ABSTRACT

This work presents joint iterative power allocation and interference suppression algorithms for spread spectrum networks with multiple relays and the amplify and forward cooperation strategy. 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 is proposed. 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 are derived. In order to solve the proposed optimization problems efficiently, stochastic gradient (SG) algorithms for adaptive joint iterative power allocation, and receiver and channel parameter estimation are developed. The results of simulations show that the proposed algorithms obtain significant gains in performance and capacity over existing cooperative and non-cooperative schemes.

Index Terms— Spread spectrum communication, cooperative systems, optimization methods, resource allocation.

1. INTRODUCTION

The use of multiple collocated antennas enables the exploitation of the spatial diversity in wireless channels, mitigating the effects of fading and enhancing the performance of wireless communications systems. Unfortunately, due to size and cost it is often impractical to equip mobile terminals with multiple antennas. However, spatial diversity gains can be obtained when single-antenna terminals 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 multiruser 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 the assessment of the impact of multiple access interference (MAI) and intersymbol interference (ISI), the problem of partner selection [4, 8] and the bit error rate (BER) and outage performance analyzes [9]. There has been no attempt to jointly consider the problem of resource allocation and interference mitigation in cooperative multiuser spread spectrum systems so far. This problem is of paramount importance in wireless cooperative cellular, 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. Specifically, 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, 13] which only require a training sequence and the timing. More sophisticated receiver techniques are also possible [12, 14]. A joint constrained optimization framework that considers 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 SG algorithms are also developed for efficiently solving the optimization problems, mitigating the effects of MAI and ISI, and allocating the power levels across the links.

The paper is organized as follows. Section 2 describes a cooperative DS-CDMA system model with multiple relays. Section 3 formulates the problem and the constrained linear MMSE design of the receive filters subject to a global power allocation constraint, whereas Section 4 considers an individual power allocation strategy. Section 5 presents joint adaptive and iterative SG algorithms. Section 6 presents and discusses the simulation results and Section 7 draws the conclusions of this work.

2. COOPERATIVE DS-CDMA SYSTEM MODEL

Consider 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 $n_r$ fixed 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 $M \times 1$ vectors $r_{sd}[i]$ and $r_{sr}[i]$ which describe the signal received from the source to the destination and from the source to the relays, respectively, as follows

$$r_{sd}[n] = \sum_{k=1}^{K} a_{sd}[n]D_k h_{sd,k}[n]b_k[i] + \eta_{sd}[n] + n_{sd}[n],$$

$$r_{sr}[m] = \sum_{k=1}^{K} a_{sr}[m]D_k h_{sr,k}[m]b_k[i] + \eta_{sr}[m] + n_{sr}[m],$$

where $M = N + L - 1$, $n_{sr}[i]$ and $n_{sr}[i]$ 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 $\eta_{sr}[i]$ represent the intersymbol interference (ISI). The $M \times L$ matrix $D_k$ contains versions of the signature sequences of each user shifted down
by one position at each column as illustrated by

$$D_k = \begin{bmatrix} d_k(1) & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & d_k(N) \end{bmatrix}, \quad (2)$$

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 $h_{sd,k}[n], h_{sr,k}[n], h_{r,k,d}[n]$, respectively. By collecting the data vectors in (1) (including the links from relays to destination) into a $(n_r+1)M \times 1$ received vector at the destination we get

$$\begin{bmatrix} r_{sd}[n] \\ r_{1,d}[m] \\ \vdots \\ r_{n_r,d}[m] \end{bmatrix} = \begin{bmatrix} \sum_{k=1}^{K} a_{sd,k}[n] D_k h_{sd,k}[n] b_k[i] \\ \sum_{k=1}^{K} a_{r_1,d}[m] D_k h_{r_1,d}[m] b_k[i] \\ \vdots \\ \sum_{k=1}^{K} a_{r_{n_r,d}}[m] D_k h_{r_{n_r,d},d}[m] b_k[i] \end{bmatrix} + \eta[i] + n[i], \quad (3)$$

where the $(n_r+1)M \times (n_r+1)L$ block diagonal matrix $\mathcal{C}_k$ contains shifted versions of $D_k$ as shown by

$$\mathcal{C}_k = \begin{bmatrix} D_k & 0 & \cdots & 0 \\ 0 & D_k & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & D_k \end{bmatrix}. \quad (4)$$

The $(n_r+1)L \times (n_r+1)$ matrix $\mathcal{H}_k[i]$ 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 $B_k[i] = \text{diag}(b_k[i], b_k[i], \ldots, b_k[i])$ 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 ($\tilde{b}_k[i], \ldots, \tilde{b}_k[i]$) on the main diagonal, the $(n_r+1) \times 1$ vector $a_k[i] = [a_{sd,k}[n] a_{r_1,d}[m] \ldots a_{r_{n_r,d}}[m]]^T$ 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 components.

### 3. 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 (3) in a more convenient way for the proposed optimization. The $(n_r+1)M \times 1$ received vector can be written as

$$r[i] = \mathcal{C}_k \mathcal{H}_k[i] B_k[i] a_k[i] + \eta[i] + n[i], \quad (5)$$

where the $(n_r+1)M \times K(n_r+1)$ matrix $\mathcal{C}_T = [C_1, C_2, \ldots, C_K]$ contains all the signatures, the $K(n_r+1) \times K(n_r+1)$ block diagonal matrix $\mathcal{H}_T[i]$ contains the channel gains of all the links, the $K(n_r+1) \times K(n_r+1)$ diagonal matrix $B_k[i] = \text{diag}(b_k[i], b_k[i], \ldots, b_k[i], \ldots, b_k[i])$ contains the symbols transmitted from all the sources to the destination and from all the relays to the destination on the main diagonal, the $K(n_r+1) \times 1$ vector $a_T[i] = [a_{sd,k}[n] a_{r_1,d}[m] \ldots a_{r_{n_r,d}}[m], \ldots, a_{k'}[n] a_{k,d}[m] \ldots a_{k',d}[m]]^T$ of 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 $K(n_r+1) \times 1$ optimal power allocation vector $a_{T,\text{opt}}[i]$. This problem can be cast as

$$\begin{align*}
\text{subject to } a_{T[H]}[i] & a_T[i] = P_T,
\end{align*}$$

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 $W_{\text{opt}}$ and vector $a_{T,\text{opt}}$ can be obtained by transforming the above constrained optimization problem into an unconstrained one with the method of Lagrange multipliers [15] which leads to

$$\mathcal{L} = E[||b[i] - W_{H}[i] a_T[i]||^2] + \lambda a_{T[H]}[i] a_T[i] \quad \text{subject to } a_{T[H]}[i] a_T[i] = P_T,$$

where $P_T$ is the total power constraint. The expression for $a_{T,\text{opt}}[i]$ is obtained by fixing $W_{\text{opt}}[i]$ as given by (5) and then applying the Lagrangian and equating them to zero.

$$W_{\text{opt}} = R^{-1} P_{C_{\mathcal{H}}}, \quad (8)$$

where the covariance matrix of the received vector is given by $R = E[r[i] r[i]^H] = \mathcal{C}_T \mathcal{H}_T[i] B_T[i] a_T[i] a_{T[H]}[i] B_T[i]^H \mathcal{C}_T^H + \sigma^2 I$ and $P_{C_{\mathcal{H}}}$ is such that $P_{C_{\mathcal{H}}} = E[r[i] r[i]^H] = \mathcal{C}_T \mathcal{H}_T[i] B_T[i] a_T[i] a_{T[H]}[i] B_T[i]^H$ is the $(n_r+1)M \times K$ cross-correlation matrix. The matrices $R$ and $P_{C_{\mathcal{H}}}$ depend on the power allocation vector $a_T[i]$. The expression for $a_{T,\text{opt}}[i]$ is given by

$$a_{T,\text{opt}} = \mathcal{C}_T \mathcal{H}_T[i] B_T[i] a_{T,\text{opt}}[i]$$

where the $(n_r+1) \times K(n_r+1)$ covariance matrix $R_{a_T} = E[B_T[i] B_T[i]^H] \mathcal{C}_T^H W[i]^H \mathcal{C}_T \mathcal{H}_T[i] B_T[i]$ and the vector $p_{a_T} = E[B_T[i] B_T[i]^H] \mathcal{C}_T, \mathcal{H}_T[i] B_T[i] a_{T,\text{opt}}[i]$ 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 $\mathcal{H}_T[i]$. 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 $W_{\text{opt}}$. The expressions in (8) and (9) require matrix inversions with cubic complexity ($O((n_r+1)M)^3$) and $O(K((n_r+1)))$, should be iterated as they depend on each other and require channel estimation.

### 4. MMSE DESIGN WITH INDIVIDUAL POWER CONSTRAINTS

Here, it is proposed 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

$$\begin{align*}
\text{subject to } a_k[i] a_k[i] & = P_{a_k},
\end{align*}$$

where $P_{a_k} = K$, $k = 1, 2, \ldots, K$.\]
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 [15] which leads to

$$
\mathcal{L}_k = E[|b_k[i] - w_k[i]|^2 + (\sum_{i=1}^{K} C_i H_k[i] B_i[i] a_i[i] + \eta[i] + n[i])^2] + \lambda(a_k[i]^T a_k[i] - P_{A,k}), \quad k = 1, 2, \ldots, K.
$$

(11)

Fixing $a_k[i]$, taking the gradient terms of the Lagrangian and making them equal to zero yields

$$
w_{k,\text{opt}} = \mathcal{R}^{-1} p_{C_k}, \quad k = 1, 2, \ldots, K,
$$

(12)

where $R = \sum_{k=1}^{K} C_k H_k[i] B_k[i] a_k[i] a_k[i]^T B_k[i]^H H_k[i]^T C_k[i] + \sigma^2 I$ is the covariance matrix and $p_{C_k} = E[b_k[i]^T r[i]] = C_k H_k[i] a_k[i]$ is the cross-correlation vector. The quantities $R$ and $p_{C_k}$ depend on $a_k[i]$. By fixing $w_{k,\text{opt}}$, the expression for $a_k[i]$ is given by

$$
a_{k,\text{opt}} = (R + \lambda I)^{-1} p_{A_k}, \quad k = 1, 2, \ldots, K,
$$

(13)

where $R_{a_k} = \sum_{k=1}^{K} C_k H_k[i] B_k[i] a_k[i] a_k[i]^T B_k[i]^H H_k[i]^T C_k[i] + \sigma^2 I$ is the $(n+1) \times (n+1)$ covariance matrix and the $(n+1) \times 1$ cross-correlation vector is $p_{A_k} = E[b_k[i]^T r[i]] = C_k H_k[i] a_k[i]$. The expressions in (12) and (13) depend on each other and require the estimation of the channel matrices $H_k[i]$. The expressions in (12) and (13) require matrix inversions with cubic complexity ($O((n+1)M)^3$) and $O((n+1)^3)$, should be iterated as they depend on each other and user $k$ and require channel estimates. In what follows, we will develop algorithms for computing $a_{k,\text{opt}}$, $w_{k,\text{opt}}$ and the channels $H_k[i]$ for $k = 1, \ldots, K$.

5. PROPOSED ADAPTIVE ESTIMATION ALGORITHMS

In this section, we develop joint adaptive SG algorithms for efficiently estimating the parameters of the receive filters, the power allocation vectors and the channels. Although the optimization problems are not convex, the proposed algorithms did not have problems with local minima and always converged to the desired solutions.

5.1. Algorithms with a Global Constraint

Consider the Lagrangian in (7) and the computation of the instantaneous gradients with respect to $W[i]$ and $A_T[i]$. The following SG recursions can then be derived

$$
\dot{W}[i+1] = \dot{W}[i] + \mu_w B_k[i]^H r[i],
$$

(14)

$$
\dot{A}_T[i+1] = \dot{A}_T[i] + \mu_{A_T} B_k[i]^H H_k[i] C_k[i] e[i],
$$

(15)

where $e[i] = b[i] - W[i]^H r[i]$ is the error vector, $\mu_w$ and $\mu_{A_T}$ are the step sizes, and we normalize the power allocation vector as $\dot{A}_T[i] = \sqrt{P_T} \dot{A}_T[i] / \|\dot{A}_T[i]\|_2$ in order to enforce the global power constraint. The channel estimate $\dot{H}_T[i]$ needs to be computed. To this end, we first rewrite the received vector as $r[i] = C_T B_T[i] A_T[i] h_T[i] + \eta[i] + n[i]$, where $B_T[i]$ is a $(n+1) \times K(n+1) L \times 1$ matrix with the amplitudes of all the links on the main diagonal, $A_T[i]$ is a $(n+1) \times K(n+1) L \times 1$ matrix with the amplitudes of all the links on the main diagonal and $h_T[i]$ is a $(n+1) \times 1$ vector with the $L$ channel gains from all $K$ users, sources and relays. The channel estimation problem is then cast as the following optimization

$$
\dot{h}_T[i] = \arg \min_{h_T[i]} E[|r[i] - C_T B_T[i] A_T[i] h_T[i]|^2]
$$

(16)

Using a SG recursion to solve the above problem, we obtain

$$
\dot{h}_T[i+1] = \dot{h}_T[i] + \mu_{h_T} A_T[i]^H B_T[i]^H (r[i] - C_T B_T[i] A_T[i] \dot{h}_T[i]),
$$

(17)

where $\mu_{h_T}$ is a step size to be adjusted. The channel matrix $H_T[i]$ is then determined as $H_T[i] = \sum_{j=1}^{K(n+1)} \dot{h}_T[i] q_{T,j}$, where $q_{T,j} = [0 \ldots 0 1 \ldots 0]$. 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 SG algorithms is $O(K(n+1) M)$ for calculating $\dot{W}[i]$, $O(K(n+1))$ for obtaining $\dot{A}_T[i]$ and $O(K(n+1) L)$ for channel estimation.

5.2. Algorithms with Individual Constraints

Consider the Lagrangian in (11) and the computation of the instantaneous gradients with respect to $w_k[i]$ and $a_k[i]$ for each user $k$. The following SG recursions for $k = 1, \ldots, K$ can then be developed

$$
\dot{w}_k[i+1] = \dot{w}_k[i] + \mu_w e[i] r[i],
$$

(18)

$$
\dot{a}_k[i+1] = \dot{a}_k[i] + \mu_a B_k[i]^H H_k[i] C_k[i] \dot{w}_k[i] e[i],
$$

(19)

where the error signal $e[i] = b_k[i] - \dot{w}_k[i]^T r[i]$, $\mu_w$ and $\mu_a$ are step sizes. The channel estimates are computed via a similar SG recursion to (17) and yields

$$
\dot{h}_k[i+1] = \dot{h}_k[i] + \mu_h A_k[i]^H B_k[i]^H e[i] r[i] - C_k B_k[i] A_k[i] \dot{h}_k[i],
$$

(20)

where $B_k[i]$ is a $(n+1) \times (n+1)+1 L \times 1$ matrix with the symbols of user $k$ transmitted from the sources and the relays on the main diagonal, $A_k[i]$ is a $(n+1) \times (n+1)+1 L \times 1$ matrix with the amplitudes of all the links on the main diagonal and $h_k[i]$ is a $(n+1) \times 1$ vector with the channel gains for each link and user $k$. The channel matrix $H_k[i]$ is obtained as $H_k[i] = \sum_{j=1}^{K(n+1)} \dot{h}_k[i] q_{k,j}$, where $q_{k,j} = [0 \ldots 0 1 \ldots 0]$. The complexities of the proposed SG algorithms are $O((n+1) M)$ for computing $\dot{w}_k[i]$, $O(n+1)$ for obtaining $\dot{a}_k[i]$ and $O((n+1) L)$ for channel estimation.

6. SIMULATIONS

We assess the bit error ratio (BER) performance of the proposed joint power allocation and interference suppression (JPAS) algorithms with global (GPC) and individual power (IPC) constraints and compare them with 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 $P_T = K P_{A,k}$, whereas it follows a log-normal distribution for the users with associated standard deviation equal to 3 dB. We adopt the AF cooperative strategy with repetitions (the noise amplification
is considered [3]) and all the relays and the destination terminal are equipped with linear MMSE receivers, which have full channel and noise variance knowledge.

The proposed JPAIS method is first considered with the MMSE expressions of (8) and (9) using a global power constraint (JPAIS-GPC), and (12) and (13) with individual power constraints (JPAIS-IPC). The proposed scheme is compared 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 MMSE expressions, 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 JPAI-GPS, while its complexity is higher.

The second experiment depicted in Fig. 2 shows the BER performance of the proposed SG adaptive algorithms (JPAIS) against the existing NCIS and CIS schemes with $n_r = 2$ relays. All techniques employ SG algorithms for estimation of the coefficients of the channel, the receive filters and the power allocation for each user (JPAIS only). The results show that the proposed adaptive estimation algorithms converge to approximately the same level of the MMSE schemes, which have full channel and noise variance knowledge.

7. CONCLUSIONS

Joint iterative power allocation and interference mitigation techniques for DS-CDMA networks with multiple relays and the amplify and forward cooperation strategy were proposed. A joint constrained optimization framework and algorithms for 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 developed. The results showed that the proposed techniques obtain significant gains in performance and capacity over existing schemes. Future work will consider distributed space-time coding, synchronization issues and blind estimation.

8. REFERENCES