Tensor-Based Multiuser Detection for Uplink DS-CDMA Systems with Cooperative Diversity

Antonio Augusto Teixeira Peixoto and Carlos Alexandre Rolim Fernandes

***Abstract*— In the present paper, a semi-blind receiver for a multiuser uplink DS-CDMA (Direct-Sequence Code-Division Multiple-Access) system based on relay aided cooperative communications is proposed. For the received signal, a quadrilinear Parallel Factor (PARAFAC) tensor decomposition is adopted, such that the proposed receiver can semi-blindly estimate the transmitted symbols, channel gains and spatial signatures of all users. The estimation is done by fitting the tensor model using the Alternating Least Squares (ALS) algorithm. With computational simulations, we provide the performance evaluation of the proposed receiver for various scenarios.**

***Keywords*— Semi-blind receiver, DS-CDMA, Cooperative communications, PARAFAC, Tensor model, Alternating least squares.**

I. Introduction

Cooperative diversity is a new way for granting better data rates, capacity, fading mitigation, spatial diversity and coverage in wireless networks [1], so that, its promising characteristics have put it into research interest lately. The basic idea behind it is making the network nodes help each other, allowing an improvement in the throughput without increasing the power at the transmitter, similarly to multiple-input multiple-output (MIMO) systems. There are some cooperative protocols available, like the amplify-and-foward (AF) and the decode-and-foward (DF) [2]. In means of simplicity, the AF protocol is of good choice because the relay node will just amplify the user's signals and fowards it to the destination. Latency and complexity are then keep small on this protocol.

An important mathematical tool used in this work is tensor based models. An advantage of using tensors in comparison to matrices is the fact that tensors allows us the use of multidimensional data, allowing a better understanding and precision for a multidimensional perspective. Due to its powerful signal processing capabilities, tensors can be found applied to many fields, for example, in chemometrics and others [3].

The Parallel Factor (PARAFAC) decomposition [3], [4] was first used in wireless communications systems in [5], where a blind receiver was proposed for a DS-CDMA system and a tensor was used to model the received signal as a multidimensional variable. After, many other works using tensor decompostions in telecommunications were developed. Wireless MIMO systems had also been proposed with tensor approaches, which led to the development of new tensor models, as in [6], where a constrained factor decomposition was proposed, and in [7], where a new constrained tensor model called PARATUCK was proposed. An overview of some of these tensor models can be found in [8].

There are other examples of tensor decompositions in wireless cooperative communications like in [9], where a receiver was proposed for a two-way AF relaying system with multiple antennas at the relay nodes adopting tensor based estimation. In [10], an unified multiuser receiver based on a trilinear tensor model was proposed for uplink multiuser cooperative diversity systems employing an antenna array at the destination node. There are also recent works, as [11], where a two-hop MIMO relaying system was proposed adopting two tensor approaches (PARAFAC and PARATUCK), and in [12], where a one-way two-hop MIMO AF cooperative scheme was employed with a nested tensor approach. In [13], receivers were based on a trilinear decomposition on a cooperative scenario exploiting spreading diversity at the relays. In [14], a similar scenario was proposed without spreading, but with different time-slots for each relay transmission. [15] presented a new tensor decomposition called nested Tucker decomposition (NTD), applied to an one-way two-hop MIMO relay communication system.

In contrast to the works earlier mentioned, which are based on trilinear tensor models, we move to a quadrilinear PARAFAC decomposition in this paper. Indeed, we propose a semi-blind multiuser receiver able to jointly estimate the channel gains, antenna responses and transmitted symbols, exploiting the uniqueness properties of a fourth order tensor. More specifically, we are considering a cooperative AF relay aided scenario where direct-sequence spreading is used at the relays, thus, taking advantage of cooperative and spreading diversity.

This work extends [5] by considering a cooperative link with R relays. Moreover, in comparisson to [10] and [14], our work admits spreading at the relays by using orthogonal codes, and, in contrast to [13], the proposed system considers the relays transmitting in different time-slots instead of all relays transmitting simultaneously to the base station. An advantage of the proposed work, with respect to the previous ones, is its greater flexibility on the choice of some system parameters. By choosing the system parameters, such as the number of relays or the spreading code length, we get the models from [5], [10], [13] and [14]. It is also worth mentioning that the proposed receiver explores spatial and cooperative diversities.

The present work is structured as follows. Section II lays out the adopted system model, including the cooperative scenario and environment assumptions. Section III shows the quadrilinear tensor model used, Section IV presents the proposed receiver, Section V shows the simulations results and Section

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VI summarizes the conclusions.

The notation used in this paper is presented here. Scalars are denoted by italic Roman letters (a,b,...), vectors as lower-case boldface letters (**a**,**b**,...), matrices as upper-case boldface letters (**A**,**B**,...) and tensors as calligraphic letters ($\mathcal{A}$,$\mathcal{B}$,...). To retrieve the element (*i*,*j*) of **A**, we use $[\mathbf{A}_{i,j}]$.$\mathbf{A}^T$ and $\mathbf{A}^\dagger$ stands for the transpose and the pseudo-inverse of **A** respectively. The operator $diag_j[\mathbf{A}]$ is the diagonal matrix formed by the *j*-th row of **A**. The operator $\circ$ denotes the outer product of two vectors and $\diamond$ denotes the Khatri-Rao product between $\mathbf{A} \in \mathbb{C}^{I\times R}$ and $\mathbf{B} \in \mathbb{C}^{J\times R}$, resulting in $\mathbf{A} \diamond \mathbf{B} = [a_1 \otimes b_1, ..., a_R \otimes \mathbf{B}_R] \in \mathbb{C}^{IJ\times R}$.

II. System Model

The system model considered in this work is a DS-CDMA uplink with *M* users transmitting to a base station with the help of relay-aided links using the AF protocol. The links between a given user and one relay are called source-relay (SR) and the ones between a relay and the base station are called relay-destination (RD). The base station has an uniform linear array of *K* antennas. Each of the *M* users will transmit to its *R* associated AF relays. The *R* relays of a given user use direct-sequence spreading on the user signal, with a spreading code of length *P*, where the same code is used by all relays of a given user. Also, the relays and users are single antenna devices operating in half-duplex mode.

It is assumed perfect synchronization at the symbol level to avoid intersymbol interference, frequency-flat fading is considered and all channels are independent. We consider that each user communicates with its *R* associated relays and that each relay fowards the signal using a different time-slot. We also assume that an user and its relays are all located inside a cluster, such that, the signal received at a relay located within the cluster of the *m*-th user contains no significant interference from the other users, as Fig. 1 shows. This assumption was also made in [10] and in [14]. An interpretation of this assumption is that a user and its relays are located in a cell, while the other users and their associated relays are located in other cells, modeled as co-channel interferers.

The signal received by the *r*-th relay of the *m*-th user is given by:

$$u^{(SR)}_{r,m,n} = h^{(SR)}_{r,m} s_{n,m} + v^{(SR)}_{r,m,n}, \quad (1)$$

where $h^{(SR)}_{r,m}$ is the channel coefficient between the *m*-th user and its *r*-th relay, $s_{n,m}$ is the *n*-th symbol of the *m*-th user and $v^{(SR)}_{r,m,n}$ is the additive white gaussian noise (AWGN) component. All the data symbols $s_{n,m}$ are independent and identically distributed, with $1 \leq m \leq M$, and uniformly distributed over a Quadrature Amplitude Modulation (QAM) or a Phase-Shift Keying (PSK) alphabet.

The signal received at the *k*-th antenna of the base station, trough the *r*-th time slot, on the *n*-th symbol period and *p*-th chip of the spreading code, on the RD link is given by:

$$x^{(RD)}_{k,r,n,p} = \sum_{m=1}^{M} h^{(RD)}_{k,r,m} g_{r,m} u^{(SR)}_{r,m,n} c_{p,m} + v^{(RD)}_{k,r,n,p}, \quad (2)$$

where $h^{(RD)}_{k,r,m}$ is the channel coefficient between the *k*-th receive antenna and the *r*-th relay associated with the *m*-th

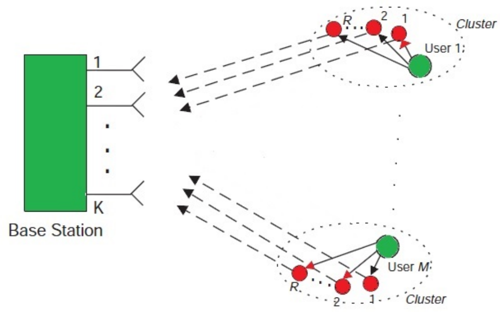

Fig. 1. System model - Uplink for multiuser cooperative scenario.

user, $v^{(RD)}_{k,r,n,p}$ is the corresponding noise of the RD link, $g_{r,m}$ is the amplification factor applied by the *r*-th relay of the *m*-th user and $c_{p,m}$ is the *p*-th chip of the spreading code of the *m*-th user. Substituting (1) into (2), we get:

$$x^{(RD)}_{k,r,n,p} = \sum_{m=1}^{M} h^{(RD)}_{k,r,m} h^{(SR)}_{r,m} g_{r,m} s_{n,m} c_{p,m} + v^{(SRD)}_{k,r,n,p}, \quad (3)$$

$$v^{(SRD)}_{k,r,n,p} = \sum_{m=1}^{M} h^{(RD)}_{k,r,m} g_{r,m} v^{(SR)}_{r,m,n} c_{p,m} + v^{(RD)}_{k,r,n,p}. \quad (4)$$

The term $v^{(SRD)}_{k,r,n,p}$ is the total noise component through the source-relay-destination (SRD) link, from an user to the base station.

Regarding the propagation scenario adopted in the system model, let us also consider the following assumption. All links are subject to multipath propagation and all possible scatters are located far away from the base station, so that all the signals transmitted by the relays arrive at the destination with approximatively the same angle of arrival. The angle spread is small compared to the spatial resolution of the antenna array at the base station. This is truly valid when the user and its relays are close to each other and the base station experiences no scattering around its antennas. This is very common in suburban areas where the base station is placed on the top of a tall building or in a tower [16]. The channel coefficient $h^{(RD)}_{k,r,m}$ may be defined as:

$$h^{(RD)}_{k,r,m} = \sum_{l=1}^{L^{(RD)}_{r,m}} a_k(\theta_m) \beta^{(RD)}_{l,r,m}, \quad (5)$$

where θ_m is the mean angle of arrival of the *m*-th scattering cluster, $a_k(\theta_m)$ is the response of the *k*-th antenna of the *m*-th scattering cluster, defined as $a_k(\theta_m)$ = exp(jθ_m), where θ_m is an uniform random variable with zero mean and variance of 2π, $\beta^{(RD)}_{l,r,m}$ is the fading envelope of the *l*-th path between the *r*-th relay of the *m*-th user and the base station. $L_{r,m}$ is the total number of multipaths. (5) can be approximated as follows:

$$h^{(RD)}_{k,r,m} \approx a_k(\theta_m) \gamma^{(RD)}_{r,m}, \quad (6)$$

where $\gamma^{(RD)}_{r,m}$ is defined as $\gamma^{(RD)}_{r,m} = \sum_{l=1}^{L^{(RD)}_{r,m}} \beta^{(RD)}_{l,r,m}$. Now, by substituting (6) into (3), we get:

$$x^{(RD)}_{k,r,n,p} = \sum_{m=1}^{M} a_k(\theta_m)\gamma^{(RD)}_{r,m} h^{(SR)}_{r,m} g_{r,m} s_{n,m} c_{p,m} + v^{(SD)}_{k,r,n,p} \tag{7}$$

and again, substituting (6) into (4), we get:

$$v^{(SRD)}_{k,r,n,p} = \sum_{m=1}^{M} a_k(\theta_m)\gamma^{(RD)}_{r,m} g_{r,m} v^{(SR)}_{r,m,n} c_{p,m} + v^{(RD)}_{k,r,n,p}. \tag{8}$$

The transmission rate for each user is given by 1/(R+1), thus, the total transmission rate on the system is M/(R+1).

III. Proposed Tensor Model

The model above described for the RD links can be viewed as a four-way array with its dimensions directly related to space (receive antennas at the base station), cooperative slots (cooperative channels), time (symbols) and spreading codes (chip). In this section, we model the received signal as a 4-th order tensor using a PARAFAC decomposition as shown in [8] and in [17]. Let $\mathcal{Y}$ be a M-component, quadrilinear PARAFAC model, so that $\mathcal{Y} \in \mathbb{C}^{K\times R\times N\times P}$ is a 4-th order tensor collecting the baseband RD data signals at the base station:

$$[\mathcal{Y}]_{k,r,n,p} = x^{(RD)}_{k,r,n,p} \tag{9}$$

for k = 1,...,K, r = 1,...,R, n = 1,...,N and p = 1,...,P.

In order to simplify the presentation, we omit the AWGN terms and assume that the channel is constant for N symbol periods throughout the rest of this section. A typical element of $\mathcal{Y}$, denoted by $y_{k,r,n,p}$ = $[\mathcal{Y}_{k,r,n,p}]$ is given by:

$$y_{k,r,n,p} = \sum_{m=1}^{M} a_k(\theta_m) h_{r,m} s_{n,m} c_{p,m}. \tag{10}$$

The channel coefficient $h_{r,m}$ is defined as:

$$h_{r,m} = \gamma^{(RD)}_{r,m} h^{(SR)}_{r,m} g_{r,m}. \tag{11}$$

(10) corresponds to a PARAFAC decomposition with spatial, cooperative slots, time and code indices, in other words, a quadrilinear data tensor. The data tensor $\mathcal{Y}$ can be expressed as:

$$\mathcal{Y} = \sum_{m=1}^{M} \mathbf{A}_{.,m} \circ \mathbf{H}_{.,m} \circ \mathbf{S}_{.,m} \circ \mathbf{C}_{.,m}, \tag{12}$$

where $\circ$ denotes the outer product, $\mathbf{A} \in \mathbb{C}^{K\times M}$ is the antenna array response matrix with $[\mathbf{A}]_{k,m}$ = $a_k(\theta_m)$, $\mathbf{H} \in \mathbb{C}^{R\times M}$ is the channel matrix with $[\mathbf{H}]_{r,m}$ = $h_{r,m}$, $\mathbf{S} \in \mathbb{C}^{N\times M}$ is the symbol matrix with $[\mathbf{S}]_{n,m}$ = $s_{n,m}$ and $\mathbf{C} \in \mathbb{C}^{P\times M}$ is the spreading codes matrix with $[\mathbf{C}]_{p,m}$ = $c_{p,m}$. In (12), we have the PARAFAC decomposition of the data tensor $\mathcal{Y}$ as a sum of M rank-1 components.

A. Unfolding Matrices

We can also rewrite (12) in an unfolding matricial form. Let $\mathbf{Y}_1 \in \mathbb{C}^{KRN\times P}$ be defined as the tensor $\mathcal{Y} \in \mathbb{C}^{K\times R\times N\times P}$ unfolded into a matrix, as follows:

$$\mathbf{Y}_1 = (\mathbf{A} \diamond \mathbf{H} \diamond \mathbf{S})\mathbf{C}^T, \tag{13}$$

where $\diamond$ denotes the Khatri-Rao product (column-wise Kronecker product) [4]. There are also other unfolded matrices, as, for instance:

$$\mathbf{Y}_2 = (\mathbf{C} \diamond \mathbf{A} \diamond \mathbf{H})\mathbf{S}^T, \tag{14}$$

$$\mathbf{Y}_3 = (\mathbf{S} \diamond \mathbf{C} \diamond \mathbf{A})\mathbf{H}^T, \tag{15}$$

$$\mathbf{Y}_4 = (\mathbf{H} \diamond \mathbf{S} \diamond \mathbf{C})\mathbf{A}^T, \tag{16}$$

with $\mathbf{Y}_2 \in \mathbb{C}^{PKR\times N}$, $\mathbf{Y}_3 \in \mathbb{C}^{NPK\times R}$ and $\mathbf{Y}_4 \in \mathbb{C}^{RNP\times K}$.

B. Uniqueness Properties

One of the most important properties of the tensor model obtained in (10) and (12) is its essential uniqueness under certain conditions [17], [18]. The uniqueness property of the quadrilinear PARAFAC decomposition by Kruskal's condition described in [17], [18], and in [19], is given as follows:

$$\kappa_{\mathbf{A}} + \kappa_{\mathbf{H}} + \kappa_{\mathbf{S}} + \kappa_{\mathbf{C}} \geq 2M + 3, \tag{17}$$

where $\kappa_{\mathbf{A}}$ is the Kruskal rank of the matrix **A**, (similarly to **H**, **S** and **C**). The Kruskal rank of a matrix corresponds to the greatest integer κ, such that every set of κ columns of the matrix is linearly independent. If the condition (17) is satisfied, the factor matrices **A**, **H**, **S** and **C** are essentially unique, hence, each factor matrix can be determined up to column scaling and permutation. This uniqueness properties of the PARAFAC decomposition means that any other set of matrices ($\mathbf{A}^{'}$, $\mathbf{H}^{'}$, $\mathbf{C}^{'}$ and $\mathbf{S}^{'}$) that satisfies (11) is related with the original matrix set (**A**, **H**, **C** and **S**) by $\mathbf{A}^{'}$ = $\mathbf{A}\Pi\Delta_{\mathbf{A}}$, $\mathbf{H}^{'}$ = $\mathbf{H}\Pi\Delta_{\mathbf{H}}$, $\mathbf{C}^{'}$ = $\mathbf{C}\Pi\Delta_{\mathbf{C}}$ and $\mathbf{S}^{'}$ = $\mathbf{S}\Pi\Delta_{\mathbf{S}}$, where $\Pi \in \mathbb{C}^{M\times M}$ is a permutation matrix and $\Delta_{\mathbf{A}}$, $\Delta_{\mathbf{H}}$, $\Delta_{\mathbf{C}}$ and $\Delta_{\mathbf{S}}$ are diagonal matrices that meet $\Delta_{\mathbf{A}}\Delta_{\mathbf{H}}\Delta_{\mathbf{C}}\Delta_{\mathbf{S}}$ = **I**.

Now, let us assume that **A**, **H**, **C** and **S** are all full κ-rank (a matrix is said to have full κ-rank if its κ-rank is equal to the minimum between the number of rows and columns), where the κ-rank denotes the Kruskal rank of a matrix, thus (17) becomes:

$$min(K,M) + min(R,M) + min(N,M) + min(P,M) \geq 2M + 3. \tag{18}$$

Given that a matrix whose columns are drawn independently from an absolutely continuous distribution has full rank with probability one [5], then matrix **H** has full κ-rank with probability one. Also, the matrix **A** is full κ-rank because we model it as a Vandermonde matrix with distinc generators, as the user signals arrive at the base station array with different angles of arrival. The symbols matrix **S** is full κ-rank with high probability if N is sufficiently large in comparison to the modulation cardinality and the number of users. At last, for the matrix **C**, full κ-rank is possible if a certain length of spreading codes is used.

With the assumptions above, we can determine some parameters of the adopted system, for example, the number of users that the proposed receiver can handle and the minimum acceptable parameters (number of antennas at base station, length of the spreading codes, number of relays or the data block length) that matches a target number of user channels to be detected. Hence, we will have flexibility when choosing K, R, N and P, which is the one of the main reasons for

Algorithm 1 ALS FITTING

1)$Initialization$: $Set\ i = 0$; $Initialize$ $\hat{\mathbf{A}}_{(i=0)}$ and $\hat{\mathbf{H}}_{(i=0)}$;
2)$i = i + 1$;
3)$\hat{\mathbf{S}}^T_{(i)} = (\mathbf{C} \diamond \hat{\mathbf{A}}_{(i-1)} \diamond \hat{\mathbf{H}}_{(i-1)})^{\dagger}\tilde{\mathbf{Y}}_2$;
4)$\hat{\mathbf{H}}^T_{(i)} = (\hat{\mathbf{S}}_{(i)} \diamond \mathbf{C} \diamond \hat{\mathbf{A}}_{(i-1)})^{\dagger}\tilde{\mathbf{Y}}_3$;
5)$\hat{\mathbf{A}}^T_{(i)} = (\hat{\mathbf{H}}_{(i)} \diamond \hat{\mathbf{S}}_{(i)} \diamond \mathbf{C})^{\dagger}\tilde{\mathbf{Y}}_4$;
6)$Repeat\ steps\ 2-5\ until\ convergence$;

considering the tensor approach. It provides different tradeoffs for our system based on the parameters. Indeed, we have from (18):

- If $P \geq M$, $N \geq M$ (typical DS-CDMA scenario), then, min(K,M) + min(R,M) $\geq$ 3. For example, let K = 2 and R = 1, we satisfy (18) and at least 1 relay and 2 antennas are sufficient for M users.
- If $P \geq M$, $N \geq M$ and $K \leq M$, then, R can be 0 if K = 3, giving us the model described in [3], a noncooperative DS-CDMA uplink.
- If $K \geq M$, $N \geq M$, $P \leq M$ and $R \leq M$, then for R = 2, P = 1 chip is sufficient for M users, therefore we get [14] (the same can be achieved if R = 3, thus P can be zero).
- If $K \geq M$, $P \geq M$, $R \leq M$ and $N \leq M$, then, for R = 1, N = 2 symbols are enough to guarantee uniqueness. It means that a short block length is sufficient for detection.

Based on the assumptions above, we can conclude that the proposed tensor model gives us flexibility about many parameters and diversity tradeoff.

IV. Receiver Algorithm

Assuming that there is no channel information at the receiver or transmitter, the receiver algorithm presented in this section is based on the ALS (Alternating Least Squares) method, which consists in fitting the quadriliear model to the received data tensor [20]. The idea behind the ALS procedure is very simple: each time, update one of the factor matrices by using the least squares estimation technique with the previous estimations of the other factor matrices. Each factor matrix is estimated, in an alternate way, always using the previous estimations of the other factor matrices. This procedure is repeated until convergence. The unfolding matrices in (13)-(16) are used to estimate **A**, **H** and **S**, where we assume knowledge of the spreading codes (matrix **C**) at the receiver.

The Quadrilinear ALS algorithm is shown in Algorithm 1. The measured error at the end of the i-th iteration is given by $e(i) = \|\tilde{\mathbf{Y}}_1 - (\hat{\mathbf{A}}_{(i)} \diamond \hat{\mathbf{H}}_{(i)} \diamond \hat{\mathbf{S}}_{(i)})\mathbf{C}^T\|_F$, where $\|.\|_F$ denotes the Frobenius norm, $\tilde{\mathbf{Y}}_1$, $\tilde{\mathbf{Y}}_2$, $\tilde{\mathbf{Y}}_3$ and $\tilde{\mathbf{Y}}_4$ are the noisy unfolding matrices and $\hat{\mathbf{A}}_{(i)}, \hat{\mathbf{H}}_{(i)}$ and $\hat{\mathbf{S}}_{(i)})$ are the estimates of the factor matrices at the i-th iteration. The convergence of the algorithm is obtained when $|e(i) - e(i-1)| < 10^{-6}$.

After obtaining the estimation of **A**, **H** and **S**, it is necessary to remove the scaling ambiguity. The scaling ambiguity of $\hat{\mathbf{A}}$ is removed by considering that the first row of **A** is known, which is possible because **A** is a vandermonde matrix. The same can be done to remove the scaling ambiguity from $\hat{\mathbf{S}}$. It is assumed that the first row of **S** is known and the scaling ambiguity is removed by dividing the first row of $\hat{\mathbf{S}}$ by the first row of **S**. After obtaining the scaling matrix of $\hat{\mathbf{A}}$ and $\hat{\mathbf{S}}$, we can find the scaling matrix $\Delta_{\mathbf{H}}$ of $\hat{\mathbf{H}}$ with $\Delta_{\mathbf{A}}\Delta_{\mathbf{S}}\Delta_{\mathbf{H}} = \mathbf{I}$.

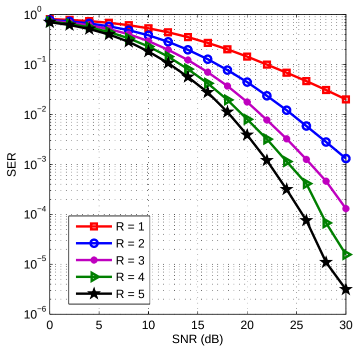

Fig. 2. SER versus SNR performance of the proposed receiver for a different number of relays.

V. Simulation Results

This section presents computer simulations results for performance evaluation purposes with the following scenario. The wireless links have frequency-flat Rayleigh fading with path loss expoent equal to 3, the base station antenna array is composed by K antennas, 16-QAM modulation is used and Hadamard codes are considered for spreading sequences. The symbol error rate (SER) curves are shown as a function of the signal-to-noise ratio (SNR) of the RD link. The mean results were obtained by 10000 independent Monte Carlo samples. The AF relays have variable gains and the source power P_s and the relay power P_r were considered as unitary.

Figure 2 shows the SER versus SNR for the proposed technique with P = 8 chips, a datablock of N = 16 symbols, K = 2 receive antennas and M = 4 users. Then we have curves for various values of R (number of relays on the cluster). From Fig. 2, we can observe a better performance when we increase the number of relays on the system. This happens because when the number of relays is augmented, the model turns to a more cooperative scenario, exploiting cooperative diversity and resulting in better link quality.

Now, we compare the SER of the proposed receiver with the ones of the: Zero Forcing (ZF) receiver, that works under complete knowledge of **A**, **H** and **C**, the semi-blind DS-CDMA receiver proposed in [5] (non-cooperative DS-CDMA), the receiver proposed in [10] using AF (same cenario of the present work, but without spreading codes) and the receiver shown in [13], where the relays transmit at the same time.

For Figure 3, we set N = 16, P = 4, M = 4, K = 3 and R = 1 for both the ZF and the proposed receiver. For the receiver proposed in [10], only one relay is used and we set K = 3, N = 16 and M = 2. For [13], we set N = 16, P = 2, M = 4, K = 3 and R = 1. For the receiver of [5], we set P = 4, K = 3, N = 16 and M = 4. These simulations parameters were chosen to give us the same or similar spectral efficiency for all the receivers. The direct link between user

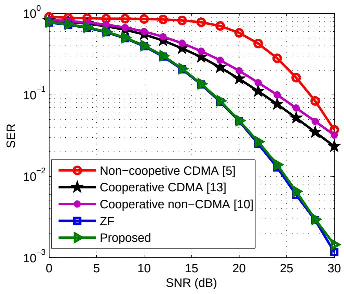

Fig. 3. SER versus SNR performance for different receivers.

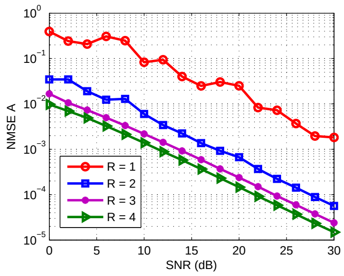

Fig. 4. NMSE of matrix **A** versus SNR for a different number of relays.

and base station (used in [5]) has three times the distance than the SR link, with path loss coeffiecient equal to 3.7. We see that the ZF receiver performed almost equal in comparison to the proposed receiver. This proves that the proposed receiver can operate without knowing the factor matrices (**A**, **H**) and still provide good performance. Both the ZF and the proposed receiver performed better than the non-cooperative semi-blind receiver described in [5], the receiver of [10] and the one of [13].

The addition of spreading makes the proposed receiver obtain better performance in comparison to [10]. The proposed receiver also went better than [5] because of the cooperative scenario (short relay-aided links instead of extended direct links). The espectral efficiency for each configuration is: $M/(RP+1)$ for the proposed receiver and the ZF, $M/(R+1)$ for the receiver described in [10], M/P for [5] and $M/2P$ for [13].

Fig. 4 depicts the Normalized Mean Square Error (NMSE) of the matrix **A**. This figure shows us the capacity of the proposed receiver to satisfactorily estimate spatial signatures. It is observed a linear decrease in the NMSE as a function of the SNR, as expected. Moreover, a small gain is observed when R is increased, for the same reasons above explained.

VI. Conclusions

In this paper, we have proposed a tensor-based receiver that can jointly and semi-blindly estimate some parameters of the system (a cooperative DS-CDMA uplink): channel gains, antenna array responses and transmitted symbols. The estimation consists in fitting a PARAFAC tensor model to the received data using the ALS algorithm. Another characteristic of the proposed receiver is its powerful uniqueness property that allows some flexibility in choosing the parameters of the system, like the number of relays, number of antennas at the base station, spreading codes or data block length. Thus, we are able to cover lots of pratical scenarios. The results showed us that the proposed receiver performs well in comparison to the receivers described in [5], [10], [13] and the ZF receiver. This work may be extendend by using another algorithm instead of the ALS, as in [14]. Also, the frequency-flat fading could be changed to frequency-selective fading.

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