Joint Iterative Power Adjustment and Interference Suppression Algorithms for Cooperative DS-CDMA Networks

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Abstract—This work presents joint iterative power allocation and interference suppression algorithms for DS-CDMA networks which employ multiple relays and the amplify and forward cooperation strategy. We propose a joint constrained optimization framework that considers the allocation of power levels across the relays subject to individual and global power constraints and the design of linear receivers for interference suppression. We derive constrained minimum mean-squared error (MMSE) expressions for the parameter vectors that determine the optimal power levels across the relays and the parameters of the linear receivers. In order to solve the proposed optimization problems efficiently, we develop recursive least squares (RLS) algorithms for adaptive joint iterative power allocation, and receiver and channel parameter estimation. Simulation results show that the proposed algorithms obtain significant gains in performance and capacity over existing schemes.

I. INTRODUCTION

Multiple collocated antennas enable the exploitation of the spatial diversity in wireless channels, mitigating the effects of fading and enhancing the performance of wireless communications systems. Due to size and cost it is often impractical to equip mobile terminals with multiple antennas. However, spatial diversity gains can be obtained when terminals with single antennas establish a distributed antenna array through cooperation [1]-[3]. In a cooperative transmission system, terminals or users relay signals to each other in order to propagate redundant copies of the same signals to the destination user or terminal. To this end, the designer must employ a cooperation strategy such as amplify-and-forward (AF) [3], decode-and-forward (DF) [3], [4] and compress-and-forward (CF) [5].

Recent contributions in the area of cooperative and multihop communications have considered the problem of resource allocation [6], [7]. However, there is very little work on resource allocation strategies in multiuser spread spectrum systems. In particular, prior work on cooperative multiuser spread spectrum DS-CDMA systems in interference channels has not received much attention and has focused on problems such as the impact of multiple access interference (MAI) and intersymbol interference (ISI), the problem of partner selection [4], [8] and the analysis of the bit error rate (BER) and outage performances [9]. The problem of resource allocation and interference mitigation in cooperative multiuser spread spectrum systems has not been jointly dealt with so far. This problem is of paramount importance in cooperative wireless ad-hoc and sensor networks [10], [11] that utilize spread spectrum systems.

In this work, spread spectrum systems which employ multiple relays and the AF cooperation strategy are considered. The problem of joint resource allocation and interference mitigation in multiuser DS-CDMA with a general number of relays is addressed. In order to facilitate the receiver design, we adopt linear multiuser receivers [12] which only require a training sequence and the timing. More sophisticated receiver techniques are also possible [13], [19]. A joint constrained optimization framework that deals with the allocation of power levels among the relays subject to individual and global power constraints and the design of linear receivers is proposed. MMSE expressions that jointly determine the optimal power levels across the relays and the linear receivers are derived. Joint adaptive and iterative recursive least squares (RLS) algorithms are also developed for solving the optimization problems, mitigating the effects of MAI and ISI, and allocating the power levels across the links.

This paper is organized as follows. Section II describes a cooperative DS-CDMA system model with multiple relays. Section III formulates the problem and the constrained linear MMSE design of the receiver and the power allocation. The proposed RLS algorithms for the estimation of the receive filter, the power allocation and the channels subject to a global and individual power constraints are developed in Sections IV and V, respectively. Section VI presents and discusses the simulations and Section VII draws the conclusions.

II. COOPERATIVE DS-CDMA SYSTEM MODEL

Consider the uplink of a synchronous DS-CDMA system communicating over multipath channels with QPSK modulation, K users, N chips per symbol and L as the maximum number of propagation paths for each link. The network is equipped with an AF protocol that allows communication in multiple hops using nr relays in a repetitive fashion. We assume that the source node or terminal transmits data organized in packets with P symbols, there is enough training and control data to coordinate transmissions and cooperation, and the linear receivers at the relay and destination terminals are perfectly synchronized. The received signals are filtered by a matched filter, sampled at chip rate and organized into M × 1 vectors rsd[i] and rsr[i] which describe the signal received from the source to the destination and from the source to the relays, respectively, as follows

\[
\begin{align*}
    r_{sd}[n] & = \sum_{k=1}^{K} a_{sd}^k[n] D_k h_{sd,k}[n] b_k[n], \\
    r_{sr,j}[n] & = \sum_{k=1}^{K} a_{sr,j}^k[n] D_k h_{sr,j,k}[n] b_k[n],
\end{align*}
\]

where \( M = N + L - 1 \), \( n_{sd}[i] \) and \( n_{sr,j}[i] \) are zero mean complex Gaussian vectors with variance \( \sigma^2 \) generated at the receiver of the destination and the relays, and the vectors \( \eta_{sd}[i] \) and \( \eta_{sr,j}[i] \) represent the intersymbol interference (ISI). The \( M \times L \) matrix \( D_k \) has the signature sequences of each user shifted down by one position at each column to form

\[
D_k = \begin{bmatrix}
    d_k(1) & 0 & \cdots \\
    \vdots & \ddots & \vdots \\
    d_k(N) & \cdots & d_k(1) \\
    0 & \cdots & d_k(N)
\end{bmatrix},
\]

where \( d_k = [d_k(1), d_k(2), \ldots, d_k(N)] \) stands for the signature sequence of user \( k \), the \( L \times 1 \) channel vectors from source to destination, source to relay, and relay to destination are \( h_{sd,k}[n], h_{sr,j,k}[n], h_{sr,j,sd}[n] \), respectively. By collecting the data vectors in...
(including the links from relays to destination) into a \((n_r + 1)M \times 1\) received vector at the destination we get

\[
\begin{bmatrix}
    r_{sd}[n] \\
r_{s1,d}[m] \\
\vdots \\
r_{r_n,d}[m]
\end{bmatrix}
= \begin{bmatrix}
    \sum_{k=1}^{K} a_{sd,k}[n] D_k h_{sd,k}[n] b_k[i] \\
    \sum_{k=1}^{K} a_{s1,d}[m] D_k h_{r1,d,k}[m] b_k[i] \\
\vdots \\
    \sum_{k=1}^{K} a_{r_n,d,k}[m] D_k h_{r_n,d,k}[m] b_k[i] \\
    \end{bmatrix} + \eta[i] + n[i]
\]

Rewriting the above signals in a compact form yields

\[
r[i] = \sum_{k=1}^{K} C_k h_k[i] B_k[i] a_k[i] + \eta[i] + n[i],
\]

where the \((n_r + 1)M \times (n_r + 1)L\) block diagonal matrix \(C_k\) contains shifted versions of \(D_k\) as shown by

\[
C_k = \begin{bmatrix}
    D_k & 0 & \ldots & 0 \\
    0 & D_k & \ldots & 0 \\
    \vdots & \ddots & \ddots & \vdots \\
    0 & \ldots & 0 & D_k
\end{bmatrix}.
\]

The \((n_r + 1)L \times (n_r + 1)\) matrix \(h_k[i]\) contains the channel gains of the links between the source and the destination, and the relays and the destination. The \((n_r + 1) \times (n_r + 1)\) diagonal matrix \(B_k[i] = \text{diag}(b_k[i], b_k^{r1}[i], \ldots, b_k^{r_n}[i])\) contains the symbols transmitted from the source to the destination \(b_k[i]\) and the \(n_r\) symbols transmitted from the relays to the destination \(b_k^{r1}[i], \ldots, b_k^{r_n}[i]\) on the main diagonal, the \((n_r + 1) \times 1\) vector \(a_k[i] = [a_{sd,k}[n], a_{s1,d}[m], \ldots, a_{r_n,d}[m]]^T\) of the amplitudes of the links, the \((n_r + 1)M \times 1\) vector \(\eta[i]\) with the ISI terms and \((n_r + 1)M \times 1\) vector \(n[i]\) with the noise.

### III. PROBLEM FORMULATION AND PROPOSED MMSE DESIGN

This section formulates the problem of MMSE joint power allocation and interference suppression for a cooperative DS-CDMA network. Two constrained optimization problems are proposed in order to describe the joint power allocation and interference suppression problems subject to a global and individual power constraints.

#### A. MMSE Design with Global Power Constraint

The MMSE design of the power allocation of the links across the source, relay and destination terminals and interference suppression filters is presented using a global power constraint. Let us express the received vector in (5) in a more convenient way for the proposed optimization. The \((n_r + 1)M \times 1\) received vector can be written as

\[
r[i] = C_T H_T[i] B_T[i] a_T[i] + \eta[i] + n[i],
\]

where the \((n_r + 1)M \times K(n_r + 1)\) matrix \(C_T = [C_1, C_2, \ldots, C_K]\) contains all the symbols, the \((n_r + 1)L \times K(n_r + 1)\) block diagonal matrix \(H_T[i] = [H_1[i], H_2[i], \ldots, H_K[i]]\) contains the channel gains of all the links, the \((n_r + 1) \times (n_r + 1)\) diagonal matrix \(B_T[i] = \text{diag}(b_T[i], b_T^{r1}[i], \ldots, b_T^{r_n}[i])\) contains the symbols transmitted from all the sources to the destination and from all the relays to the destination on the main diagonal, the \((n_r + 1) \times 1\) vector \(a_T[i] = [a_{sd,k}[n], a_{s1,d}[m], \ldots, a_{r_n,d}[m]]^T\) contains the amplitudes of all the links.

Consider an MMSE design of the receivers for the users represented by a \((n_r + 1)M \times K\) parameter matrix \(W[i] = [w_1[i], \ldots, w_K[i]]\) and for the computation of the \((n_r + 1) \times 1\) optimal power allocation vector \(a_T[i]\). This problem is cast as

\[
\begin{align*}
    [W_{opt}, a_{T,opt}] & = \arg \min_{W[i], a_T[i]} E[||b[i] - W[i]a_T[i]||^2] \\
    \text{subject to } a_T[i] a_T[i] & = P_T,
\end{align*}
\]

where the \(K \times 1\) vector \(b[i] = [b_1[i], \ldots, b_K[i]]^T\) represents the desired symbols. The MMSE expressions for the parameter matrix \(W_{opt}\) and vector \(a_{T,opt}\) can be obtained by transforming the above constrained optimization problem into an unconstrained one with the method of Lagrange multipliers [20] which leads to

\[
\begin{align*}
    \mathcal{L} &= E[||b[i] - W[i]a_T[i] + \eta[i] + n[i]||^2] + \lambda(a_T[i] a_T[i] - P_T),
    \\
    \text{Fixing } a_T[i], \text{ taking the gradient terms of the Lagrangian and equating them to zero yields }
    \\
    W_{opt} &= R^{-1} P_{opt}, \quad \lambda = \sigma^2,
\end{align*}
\]

where the covariance matrix of the received vector is given by 

\[
R = E[||b[i]||^2] = C_T H_T[i] B_T[i] a_T[i] a_T[i]^H H_T[i] B_T[i] + \sigma^2 I
\]
and \(P_{opt} = E[||b[i]||^2] = E[C_T H_T[i] B_T[i] a_T[i] a_T[i]^H]\) is the \((n_r + 1)M \times K\) cross-correlation matrix. The matrices \(R\) and \(P_{opt}\) depend on the power allocation vector \(a_T[i]\).

The expression for \(a_T[i]\) is obtained by fixing \(W[i]\), taking the gradient terms of the Lagrangian and equating them to zero which leads to

\[
[\hat{a}_T[i], a_T[i]] = R_{opt}^{-1} P_{opt}, \quad \lambda = \sigma^2
\]

where the \(K(n_r + 1) \times K(n_r + 1)\) covariance matrix \(R_{opt} = E[||b[i]||^2] C_T H_T[i] B_T[i] a_T[i] a_T[i]^H H_T[i] B_T[i] + \sigma^2 I\) and the vector \(P_{opt} = E[||b[i]||^2] = E[C_T H_T[i] B_T[i] a_T[i] a_T[i]^H]\) is a \((n_r + 1) \times 1\) cross-correlation vector. The Lagrange multiplier \(\lambda\) in the expression above plays the role of a regularization term and has to be determined numerically due to the difficulty of evaluating its expression. The expressions in (8) and (9) depend on each other and require the estimation of the channel matrix \(H_T[i]\). Thus, it is necessary to iterate (8) and (9) with initial values to obtain a solution and to estimate the channel. In addition, the network has to convey all the information necessary to compute the global power allocation including the filter \(W_{opt}\). The expressions in (8) and (9) require matrix inversions with cubic complexity (\(O((n_r + 1)M)^3\)) and \(O(K(n_r + 1))^3\), should be iterated as they depend on each other and require channel estimation.

#### B. MMSE Design with Individual Power Constraints

Here, it is posed an optimization problem that considers the joint design of a linear receiver and the calculation of the optimal power levels across the relays subject to individual power constraints. Consider an MMSE approach for the design of the receive filter \(w_k[i]\) and vector \(a_k[i]\) for user \(k\). This problem can be cast as

\[
\begin{align*}
    [w_{opt,k}, a_{k,opt}] & = \arg \min_{w_k[i], a_k[i]} ||b_k[i] - w_k[i] r[i][i]||^2 \\
    \text{subject to } a_k[H[i] a_k[i]] & = P_{Ak}, \quad k = 1, 2, \ldots, K.
\end{align*}
\]

The expressions for the parameter vectors \(w_k[i]\) and \(a_k[i]\) can be obtained by transforming the above constrained optimization problem into an unconstrained one with the help of the method of Lagrange multipliers [20] which leads to

\[
\begin{align*}
    \mathcal{L} &= E[||b_k[i] - w_k[i] r[i][i]||^2] + \lambda(a_k[i] a_k[i] - P_{Ak}), \quad k = 1, 2, \ldots, K.
    \\
    \text{Fixing } a_k[i], \text{ taking the gradient terms of the Lagrangian and equating them to zero yields }
    \\
    w_{opt,k} &= R^{-1} P_{opt}, \quad k = 1, 2, \ldots, K,
\end{align*}
\]

where \(R = \sum_{k=1}^{K} C_k H_k[i] B_k[i] a_k[i] a_k[i]^H H_k[i] B_k[i] + \sigma^2 I\) is the covariance matrix and \(P_{opt} = E[||b_k[i] r[i][i]||^2] = C_k H_k[i] a_k[i]\) is...
the cross-correlation vector. The quantities $\mathbf{R}$ and $\mathbf{pC_M}$ depend on $\alpha_k[i]$. By fixing $\mathbf{w}_k[i]$, the expression for $\alpha_k[i]$ is given by

$$a_{k,\text{opt}} = (\mathbf{R}_{a,k} + \lambda I)^{-1}\mathbf{p}_{a,k}, \quad k = 1, 2, \ldots, K,$$

(13)

where $\mathbf{R}_{a,k} = \sum_{k=1}^{K} B_i^H[i] \mathbf{H}_i \mathbf{C}_i \mathbf{w}_k[i] \mathbf{w}_k[i]^H \mathbf{C}_i \mathbf{H}_i \mathbf{B}_k[i]$ is the $(n_r+1) \times (n_r+1)$ covariance matrix and the $(n_r+1) \times 1$ cross-correlation vector is $\mathbf{p}_{a,k} = [E[|b[i]|^2 B_i^H[i] \mathbf{H}_i \mathbf{C}_i \mathbf{w}_k[i]]]$. The expressions in (12) and (13) depend on each other and should be iterated. They also require the estimation of the channel matrices $\mathbf{H}_k[i]$ and need matrix inversions with cubic complexity ($O((n_r+1)^3)$) and $O((n_r+1)^5)$. In what follows, we will develop algorithms for computing $\alpha_{k,\text{opt}}, \mathbf{w}_k[i]$ and the channels $\mathbf{H}_k[i]$ for $k = 1, \ldots, K$.

IV. PROPOSED JOINT ESTIMATION ALGORITHMS WITH A GLOBAL POWER CONSTRAINT

Here we present adaptive joint estimation algorithms to determine the parameters of the linear receiver, the power allocation and the channel with a global power constraint.

A. Receiver and Power Allocation Parameter Estimation

Let us now consider the following proposed least squares (LS) optimization problem

$$\hat{\mathbf{W}}[i], \hat{\mathbf{a}}_T[i] = \arg \min_{\mathbf{W}[i] \in \mathbb{C}^{N \times N}, \mathbf{a}_T[i]} \left\| \sum_{i=1}^{n_r} \alpha_i^{-1} |b[i]| - W^H[i] r[i] \right\|^2$$

subject to $\mathbf{a}_T[i] \mathbf{a}_T[i]^H = P_T$, (14)

where $\alpha$ is a forgetting factor. The goal is to develop a recursive cost-effective solution to (14). To this end, we will resort to the theory of adaptive algorithms (20) and derive a constrained joint iterative recursive least squares (RLS) algorithm. This algorithm will compute $\hat{\mathbf{W}}[i]$ and $\hat{\mathbf{a}}_T[i]$ and will exchange information between the recursions. The part of the algorithm to compute $\hat{\mathbf{W}}[i]$ uses $\Phi[i] = \mathbf{R}[i] = \sum_{i=1}^{n_r} \alpha_i^{-1} |r[i]| r[i] r[i]^H$ and is given by

$$k[i] = \frac{\alpha_i^{-1} \Phi[i] r[i]}{1 + \alpha_i^{-1} r[i] \Phi[i] r[i]},$$

(15)

$$\Phi[i] = \alpha_i^{-1} \Phi[i] - \alpha_i^{-1} k[i] r[i] \Phi[i] r[i],$$

(16)

$$W[i] = W[i-1] + \alpha_i \epsilon_i,$$

(17)

where the $a \text{ priori}$ estimation error is given by

$$\epsilon_i = b[i] - W^H[i-1] r[i].$$

(18)

The derivation for the recursion that estimates the power allocation $\hat{\mathbf{a}}_T[i]$ presents a difficulty related to the enforcement of the constraint and how to incorporate it into an efficient RLS algorithm. A modification is required in order to complete the derivation of the proposed RLS algorithm. This is because the problem in (14) incorporates a Lagrange multiplier (\lambda) to ensure the global power constraint, which is difficult to include in the matrix inversion lemma.

Our approach is to obtain a recursive expression by relaxing the constraint and then ensure the constraint is incorporated via a subsequent normalization procedure. In order to develop the recursions for $\hat{\mathbf{a}}_T[i]$, we need to compute the inverse of $\mathbf{R}_{a,k}[i] = \sum_{i=1}^{n_r} B_i^H[i] \mathbf{H}_i \mathbf{C}_i \mathbf{w}_k[i] \mathbf{w}_k[i]^H \mathbf{C}_i \mathbf{H}_i \mathbf{B}_k[i]$. To this end, let us first define $\Phi_{a,T} = \mathbf{R}_{a,T}[i]$ and employ the matrix inversion lemma (20) as follows:

$$k_{a,T}[i] = \frac{\alpha_i^{-1} \Phi_{a,T}[i] B_i^H[i] \mathbf{H}_i \mathbf{C}_i \mathbf{w}_k[i] \mathbf{w}_k[i]^H \mathbf{C}_i \mathbf{H}_i \mathbf{B}_k[i]}{1 + \alpha_i^{-1} W^H[i] \mathbf{C}_i \mathbf{H}_i [i] [B_i^H[i] \mathbf{H}_i \mathbf{C}_i \mathbf{w}_k[i] \mathbf{w}_k[i]^H \mathbf{C}_i \mathbf{H}_i \mathbf{B}_k[i]]},$$

(19)

$$\Phi_{a,T}[i] = \alpha_i^{-1} \Phi_{a,T}[i-1] - \alpha_i^{-1} k_{a,T}[i] W^H[i] \mathbf{C}_i \mathbf{H}_i [i] [B_i^H[i] \mathbf{H}_i \mathbf{C}_i \mathbf{w}_k[i] \mathbf{w}_k[i]^H \mathbf{C}_i \mathbf{H}_i \mathbf{B}_k[i]]$$

(20)

After some algebraic manipulations, we get

$$\hat{\mathbf{a}}_T[i] = \hat{\mathbf{a}}_T[i] + k_{a,T}[i] \hat{\epsilon}_{a,T}[i]$$

(21)

where the $a \text{ priori}$ estimation error for this recursion is

$$\hat{\epsilon}_{a,T}[i] = b[i] - \mathbf{a}_T[i] \mathbf{B}_i^H[i] \mathbf{H}_i \mathbf{C}_i \mathbf{w}_k[i] \mathbf{w}_k[i]^H \mathbf{C}_i \mathbf{H}_i \mathbf{B}_k[i]$$

(22)

In order to ensure the individual power constraint $\mathbf{a}_T[i] \mathbf{a}_T[i]^H = P_T$, we apply the following rule

$$\hat{\mathbf{a}}_T[i] \leftarrow P_T \hat{\mathbf{a}}_T[i] \left( \mathbf{a}_T[i] \mathbf{a}_T[i]^H \right)^{-1}$$

(23)

The algorithms for recursive computation of $\hat{\mathbf{W}}[i]$ and $\hat{\mathbf{a}}_T[i]$ require estimates of the channel vector $\mathbf{H}_k[i]$, which will also be developed in what follows. The complexity of the proposed algorithm is $O((n_r+1)M^2)$ for calculating $\hat{\mathbf{W}}[i]$ and $O((K(n_r+1))^2)$ for obtaining $\hat{\mathbf{a}}_T[i]$.

B. Channel Estimation with a Global Power Constraint

We present a channel estimator that considers jointly all the $K$ users and exploits the knowledge of the receive filter matrix $\hat{\mathbf{W}}[i]$ and the power allocation vector $\hat{\mathbf{a}}_T[i]$. Let us rewrite $r[i]$ as

$$r[i] = \mathbf{C}_T \tilde{B}_T[i] \hat{\mathbf{A}}_T[i] h[i] + \eta[i] + n[i],$$

(24)

where $\tilde{B}_T[i]$ is a $\mathbf{N}(n_r+1) \times \mathbf{N}(n_r+1)$ L matrix with the symbols of all K users transmitted from the sources and the relays on the main diagonal, $\hat{\mathbf{A}}_T[i]$ is a $\mathbf{N}(n_r+1) \times \mathbf{N}(n_r+1)$ L matrix with the amplitudes of all the links on the main diagonal and $\lambda[i]$ is a $\mathbf{N}(n_r+1) \times 1$ vector with the L channel gains from all K users, sources and relays. A channel estimator can be derived from the following optimization problem

$$\hat{h}_{T}[i] = \arg \min_{h_T[i]} \left\| \sum_{l=1}^{n_r} \alpha_i^{-1} |r[i] - \mathbf{C}_T \tilde{B}_T[i] \hat{\mathbf{A}}_T[i] h[i])|^2 \right\|^2$$

(25)

The solution to the above optimization problem is given by

$$\hat{h}_{T}[i] = \tilde{\mathbf{R}}_{h_T}[i] \hat{\mathbf{p}}_{h_T}[i],$$

(26)

where

$$\tilde{\mathbf{R}}_{h_T}[i] = \alpha_i^{-1} \tilde{\mathbf{R}}_{h_T}[i-1] - \alpha_i^{-2} \tilde{\mathbf{R}}_{h_T}[i-1] \mathbf{K}[i-1] + \mathbf{K}[i-1] \mathbf{K}[i-1]^+$$

(27)

$$\hat{\mathbf{p}}_{h_T}[i] = \alpha \hat{\mathbf{p}}_{h_T}[i-1] + \mathbf{K}[i-1] \hat{\mathbf{q}}_{T,j},$$

(28)

and

$$\mathbf{K}[i] = \sum_{j=1}^{K(n_r+1)} h_T[i] q_{T,j},$$

(30)

where $q_{T,j} = \begin{bmatrix} 0 \ldots & 0 & 1 & 0 & \ldots & 0 \end{bmatrix}$.

This algorithm jointly estimates the coefficients of the channels across all the links and for all users subject to a global power constraint. The complexity of the proposed RLS channel estimation algorithm is $O((K(n_r+1))^2)$.

V. PROPOSED JOINT ESTIMATION ALGORITHMS WITH INDIVIDUAL POWER CONSTRAINTS

In this section, we present adaptive algorithms to determine the parameters of the linear receiver, the power allocation and the channel subject to individual power constraints. Unlike the algorithms presented in the previous section, the algorithms proposed here are suitable for distributed resource allocation, detection and estimation.
A. Receiver and Power Allocation Parameter Estimation

We develop a recursive solution to the expressions in (12) and (13) using time averages instead of the expected value. The proposed RLS algorithms will compute $\mathbf{w}_k[i]$ and $\alpha_k[i]$ for each user $k$ and will exchange information between the receivers. We fix $\alpha_k[i]$ and compute the inverse of $\mathbf{R}[i]$ using the matrix inversion lemma (28) to obtain $\mathbf{w}_k[i]$. Defining $\mathbf{F}[i] = \mathbf{R}[i]$ then we can obtain the recursions

$$k[i] = \frac{\alpha^{-1}_{k} \Phi[i] r[i]}{1 + \alpha^{-1}_{k} \Phi[i] r[i]}$$

$$\Phi[i] = \alpha^{-1}_{k} \Phi[i-1] - \alpha^{-1}_{k} k[i] r[i] \Phi[i-1]$$

where the a priori estimation error is

$$\xi[i] = b_k[i] - w_k[i-1] r[i].$$

The derivation for the recursion that estimates the power allocation follows a similar approach to the computation of $\mathbf{w}_k[i]$. In order to develop the recursions for $\mathbf{a}_k[i]$, we need to compute the inverse of $\hat{\mathbf{R}}_{a_k}[i] = \sum_{l=1}^{L} \mathbf{B}_l[i] \hat{\mathbf{H}}_l[i] \mathbf{H}_l[i] \mathbf{B}_l[i]$. To this end, let us first define $\mathbf{a}_k[i] = \hat{\mathbf{R}}_{a_k}[i]$ and proceed as follows:

$$k_{a_k}[i] = \frac{\alpha^{-1}_{k} \mathbf{a}_k[i] \mathbf{B}_l[i] \hat{\mathbf{H}}_l[i] \mathbf{H}_l[i] \mathbf{B}_l[i] \mathbf{a}_k[i]}{1 + \alpha^{-1}_{k} \mathbf{a}_k[i] \mathbf{B}_l[i] \hat{\mathbf{H}}_l[i] \mathbf{H}_l[i] \mathbf{B}_l[i] \mathbf{a}_k[i]}$$

$$\mathbf{a}_k[i] = \alpha^{-1}_{k} \mathbf{a}_k[i-1] - \alpha^{-1}_{k} k_{a_k}[i] w_k[i] \mathbf{C}_k[i] \hat{\mathbf{H}}_k[i] \mathbf{B}_k[i] \mathbf{a}_k[i-1]$$

where the a priori estimation error for this equation is

$$\xi_{a_k}[i] = b_k[i] - \hat{a}_{k}[i] \mathbf{B}_l[i] \hat{\mathbf{H}}_l[i] \mathbf{H}_l[i] \mathbf{B}_l[i] \mathbf{a}_k[i].$$

In order to ensure the individual power constraint $\alpha_k[i] \mathbf{a}_k[i] = P_{A,k}$, we apply the rule

$$\mathbf{a}_k[i] = \mathbf{P}_{A,k} \mathbf{a}_k[i] \left( \sqrt{\alpha_k[i]} \mathbf{a}_k[i] \right)^{-1}$$

The algorithm for recursive computation of $\mathbf{w}_k[i]$ and $\mathbf{a}_k[i]$ require estimates of the channel vector $\hat{\mathbf{H}}_k[i]$, which will also be developed in what follows. The complexity of the proposed algorithm is $O((n_r+1)M^2)$ for computing $\mathbf{w}_k[i]$ and $O(n_r + 1)^2$ for obtaining $\mathbf{a}_k[i]$.

B. Channel Estimation with Individual Power Constraints

We propose here an algorithm that estimates the channels for each user $k$ across all links subject to individual power constraints and exploits the knowledge of the receiver filter $\mathbf{w}_k[i]$ and the power allocation vector $\mathbf{a}_k[i]$. Let us express the received vector in (3) as

$$\mathbf{r}[i] = \sum_{k=1}^{K} \mathbf{C}_k \hat{\mathbf{B}}_k[i] \hat{\mathbf{A}}_k[i] \mathbf{h}_k[i] + \eta[i] + \mathbf{n}[i],$$

where $\hat{\mathbf{B}}_k[i]$ is a $(n_r+1)L \times (n_r+1)L$ matrix with the symbols of user $k$ transmitted from the sources and the relays on the main diagonal, $\hat{\mathbf{A}}_k[i]$ is a $(n_r+1)L \times (n_r+1)L$ matrix with the amplitudes of all the links on the main diagonal and $\mathbf{h}_k[i]$ is a $K(n_r+1)L \times 1$ vector with the $L$ channel gains for user $k$, and each link. A channel estimation algorithm can be developed solving the optimization problem

$$\hat{h}_k[i] = \arg\min_{h_k[i]} \sum_{l=1}^{L} \alpha^{l-1}_{k} ||\mathbf{r}[l] - \mathbf{C}_k \hat{\mathbf{B}}_k[i] \hat{\mathbf{A}}_k[i] \mathbf{h}_k[i] ||^2,$$

for $k = 1, 2, \ldots, K$.

The solution to the above optimization problem is

$$\hat{h}_k[i] = \hat{R}_{h_k}[i]^{-1} \mathbf{p}_{h_k}[i], \quad \text{for } k = 1, 2, \ldots, K$$

where

$$\hat{R}_{h_k}[i] = \alpha^{-1} \hat{R}_{h_k}[i-1] - \alpha^{-2} \hat{R}_{h_k}[i-1] \mathbf{p}_{h_k}[i] \mathbf{p}_{h_k}[i]^H \hat{R}_{h_k}[i-1] \mathbf{p}_{h_k}[i] + 1$$

$$\mathbf{p}_{h_k}[i] = \alpha \hat{p}_{h_k}[i-1] + \mathbf{v}_k[i] r[i]$$

and

$$\mathbf{v}_k[i] = \mathbf{C}_k \hat{\mathbf{B}}_k[i] \hat{\mathbf{A}}_k[i].$$

The channel matrix $\hat{\mathbf{H}}_k[i]$ is obtained as follows:

$$\hat{\mathbf{H}}_k[i] = \sum_{j=1}^{n_r+1} \hat{h}_k[i] q_{k,j},$$

where $q_{k,j} = [0 \ldots 0 1 0 \ldots 0]$. This algorithm estimates the coefficients of the channels of each user $k$ across all the links subject to individual power constraints. The complexity is $O((n_r+1)L^2)$.

VI. SIMULATIONS

We evaluate the bit error ratio (BER) performance of the proposed joint power allocation and interference suppression (JPAIS) algorithms with global (GPC) and individual power (IPC) constraints and compare them with interference suppression schemes without cooperation (NCIS) and with cooperation (CIS) using an equal power allocation across the relays. We consider a stationary DS-CDMA network with randomly generated spreading codes with a processing gain $N = 16$. The fading channels are generated considering a random power delay profile with gains taken from a complex Gaussian variable with unit variance and mean zero, $L = 3$ paths spaced by one chip, and are normalized for unit power. The power constraint parameter $P_{A,k}$ is set for each user so that one can control the SNR (SNR = $P_{A,k}/\sigma^2$) and $P_T = KP_{A,k}$, whereas it follows a log-normal distribution for with associated standard deviation of 3 dB. We adopt the AF cooperative strategy with repetitions and all the relays and the destination terminal are equipped with linear MMSE receivers. We employ packets with 1500 QPSK symbols and average the curves over 1000 runs. The receivers have either full knowledge of the channel and the noise variance or are adaptive and estimate all the required coefficients and the channels using the proposed RLS algorithms with optimized parameters. For the adaptive receivers, we provide training sequences with 200 symbols placed at the preamble of the packets. After the training sequence, the adaptive receivers are switched to decision-directed mode.

We first consider the proposed JPAIS method with the MMSE expressions of (6) and (9) using a global power constraint (JPAIS-GPC), and (12) and (13) with individual power constraints (JPAIS-IPC). We compare the proposed scheme with a non-cooperative approach (NCIS) and a cooperative scheme with equal power allocation (CIS) across the relays for $n_r = 1, 2$ relays. The results shown in Fig. 1 illustrate the performance improvement achieved by the proposed JPAIS scheme and algorithms, which significantly outperform the CIS and the NCIS techniques. As the number of relays is increased so is the performance, reflecting the exploitation of the spatial diversity. In the scenario studied, the proposed JPAIS-IPC approach can accommodate up to 3 more users as compared to the CIS scheme and double the capacity as compared with the NCIS for the same performance. The proposed JPAIS-GPC is superior to the JPAIS-IPC and can accommodate up to 2 more users than the JPAIS-GPS, while its complexity is higher.
The second experiment depicted in Fig. 2 shows the BER performance of the proposed adaptive algorithms (JPAIS) against the existing NCIS and CIS schemes with \( n_r = 2 \) relays. All techniques employ RLS algorithms for the estimation of the coefficients of the channel, the receiver filters and the power allocation for each user (JPAIS only). The complexity of the proposed algorithms is quadratic with the filter length of the receivers and the number of relays \( n_r \), whereas the optimal MMSE schemes require cubic complexity. From the results, we can verify that the proposed adaptive joint estimation algorithms converge to approximately the same level of the MMSE schemes, which have full channel and noise variance knowledge. Again, the proposed JPAIS-GPC is superior to the JPAIS-IPC but requires higher complexity and joint demodulation of signals, whereas the JPAIS-IPC renders itself to a distributed implementation.

**VII. CONCLUDING REMARKS**

This work proposed joint iterative power allocation and interference mitigation techniques for DS-CDMA networks with multiple relays and the AF cooperation strategy. A joint constrained optimization framework and algorithms that consider the allocation of power levels across the relays subject to global and individual power constraints and the design of linear receivers for interference suppression were proposed. The results of simulations showed that the proposed methods obtain significant gains in performance and capacity over existing non-cooperative systems and cooperative schemes.

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