Iterative Multiuser Detection for Cooperative MIMO Systems over Quasi-Static Fading Channels

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***Abstract*—In this paper, we propose a cooperative multiuser system for multiple-antenna terminals under quasi-static fading. The system employs a bit-interleaved code modulation scheme that combines space-time coding and cooperation based on the decode-and-forward protocol at the transmitter and iterative multiuser detection based on parallel interference cancellation and minimum mean square error filtering at the receiver. We investigate an approach that allows to provide diversity from different channels to each user up to full diversity. Frame error rate performance under Monte Carlo simulations is shown to confirm the effectiveness of the proposed schemes.**

***Index Terms*—Cooperative communications, interference cancellation, iterative receivers, MIMO systems, MMSE filtering, multiuser detection, space-time coding.**

I. Introduction

WIRELESS communications receive large interests in the current society and wireless-system design is in continuous evolution in order to meet the expectations of new emerging applications. Slow fading is a major cause for severe degradation of system performance, and providing diversity to the system is among the main techniques to combat fading [1], [2]. Multi-antenna systems have been shown to increase diversity and/or capacity [3], [4], with many different solutions proposed depending on the specific Multiple-Input Multiple-Output (MIMO) scenario [2]. Moreover, user cooperation [5], [6] represents a popular technique for spatial diversity, as it provides virtual multiple-antenna arrays even in the case of single-antenna users. Various protocols have been studied in the literature, such as amplify-and-forward and decode-and-forward [7], [8], coded cooperation [9], [10], signal and/or code superposition [11], [12], [13].

MultiUser Detection (MUD) is a fundamental technique that allows to achieve optimum performance in the case of interference-limited scenarios [14], and iterative MUD receivers have shown to achieve almost optimum performance with contained complexity [15]. A Posteriori Probability (APP) detection, optimal but exponentially complex, is usually replaced with Parallel Interference Cancellation (PIC) and Minimum Mean Square Error (MMSE) filtering [16]. PIC-MMSE MUD has been shown to perform less than 1 dB away from optimum belief propagation [17]. Three different detectors have been studied for two-user cooperative MIMO systems with iterative receivers under slow-fading scenarios [18]: (i) a joint detector, in which all the received information are processed jointly; (ii) a separate detector, in which the information related to each user is treated separately; and (iii) a distributed-matrix-Alamouti detector, in which the information related to each user is treated separately and inter-user interference is partially removed by Alamouti combining [19]. The idea was to combine MUD techniques with a cooperative protocol in order to increase the information rate of the system, i.e. achieving better spectral efficiency. After the information of each user has been made available to the partner via orthogonal transmission, both users relay the partner information simultaneously, thus providing a multiuser interfering transmission. The joint detector showed the worst performance (although it had shown to be optimum under APP detection [20], [21]), while both the separate detector and the distributed-matrix-Alamouti detector showed excellent performance with high diversity orders, the former slightly better in terms of achieved Frame Error Rate (FER) and the latter slightly better in terms of required computational complexity. Recently, similar transmission and reception schemes have been proposed and analyzed also in the framework of coded cooperation [22].

The main contribution of this paper is to provide a generalization for the separate detector analyzed in [18] in order to deal with arbitrary number of transmitting users. The scheme is tunable, meaning that the diversity order achieved by each user may be chosen up to full diversity (for each user) with a corresponding increase in the computational complexity at the receiver and a reduction in the spectral efficiency. Linear MUD (based on PIC and MMSE filtering as in [16], [23]) and cooperative techniques (based on the decode-and-forward protocol as in [7], [8]) are effectively combined and exploited to achieve good performance with contained complexity. Use of space-time precoding is also crucial in order to potentially attain full diversity of the wireless channel [24]. Performance of various system configurations are presented in terms of FER with respect to Signal-to-Noise Ratio (SNR) obtained with Monte Carlo simulations.

The outline of the paper is the following: in Sec. II we present the system model under investigation; we then derive the equations for the detection operation at the receiver in

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Sec. III that lead to an analysis of the global receiver; Sec. IV highlights and compares the performance of the proposed schemes obtained via numerical simulations, and finally Sec. V gives the concluding remarks.

Notation – Lower-case bold letters denote vectors, with a_n denoting the nth element of $\boldsymbol{a}$; upper-case bold letters denote matrices, with $A_{n,m}$ denoting the (n,m)th element of $\boldsymbol{A}$; $\boldsymbol{I}_N$ denotes the $N \times N$ identity matrix, and $\boldsymbol{e}_N^{(n)}$ denotes the nth column of $\boldsymbol{I}_N$; $\boldsymbol{0}_{N\times M}$ denotes the $N \times M$ null matrix; $\mathrm{diag}(\boldsymbol{a})$ denotes a diagonal matrix with $\boldsymbol{a}$ on the main diagonal; $\mathbb{E}\{\cdot\}$, $(\cdot)^*$, $(\cdot)^t$ and $(\cdot)^\dagger$ denote expectation, conjugate, transpose and conjugate transpose operators; $\delta_{n,m}$ denotes the Kronecker delta; $\otimes$ denotes the Kronecker matrix product; $\mathrm{vec}(\boldsymbol{A})$ is a vector containing the elements of $\boldsymbol{A}$ stacked column-by-column; $\sim \mathcal{N}_{\mathbb{C}}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ means "distributed according to a circularly symmetric complex normal distribution with mean $\boldsymbol{\mu}$ and covariance $\boldsymbol{\Sigma}$."

II. System Model

We consider a system with U users and one base station in the uplink communication mode. Each user is equipped with n_t transmit antennas, while the base station is equipped with n_r receive antennas. The users transmit their own information to the base station and they also cooperate to send each other's information. We assume half-duplex transmission, in which terminals cannot transmit and receive simultaneously. The considered cooperative protocol is the decode-and-forward protocol, in which users decode each others signals before re-encoding and forwarding to the base station. We consider a quasi-static fading channel, in which a codeword undergo one single channel realization between a given pair of transmit/receive antennas.

Each user independently encodes a group of L_b information bits using a rate-R convolutional code and a bit interleaver. The resulting channel codeword of pL code bits is mapped into a string of L complex symbols, $(z_1, \ldots, z_L)$, using a 2^p-Phase Shift-Keying (PSK) modulation. In the presence of a unitary space-time precoder (also called space-time rotation), the string is divided into G groups, each of size M, i.e. $(z_1(g), \ldots, z_M(g))$ with $g = 1, \ldots, G$, and such that $z_l(g) = z_{(g-1)M+l}$. The size of the group is $M = sn_t$ complex symbols, where s is the time spreading factor of the space-time rotation $\boldsymbol{S}$. Omitting the index g for sake of simplicity, each group is independently processed as follows. Modulated symbols are placed in a matrix $\boldsymbol{Z}$ of size $n_t \times s$. The space-time rotation $\boldsymbol{S}$ of size $sn_t \times sn_t$ is then applied to $\boldsymbol{Z}$ in order to obtain the space-time codeword $\boldsymbol{X}$ of size $n_t \times s$ such that

$$\mathrm{vec}\left(\boldsymbol{X}^t\right) = \boldsymbol{S}\ \mathrm{vec}\left(\boldsymbol{Z}^t\right) \ , \tag{1}$$

where the complex symbol $X_{j,\ell}$ is transmitted over the wireless channel by the jth antenna during the ℓth time slot. It is worth noticing that in the absence of a space-time rotation, we have that $s = 1$ and $\boldsymbol{S} = \boldsymbol{I}_{n_t}$. In the following, $\boldsymbol{X}_u$, with $u = 1, \ldots, U$, is a matrix of size $n_t \times s$ containing the space-time rotated modulation symbols transmitted by the uth user.

The cooperation frame of the proposed schemes is made of $U + K - 1$ phases, that can employ either orthogonal transmissions or interfering transmissions. The relay parameter $K = 1, \ldots, U$ represents the number of relays used by each user (including itself), i.e. the number of channels through which the information of each user reaches the base station. It is then related to the achieved diversity order[1]. Each phase involves s time slots. More specifically, two operating modes are found in the cooperative frame:

- *broadcasting* — it includes the first U phases and employs orthogonal transmissions; the uth user broadcasts its symbols $\boldsymbol{X}_u$ to the base station and to the other users in the uth phase;
- *relaying* — it includes the remaining $K - 1$ phases and employs simultaneous (interfering) transmissions; each user relays (simultaneously to the other users) the previous-user information following a round robin ordering.

Figs. 1(a) and 2(a) show the cooperation frames of a cooperative systems with $U = 3$ users and with $K = 2$ and $K = 3$, respectively. In addition, Figs. 1(b) and 2(b) show analogous cooperation frames for cooperative systems (again with $U = 3$ users and with $K = 2$ and $K = 3$, respectively) employing orthogonal transmissions both in the broadcasting phases as well as in the relaying phases. The two systems are denoted *non-orthogonal scheme* and *orthogonal scheme*, respectively, the former being the system proposed in this paper and the latter being the classical relaying system used for comparison (the reader is referred to [8] for more details).

We will assume in the sequel that each user perfectly decodes the symbols received from the others, which is a realistic situation in the sense that cooperation usually takes place between terminals that are separated by a reliable channel. In addition, we assume perfect synchronization between users and perfect channel state information at the receiver. The discrete-time model for the signal received at the base station during the first mode of the cooperation frame (i.e. U phases employing orthogonal transmissions) is then given by the following equations

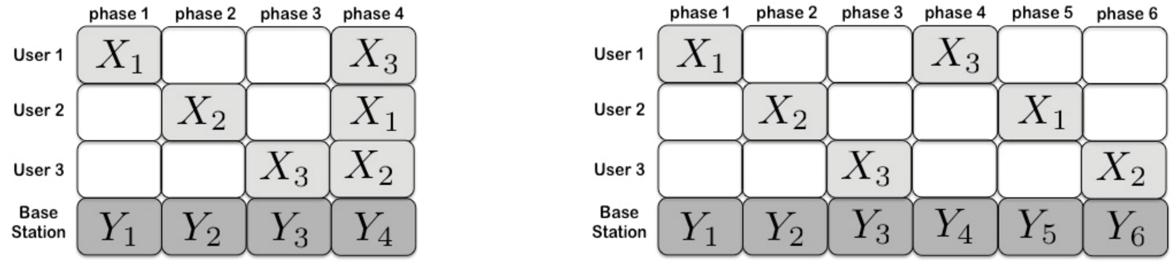
$$\boldsymbol{Y}_u = \boldsymbol{H}_u \boldsymbol{X}_u + \boldsymbol{W}_u \ , \quad u = 1, \ldots, U \ , \tag{2}$$

where $\boldsymbol{Y}_j$ is a matrix of size $n_r \times s$ denoting the signal received by the base station during the jth phase of the cooperation frame, $\boldsymbol{W}_j$ is the corresponding additive noise with circularly symmetric complex Gaussian zero-mean components whose variance is η_0, and $\boldsymbol{H}_u$ is a matrix of size $n_r \times n_t$ with complex i.i.d circularly symmetric Gaussian zero-mean coefficients with unit variance denoting the links from the uth user to the base station. The discrete-time model for the signal received at the base station during the second mode of the cooperation frame (i.e. $K - 1$ phases employing interfering transmissions) is given by the following equations

$$\boldsymbol{Y}_{U+k} = \sum_{\ell=1}^{U} \boldsymbol{H}_{\mathrm{mod}(\ell+k)} \boldsymbol{X}_\ell + \boldsymbol{W}_{U+k} \ , \quad k = 1, \ldots, K-1 \ , \tag{3}$$

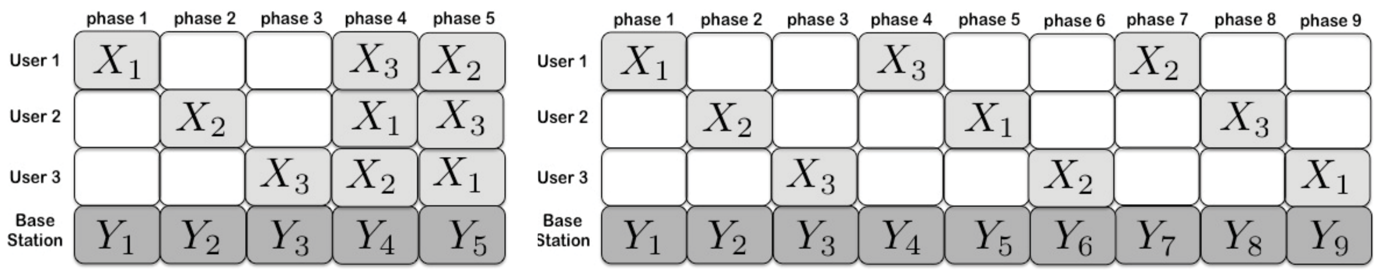
where $\mathrm{mod}\,(\cdot)$ denotes the modulo operation over the set of integers $\{1, \ldots, U\}$, i.e. the modulo$-U$ except from replacing 0 with U.

[1]It is worth noticing that $K = 1$ corresponds to a non-cooperative system.



(a) Non-orthogonal scheme (proposed). (b) Orthogonal scheme (comparison).

Fig. 1. Structure of the cooperation frame for a system with $U = 3$ users and relay parameter $K = 2$. White blocks represent inactive slots, grey blocks represent active slots (light grey for transmitting and dark grey for receiving).



(a) Non-orthogonal scheme (proposed). (b) Orthogonal scheme (comparison).

Fig. 2. Structure of the cooperation frame for a system with $U = 3$ users and relay parameter $K = 3$. White blocks represent inactive slots, grey blocks represent active slots (light grey for transmitting and dark grey for receiving).

TABLE I

DIVERSITY ORDER, COMPUTATIONAL COMPLEXITY, SPECTRAL EFFICIENCY, AND ASYMPTOTIC SPECTRAL EFFICIENCY WITH FULL DIVERSITY FOR THE (PROPOSED) NON-ORTHOGONAL AND (COMPARISON) ORTHOGONAL COOPERATIVE SCHEMES.

	Non-Orthogonal Scheme (proposed)	Orthogonal Scheme (comparison)
Diversity Order (under ideal interference cancellation)	Ksn_r	Ksn_r
Computational Complexity (size of the matrix to invert)	$Ksn_r \times Ksn_r$	$Ksn_r \times Ksn_r$
Spectral Efficiency (symbols per channel use)	$Un_t/(U+K-1)$	n_t/K
Asymptotic Spectral Efficiency with $K = U >> 1$ (symbols per channel use)	$n_t/2$	n_t/U

III. Receiver Architecture

The base station is provided with an iterative receiver made of three blocks: (i) the first block pre-processes the received signals in order to provide suitable information for MUD; (ii) the MUD block aims to unveil the contributions of each complex symbol from the received signal; (iii) finally, the soft-input soft-output (SISO) decoders perform the decoding of the convolutional codewords for each user by means of a BCJR algorithm [25]. The receiver is iterative because MUD and SISO blocks iteratively exchange their soft information before taking the final decision.

We develop here the algorithm for MUD, where the goal is to estimate each complex symbol from the received signal on the basis of Eqs. (2) and (3). The approaches is based on PIC and MMSE filtering, along the same lines in [26], [23], and exhibits different complexity and performance depending on the parameter K.

More specifically, the MUD applies PIC and MMSE filtering separately for each user turning Eqs. (2) and (3) in the following equations

$$\boldsymbol{Y}[u] = \boldsymbol{H}[u]\boldsymbol{X}_u + \sum_{\ell \neq u} \boldsymbol{K}[\ell]\boldsymbol{X}_\ell + \boldsymbol{W}[u] , \quad u = 1, \ldots, U , \tag{4}$$

where

$$\boldsymbol{Y}[u] = \left(\boldsymbol{Y}_u^t, \boldsymbol{Y}_{U+1}^t, \ldots, \boldsymbol{Y}_{U+K-1}^t\right)^t$$

is a matrix of size $Kn_r \times s$ containing the received symbols related to the uth user,

$$\boldsymbol{W}[u] = \left(\boldsymbol{W}_u^t, \boldsymbol{W}_{U+1}^t, \ldots, \boldsymbol{W}_{U+K-1}^t\right)^t$$

is a matrix of size $Kn_r \times s$ containing the noise components for the uth user,

$$\boldsymbol{H}[u] = \left(\boldsymbol{H}_u^t, \boldsymbol{H}_{\mathrm{mod}(u+1)}^t, \ldots, \boldsymbol{H}_{\mathrm{mod}(u+K-1)}^t\right)^t$$

is a matrix of size $Kn_r \times n_t$ containing the channel coefficients related to the uth user, and

$$\boldsymbol{K}[\ell] = \left(\boldsymbol{0}_{n_t \times n_r}, \boldsymbol{H}_{\mathrm{mod}(\ell+1)}^t, \ldots, \boldsymbol{H}_{\mathrm{mod}(\ell+K-1)}^t\right)^t$$

are matrices of size $Kn_r \times n_t$ containing the channel coefficients related to the interfering users. Rewriting Eq. (4) in vector form, we get

$$\boldsymbol{y}_u = \boldsymbol{A}_u \boldsymbol{z}_u + \sum_{\ell \neq u} \boldsymbol{B}_\ell \boldsymbol{q}_\ell + \boldsymbol{w}_u \ , \quad u = 1, \ldots, U \ , \tag{5}$$

where $\boldsymbol{y}_u = \mathrm{vec}\left(\boldsymbol{Y}[u]^t\right)$ is a vector of length Ksn_r containing the received signal related to the uth user, $\boldsymbol{z}_u = \mathrm{vec}\left(\boldsymbol{Z}_u^t\right)$ is a vector of length sn_t containing the symbol from the user of interest, $\boldsymbol{q}_\ell = \boldsymbol{z}_\ell$ is introduced only to highlight the interfering symbols with respect to the user of interest, $\boldsymbol{w}_u = \mathrm{vec}\left(\boldsymbol{W}[u]^t\right)$ is a vector of length Ksn_r containing the noise components, and where

$$\begin{aligned} \boldsymbol{A}_u &= \left(\boldsymbol{H}[u] \otimes \boldsymbol{I}_s\right) \boldsymbol{S} \ , \\ \boldsymbol{B}_\ell &= \left(\boldsymbol{K}[\ell] \otimes \boldsymbol{I}_s\right) \boldsymbol{S} \ , \end{aligned}$$

are matrices of size $Ksn_r \times sn_t$ containing the channel coefficients and the rotation coefficients.

We define $\tilde{\boldsymbol{z}} = \mathbb{E}\{\boldsymbol{z}\}$ and $\tilde{\boldsymbol{q}} = \mathbb{E}\{\boldsymbol{q}\}$. They are assumed to be available from the SISO decoders and null at the first iteration. Also, we define

$$\boldsymbol{Q}_u = \sum_{\ell \neq u} \boldsymbol{B}_\ell \mathrm{diag}(\boldsymbol{v}_\ell) \boldsymbol{B}_\ell^\dagger$$

where the nth element of $\boldsymbol{v}_\ell$ is given by $v_{\ell n} = 1 - |\tilde{q}_{\ell n}|^2$ and takes into account the variance of the soft information coming from the SISO decoders. Omitting the user index u for sake of simplicity, the residual term from PIC (in order to compute an estimate of the symbol z_m by the uth user) is given by

$$\tilde{\boldsymbol{y}}_{(m)} = \boldsymbol{y} - \boldsymbol{A}\tilde{\boldsymbol{z}}_{(m)} - \boldsymbol{B}\tilde{\boldsymbol{q}} \ ,$$

where $\tilde{\boldsymbol{z}}_{(m)} = \tilde{\boldsymbol{z}} - \tilde{z}_m \boldsymbol{e}_{n_t}^{(m)}$ contains the interference experienced by the mth symbol. The unbiased estimation of z_m, obtained applying MMSE filtering, is then

$$\hat{z}_m = \frac{\boldsymbol{a}_{(m)}^\dagger \left(\boldsymbol{A}\mathrm{diag}(\boldsymbol{u}_{(m)})\boldsymbol{A}^\dagger + \boldsymbol{Q} + \eta_o \boldsymbol{I}_{Ksn_r}\right)^{-1} \tilde{\boldsymbol{y}}_{(m)}}{\boldsymbol{a}_{(m)}^\dagger \left(\boldsymbol{A}\mathrm{diag}(\boldsymbol{u}_{(m)})\boldsymbol{A}^\dagger + \boldsymbol{Q} + \eta_o \boldsymbol{I}_{Ksn_r}\right)^{-1} \boldsymbol{a}_{(m)}} \ , \tag{6}$$

where $\boldsymbol{a}_{(m)} = \boldsymbol{A}\boldsymbol{e}_{sn_t}^{(m)}$ is the mth column of $\boldsymbol{A}$, and where

$$u_{(m)n} = \begin{cases} 1 - |\tilde{z}_n|^2 & n \neq m \\ 1 & n = m \end{cases}$$

take into account the variance of the soft information coming from the SISO decoders.

The scheduling of the iterative algorithm at the receiver is the following:

- $\tilde{z} = 0$; $\tilde{q} = 0$;
  `% initialize extrinsic information`
- repeat $N_{\text{iterations}}$ times
  `% external loop`
  - for $g = 1, \ldots, G$; for $u = 1, \ldots, U$
    `% select the gth space-time codeword and the uth user`
    - compute A and Q;
    - for $m = 1, \ldots, M$
      `% select the mth symbol`
      - compute $y_{(m)}$;
      - compute $\hat{z}_m$;
  - deinterleave the entire string $\hat{z}$ and decode via BCJR;
  - interleave the results and update $\tilde{z}$ and $\tilde{q}$;
- output the decoded bits;

To conclude this section, we note that the contribution of the uth user is coming from the first term of the right side of Eq. (5), i.e. $\boldsymbol{A}_u \boldsymbol{z}_u$. Taking into account the effect of the space-time rotation, and assuming that the receiver is able to cancel the interference coming from the other users and from the other transmit antennas of the same user, each user potentially achieves a diversity order of Ksn_r (the reader is referred to [27] for a detailed analysis on the achievable diversity orders in the non-cooperative case). As for spectral efficiency, the scheme transmits sn_t symbols from each of the U users in $U + K - 1$ phases made each of s time slots, thus the number of symbols per channel use is $(Un_t)/(U + K - 1)$. Also, it is worth noticing that a matrix inversion, within the MMSE filtering in Eq. (6), is required for each transmitted symbol and at each iteration. The size of the matrix to invert ($Ksn_r \times Ksn_r$) may be considered as an indicator of the complexity of the receiver.

Table I summarizes the tradeoff existing in the proposed non-orthogonal scheme between the achievable diversity order, the computational complexity and the spectral efficiency. It also shows the corresponding features of the orthogonal scheme considered for comparison and based on the work in [8]. Furthermore, it is worth noticing that: (i) the space-time rotation does not affect the spectral efficiency of the system; (ii) in order to achieve full diversity Un_tn_r we need $s = n_t$ (i.e. full spreading) and $K = U$, thus corresponding to a spectral efficiency $(Un_t)/(2U - 1)$ and a size of the matrix to invert $Un_tn_r \times Un_tn_r$. For a large number of users, the scheme allows to achieve full diversity with $n_t/2$ symbols per channel use (i.e. the asymptotical spectral efficiency is independent on the number of users U), while a cooperative scheme with orthogonal transmissions would provide n_t/U symbols per channel use ((i.e. the asymptotical spectral efficiency is decreasing with the number of users U)).

In the next section FER performance obtained via numerical simulations are shown.

IV. Simulation Results

In this section we present FER performance of the proposed non-orthogonal scheme as well as for the comparison orthogonal scheme, with reference to systems with $U = 3$ users and diversity from $K = 2$ and $K = 3$ channels. Simulations have been run for systems $n_t = 2$ transmit antennas per user and $n_r = 1$ receive antenna at the base station, and time spreading

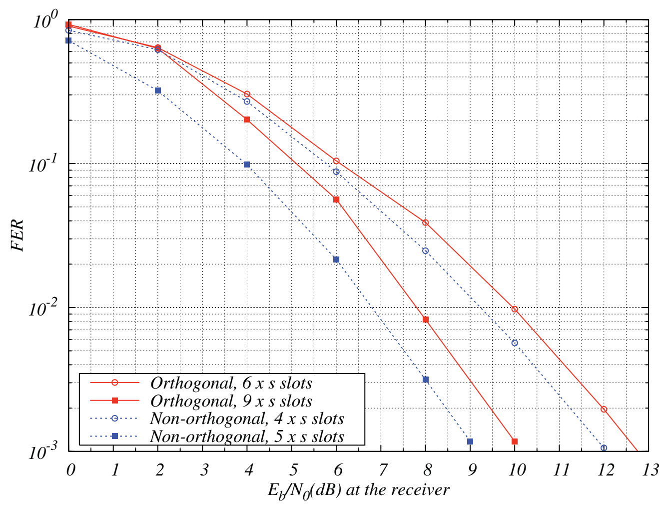


Fig. 3. FER vs. SNR performance for cooperative systems with $U = 3$ users, $n_t = 2$ transmit antennas per user, $n_r = 1$ receive antenna at the base station, time spreading factor $s = n_t$, and relay parameter $K = 2$ and $K = 3$.

factor $s = n_t$. A frame contains $N = 256$ Quadrature Phase Shift Keying (QPSK) modulated symbols (i.e. $p = 2$), and modified cyclotomic space-time rotations [28], [29] that are optimal for both iterative decoding under APP detection and MMSE detection [30] are used. The error-correcting code used is the half-rate (i.e. $R = 2$) 16-state $(23, 35)_8$ non-recursive non-systematic convolutional (NRNSC) code and the interleavers are pseudo-randomly generated. A quasi-static fading scenario has been considered for simulations, whereas channel coefficients have been generated according to a Rayleigh fading model with unitary mean power.

Fig. 3 shows the performance of both the non-orthogonal scheme and the orthogonal scheme for two different choices for the parameter K:

- $K = 2$ corresponding to a maximum order of achievable diversity of $d = Kn_tn_r = 4$;
- $K = 3$ corresponding to a maximum order of achievable diversity of $d = Kn_tn_r = 6$.

The number of iterations at the receiver is set to 10. Although both the non-orthogonal scheme and the orthogonal scheme achieve the expected order of diversity, it is apparent how the former outperforms the latter in both cases: 0.5 dB when $K = 2$ and 1 dB when $K = 3$, assuming FER$= 10^{-3}$. These observations confirm that although the non-orthogonal scheme leads to an increase in interference in the simultaneous transmission phase, a powerful iterative receiver allows to efficiently remove the interference and achieve better performance than with orthogonal cooperation. It is worth noticing that, for each simulation, the noise variance has been scaled depending on the number of phases involved in the cooperation frame in order to take into account the different spectral efficiency of the different protocols and have a more fair comparison among FER curves.

V. Conclusion

In this paper we presented a scheme for cooperative MIMO systems with arbitrary number of users. The system combines space-time coding and decode-and-forward cooperation at the transmitter and MMSE-based iterative multiuser detection at the receiver. The proposed scheme, employing an interference-free broadcasting phase followed by an interfering relaying phase, has shown to outperform in terms of FER and normalized throughput an analogous cooperative scheme employing interference-free broadcasting and relaying phases.

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