users are regenerated and subtracted from $\mathbf{r}[i]$ and this is repeated for the remaining users.

Another detection strategy which can be carried out as a particular case of the framework in (4) is the PIC. In this proposed PIC scheme users are detected on the following basis

$$\begin{aligned}\mathbf{r}_k^m[i] &= \mathbf{r}[i] - \sum_{j=1,\ j \neq k}^{K} \lambda_{k,j}^m[i]\mathbf{F}_j^m[i]\hat{\mathbf{h}}_j^m[i] \\ &= \mathbf{r}[i] - \mathbf{D}_{\boldsymbol{\mathcal{G}}_{K-1}}^m[i]\boldsymbol{\lambda}_k^m[i], \quad m = 1,\ 2,\ \ldots\end{aligned} \tag{9}$$

where k represents the desired user to be detected, m is the stage, and $\boldsymbol{\mathcal{G}}_{K-1}$ contains all but the desired kth user.

IV. PROPOSED JOINT INTERFERENCE CANCELLATION AND PARAMETER ESTIMATION METHOD

We present a novel strategy for joint IC and parameters estimation based on the framework of the previous section. The idea is to consider the problems of receiver filter, channel, and IC parameter estimation jointly and devise exponentially weighted LS expressions to solve them. Let us consider the cost functions

$$J_1(\mathbf{w}_k^m[i]) = \sum_{l=1}^{i} \alpha^{i-l}|b_k[l] - \mathbf{w}_k^{m,H}[i]\mathbf{r}_k^m[l]|^2, \tag{10}$$

$$J_2(\boldsymbol{\lambda}_k^m[i],\ \hat{\mathbf{h}}_k^m[i]) = \sum_{l=1}^{i} \alpha^{i-l}||\mathbf{F}_k^m[l]\hat{\mathbf{h}}_k^m[i] - \mathbf{r}_k^m[l]||^2, \tag{11}$$

where $\mathbf{r}_k^m[l] = \mathbf{r}[l] - \mathbf{D}_{\boldsymbol{\mathcal{G}}}^m[l]\boldsymbol{\lambda}_k^m[i]$. The optimization of (11) seeks to cancel MAI, whereas that of (10) aims to suppress the residual MAI and ISI and α is the forgetting factor. By minimizing (10) with respect to the linear receiver filter front-end $\mathbf{w}_k^m[i]$ we obtain the Wiener-Hopf-like expressions

$$\mathbf{w}_k^m[i] = \mathbf{R}_{\mathbf{r}_k^m}^{-1}[i]\mathbf{p}_{b_k}[i], \tag{12}$$

where $\mathbf{R}_{\mathbf{r}_k^m}[i] = \sum_{l=1}^{i} \alpha^{i-l}\mathbf{r}_k^m[l]\mathbf{r}_k^{m,H}[l]$ is the $M \times M$ covariance matrix and $\mathbf{p}_{b_k}[i] = \sum_{l=1}^{i} \alpha^{i-l}b_k^*[l]\mathbf{r}_k^m[l]$ is the $M \times 1$ cross-correlation vector. By taking the gradient terms of (11) with respect to the IC parameter vector $\boldsymbol{\lambda}_k^m[i]$ and equating them to zero, we get the system of linear equations

$$\boldsymbol{\lambda}_k^m[i] = \mathbf{R}_{\mathbf{D}_{\boldsymbol{\mathcal{G}}}^m}^{-1}[i]\mathbf{p}_{\mathbf{F}_k^m}[i], \tag{13}$$

where $\mathbf{R}_{\mathbf{D}_{\boldsymbol{\mathcal{G}}}^m}[i] = \sum_{l=1}^{i} \alpha^{i-l}\mathbf{D}_{\boldsymbol{\mathcal{G}}}^{m,H}[l]\mathbf{D}_{\boldsymbol{\mathcal{G}}}^m[l]$ is $P \times P$ and $\mathbf{p}_{\mathbf{F}_k^m}[i] = \sum_{l=1}^{i} \alpha^{i-l}\mathbf{D}_{\boldsymbol{\mathcal{G}}}^{m,H}[l](\mathbf{r}[l] - \mathbf{F}_k^m[l]\hat{\mathbf{h}}_k^m[i])$ is $P \times 1$. By minimizing (11) with regard to $\hat{\mathbf{h}}_k^m[i]$ we obtain

$$\hat{\mathbf{h}}_k^m[i] = \mathbf{R}_{\mathbf{F}_k^m}^{-1}[i]\mathbf{p}_{\mathbf{D}_{\boldsymbol{\mathcal{G}}}^m}[i], \tag{14}$$

where $\mathbf{R}_{\mathbf{F}_k^m}[i] = \sum_{l=1}^{i} \alpha^{i-l}\mathbf{F}_k^{m,H}[l]\mathbf{F}_k^m[l]$ is $L_p \times L_p$ and $\mathbf{p}_{\mathbf{D}_{\boldsymbol{\mathcal{G}}}^m}[i] = \sum_{l=1}^{i} \alpha^{i-l}\mathbf{F}_k^{m,H}[l](\mathbf{r}[l] - \mathbf{D}_{\boldsymbol{\mathcal{G}}}^m[l]\boldsymbol{\lambda}_k^m[i])$ is $L_p \times 1$. The expressions in (12)-(14) are not closed-form ones as the IC and the linear receiver filter parameters depend on the channel and vice-versa. This means that (12)-(14) have to be iterated in order to seek a solution. The expressions in (12)-(14) require a computational complexity of $O(M^3)$, $O(P^3)$, and $O(L_p^3)$ for the estimation of $\mathbf{w}_k^m[i]$, $\boldsymbol{\lambda}_k^m[i]$ and $\hat{\mathbf{h}}_k^m[i]$, respectively.

V. SIMULATIONS

The performance of the proposed joint IC schemes and parameter estimation algorithms is assessed and compared with the linear [2], the SIC [7], [8], the PIC [12] detectors with linear receiver front-ends using LS algorithms with $\alpha = 0.998$ as the estimation procedure and the EM-based joint detector of [13]. The DS-CDMA system employs random spreading sequences of length $N = 32$, QPSK modulation and the detected symbols are obtained by $\hat{b}_k[i] = \mathrm{sgn}[\Re(x_k[i])] + \jmath\ \mathrm{sgn}[\Im(x_k[i])]$, where $\Re(\cdot)$ and $\Im(\cdot)$ denote the real and imaginary values, $x_k[i] = \mathbf{w}_k^{m,H}[i]\mathbf{r}_k^m[i]$, and $\mathrm{sgn}[\cdot]$ is the signum function. The channels $\mathbf{h}_k[i] = [h_{k,0}[i]\ h_{k,1}[i]\ \ldots\ h_{k,L_p-1}[i]]^T$ are modeled by the UMTS Vehicular A channel model [14] with maximum Doppler frequency $f_D = 100$ Hz with a carrier frequency $f_c = 2$ GHz and the channel estimation filter uses $L_p = 5$ taps. The

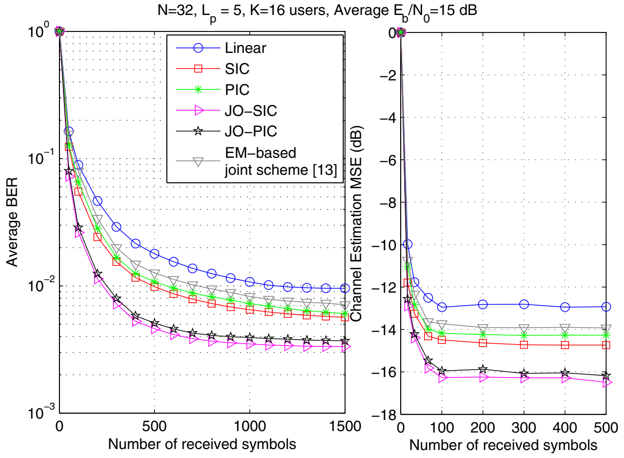

Fig. 1. BER and MSE channel estimation performance versus symbols.

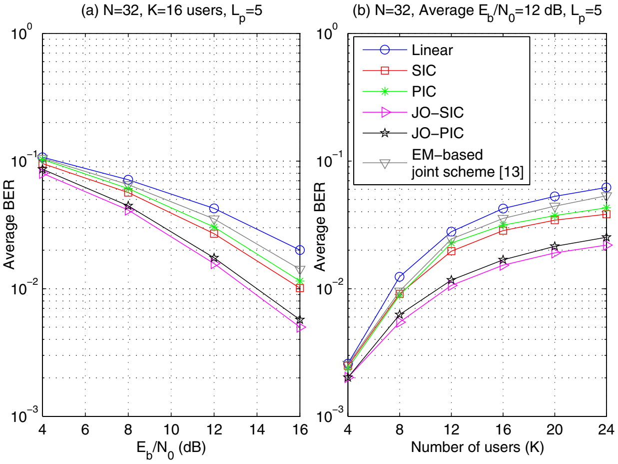

Fig. 2. BER performance of receivers versus (a) E_b/N_0 and (b) K.

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 200 runs. The packets have 1500 symbols and the training sequences have 150 symbols. After training, the receivers are switched to decision-directed mode. The receiver filters $\mathbf{w}_k^{m,H}[i]$ have $M = 36$ taps. The proposed jointly optimized algorithms with SIC and PIC receivers are denoted JO-SIC and JO-PIC, respectively. For PIC receivers [12], we used $m = 3$ stages, the amplitude estimation based on the output of the linear receiver front-end and for the JO-PIC we used $m = 3$ stages. For the SIC receivers [7], we used the amplitude estimation of [8]. All channel estimators (CE) employ exponentially weighted LS algorithms, as in (11). The linear receiver uses no IC for the CE (it solves (11) with $\mathbf{r}[l]$ in lieu of $\mathbf{r}_k^m[l]$), SIC and PIC exploit IC and use $\mathbf{r}_k^m[l]$ taken from (3), whereas the proposed JO-SIC and JO-PIC solve the LS problem of (11) with $\mathbf{r}_k^m[l]$ given by (8) and (9), respectively.

We assess the BER convergence of the proposed algorithms, receivers and the mean-squared error (MSE) performance of the channel estimators. The results, shown in Fig. 1, indicate that the proposed JO-SIC and JO-PIC receivers have the best performance among the compared schemes. The JO-SIC slightly outperforms the JO-PIC, which is followed by the SIC, the PIC, the EM-based scheme of [13] and the linear receivers. The performance of the JO-SIC and JO-PIC is significantly superior to the other approaches. This is because the proposed IC is more accurate than the existing schemes. The channel estimators of IC schemes in (14) clearly benefit from the cancellation process as compared to the linear estimator without IC. The joint IC and estimation is crucial for improving the performance of the proposed JO-SIC and JO-PIC, which achieve the best results.

The BER performance versus average E_b/N_0 and K is shown in Fig. 2. The best performance is obtained by the proposed JO-SIC and JO-PIC techniques. The plots show that the JO-SIC and JO-PIC receivers 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 schemes provide a significant capacity improvement over other analyzed methods.

VI. CONCLUSIONS

We proposed a unified framework for joint iterative parameter estimation and IC in CDMA systems. An LS joint optimization method for estimating the parameters of IC, the channel and receiver filter was also presented. The results show that the proposed methods are superior to the best known techniques.

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