A Space-Time Multi-User Detector with Decoupled Processing for Wireless Communications

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***Abstract*— This paper proposes a new space-time multi-user receiver with decoupled interference cancellation and multi-user detection for wireless (mobile) communications. The proposed receiver, called a *decoupled space-time multi-user detector* (D-ST-MUD) utilizes spatial filtering for interference cancellation and maximum likelihood (ML) multi-user detection for joint demodulation of co-channel user signals. As opposed to classical multi-user receivers, the proposed receiver enjoys the nice property of being robust to cases where short-delayed paths of co-channel users are spatially correlated. Instead of being separated by the spatial filter, these short-delayed paths are passed to the ML multi-user detector that effectively combine and jointly demodulate the user signals. The main role of the spatial filter is to suppress long-delayed paths only. As a consequence, the D-ST-MUD receiver has the attractive characteristics of dealing with more signals than antenna-elements as well as being a low-complexity ML multi-user detector.**

***Index Terms*— Space-time processing, multi-user detection, interference cancellation, decoupled processing, MLSE**

I. INTRODUCTION

In current and upcoming broad-band mobile wireless communications, increased capacity and very high data-rates are required. The tightening of channel frequency reuse in neighboring cells implies increased levels of co-channel interference (CCI). Additionally, in high-speed mobile communication services channel frequency selectivity induces inter-symbol interference (ISI) on the received signals. In order to cope with the simultaneous presence of CCI and ISI in single-carrier systems, and to keep a satisfactory bit-error-rate (BER) performance, several space-time signal processing techniques have been developed in the last years [1-7, 12-14]. Most of them are based on combinations of array processing and temporal equalization. The common objective of these combinations is to exploit the spatial and temporal signatures of the signals in order to separate them according to some performance criterion.

In [1], a space-time maximum likelihood sequence estimator (MLSE) equalizer is proposed for joint CCI/ISI suppression. Since the antenna array does not perform spatial filtering, CCI is mitigated within the MLSE based on CCI covariance estimation, which is generally a difficult task. Other approaches as [2] employ the adaptive array as a space-time filter by placing a tapped-delay line at the output of each antenna-element. In this case, the minimum mean square error (MMSE) criterion is considered. The MMSE space-time filter generally suffers from noise enhancement since it attempts to perform space-time equalization. References [3-7] rely on cascaded connections of an antenna array and a MLSE equalizer. All these approaches share the main characteristic of separating CCI cancellation from ISI equalization in a two-stage processing receiver. The antenna array is optimized to spatially cancel CCI paths only, preserving the desired user delayed paths to be combined within the MLSE. This type of processing allows to exploit path diversity of the desired user's signal while being CCI resilient.

In [3] a spatial filter is optimized with a filtered training sequence reference via a signal-to-interference plus noise (SINR) ratio criterion. The MLSE equalizer is found by imposing a unit-norm constraint on its parameters. In [4] a space-time filter is used and a joint optimizer of the space-time filter and the MLSE equalizer is proposed. Reference [5] follows the same optimization criterion of [3] but attention is given to adaptive implementation of the receiver with recursive parameter estimation. In [6] the problem of separating CCI and ISI is treated with a different optimization procedure, where a unit-norm constraint is imposed on the spatial filter coefficients. Reference [7] follows [3] and also proposes a linear constraint for the joint optimization of the spatial filter and the MLSE equalizer.

The above space-time processing approaches were generalized in [12-16] to cope with other equalizer structures and have been called decoupled space-time (D-ST) processing. In its more general meaning, the term *decoupled* accounts for the fact that interference cancellation and equalization are divided in two processing stages. In [12-15], the antenna array is followed by either a decision-feedback equalizer (DFE) or a delayed decision-feedback sequence estimation (DDFSE). In [16] attention was also given to the equalizer complexity and channel shortening was considered in the formulation of D-ST receivers through different optimization criteria.

The decoupled processing approach enjoys two main properties that are not sought by classical approaches. It offers satisfactory performance even in situations where: (1) the number of desired plus interference paths exceeds the degrees of freedom of the antenna array; (2) desired user delayed paths are spatially correlated. In fact, D-ST receivers can handle these two situations thanks to the fact that the desired user delayed paths are not discriminated in the spatial domain, i.e., the antenna array "sees" only the CCI paths. In this two situations, D-ST receivers offer satisfactory performance.

Despite of these advantageous properties, there is still undesirable drawbacks experienced by D-ST receivers that degrade its performance. We are interested in two particular situations, which constitute the main motivation of this work: (3) the number of interference paths exceeds the degrees of freedom of the antenna array and (4) interference paths are spatially correlated with desired ones. In this situations, D-ST receivers generally fails to spatially separate the paths of the desired user from those of the interferers. As a result, the desired delayed paths are not well preserved for the equalizer, which means that path diversity is not efficiently exploited. Furthermore, residual CCI at the output of the antenna array degrades MLSE performance.

One possible solution to avoid this problem is multi-user ML detection [10], where all CCI signals are detected in an optimal way. However, this approach is not generally used due to its very high computational complexity. Other approaches employ pure spatial processing with decision-feedback based on post-detection interference subtraction [11]. Even in this case, spatial correlation of desired and interferer paths is still a limiting factor.

In order to overcome the performance limitations experienced by single-users D-ST receivers as well as the complexity limitation of a classical multi-user ML detector we propose a decoupled space-time multiuser detector (D-ST-MUD) based on spatial filtering and ML detection. The proposed receiver performs *interference cancellation* at the spatial filter stage and ML multi-user detection at the MLSE stage, in a decoupled approach. The spatial filter is optimized to cancel long-delayed paths of all users (desired + interferers) while preserving short-delayed paths of all users (not only the delayed paths of the desired one). The preserved short-delayed paths are then passed to the MLSE that performs sub-optimum ML multi-user detection, exploiting path diversity of all users to be detected. This type of processing allows the D-ST-MUD receiver to deal with the aforementioned situations (3) and (4) where the single-user D-ST receiver may fail to perform well.

This work is organized as follows. Section II contains our multi-user space-time signal model. In section III, we present the single-user D-ST receiver and its optimization criterion. In section IV, we derive the proposed D-ST-MUD receiver. Section V is dedicated to simulation results for performance evaluation and section VI concludes this paper.

II. MULTI-USER SPACE-TIME SIGNAL MODEL

Let us consider a multipath wireless propagation environment where Q transmitted co-channel user signals are received by M sensors (uplink case). The propagation channel is time-dispersive over L consecutive symbol periods. The base-band representation of the signal received at the m-th antenna-element is given by

$$x_m(t) = \sum_{q=1}^{Q}\sum_{l=1}^{L_q} \alpha_{lq}(t) a_m(\theta_{lq}) u(t-\tau_{lq}) + n_m(t), \qquad (1)$$

where L_q denotes the number of paths originated from the q-th user signal and $\alpha_{lq}(t)$ is the fading envelope of the l-th path of the q-th user. The term $a_m(\theta_{lq})$ is the response of the m-th antenna-element to the l-th path of the q-th user, with θ_{lq} being the angle of incidence, also called direction of arrival (DOA). Similarly, τ_{lq} denotes the propagation delay. The term $u(\cdot)$ represents the modulated signal and $n_m(t)$ is an additive noise at the m-th antenna.

A. Time-Domain Signal Model

The transmitted modulated signal $u(t)$ can generically be written as:

$$u(t) = \sum g(t-kT)s(k), \qquad (2)$$

where $g(t-kT)$ is the combination of the transmitter and receiver filter responses to a generically transmitted symbol waveform $s(k)$. We also denote $s(k)$ as the information symbol at a discrete-time instant k. The symbol period is represented by T. In our system model with Q users and L_q paths per user, we collect K consecutive time samples of $g(k-\tau_{lq})$ and group them in a vector, which gives

$$\mathbf{g}(k-\tau_{lq}) = [g(k+K_a-\tau_{lq}) \cdots g(k-\tau_{lq}) \cdots g(k-K_c-\tau_{lq})]^T. \qquad (3)$$

The vector $\mathbf{g}(k-\tau_{lq})$ is called the time-domain channel impulse response (also called temporal signature) associated to the l-th path of the q-th user, with K_a and K_c being the number of considered anti-causal and causal samples respectively, with $K = K_a + K_c + 1$.

B. Space-Domain Signal Model

We assume that the M receive antennas are geometrically organized as as uniform linearly-spaced array (ULA). Unless otherwise stated, we will consider that fading envelope is the same for all antenna-elements of the array (beamforming approach), i.e., spacing of antenna-elements is equal to $\lambda/2$, λ being the wavelength. By grouping the responses of all antenna-elements into an M dimensional vector we have

$$\begin{aligned}\mathbf{a}(\theta_{lq}) &= [a_1(\theta_{lq})\ a_2(\theta_{lq})\ \cdots\ a_M(\theta_{lq})]^T \\ &= [1\ e^{-j\pi\sin\theta_{lq}}\ \cdots\ e^{-j\pi(M-1)\sin\theta_{lq}}]^T, \qquad (4)\end{aligned}$$

where superscript T denotes transposition of a vector or a matrix. The vector $\mathbf{a}(\theta_{lq})$ is the array response vector (also called spatial signature) associated to the (lq)-th path. Equation (1) can be rewritten in term of the $M \times 1$ received signal vector $\mathbf{x}(t)$ as

$$\mathbf{x}(t) = \sum_{q=1}^{Q}\sum_{l=1}^{L_q} \mathbf{a}(\theta_{lq})\alpha_{lq}(t)u(t-\tau_{lq}) + \mathbf{n}(t), \qquad (5)$$

where $\mathbf{a}(\theta_{lq})$, $\mathbf{x}(t) = [x_1(t)\ x_2(t) \cdots\ x_M(t)]^T$ and $\mathbf{n}(t) = [n_1(t)\ n_2(t) \cdots\ n_M(t)]^T$ are also $M \times 1$ complex vectors.

By considering that the signal at each antenna output is sampled at the symbol-rate $(1/T)$ and at time-instants $t = t_0 + kT$, with $t_0 = 0$, and occulting T for simplicity, we rewrite

$$\mathbf{x}(k) = \sum_{q=1}^{Q}\sum_{l=1}^{L_q} \mathbf{a}(\theta_{lq})\alpha_{lq}(k)u(k-\tau_{lq}) + \mathbf{n}(k), \qquad (6)$$

C. Space-Time Signal Model

Since we will explicitly deal with space and time dimensions of signals in this work, a unique signal model capturing both space and time domains of all Q signals is desirable. After describing both space- and time-domain signal models for multi-user wireless transmissions, we finally define the discrete-time representation of our multi-user space-time signal model. By using (2), (3) and (6), we have

$$\mathbf{x}(k) = \sum_{q=1}^{Q} \mathbf{H}_q \mathbf{s}_q(k) + \mathbf{n}(k), \qquad (7)$$

where

$$\mathbf{H}_q = \sum_{l=1}^{L_q} \alpha_{lq}(k)\mathbf{a}(\theta_{lq})\mathbf{g}^T(\tau_{lq}) \qquad (8)$$

is the $M \times K$ space-time channel matrix for the q-th user containing the product of both space and time signatures all of its L_q paths, and

$$\mathbf{s}(k) = [s(k+K_a) \cdots s(k) \cdots s(k-K_c)]^T \qquad (9)$$

is the vector of transmitted symbols for the q-th user, which groups $K = K_a + K_c + 1$ consecutive symbols.

III. THE DECOUPLED SPACE-TIME SINGLE-USER RECEIVER (D-ST)

A general structure of a decoupled space-time single-user (D-ST) receiver based on MLSE equalization is shown in Figure 1. Differently from classical space-time receivers as the minimum mean square error (MMSE) space-time equalizer [2], the D-ST receiver is designed to separate co-channel interference (CCI) cancellation and inter-symbol interference (ISI) equalization in two stages [15]. See also [12-14] for more details into performance evaluation of some single-user D-ST receivers in the context of TDMA/GSM systems.

The problem consists of determining the parameters of the spatial filter $\mathbf{w}$ and an *equivalent* channel impulse response (ECIR) $\mathbf{c}$ associated to the desired user, such that the spatial filter performs CCI cancellation only, passing ISI to be treated by a separate MLSE equalizer based on the ECIR $\mathbf{c}$. Contrarily from classical space-time filtering approaches, where both CCI and ISI are jointly mitigated, in the decoupled approach the ISI channel is seen as the “desired term” to be maximized over CCI plus noise. The authors have proposed in [15] two constrained optimization criteria for single-user D-ST receivers, where optimum settings for $\mathbf{w}$ and $\mathbf{c}$ are derived.

Without loss of generality we assume that the user of index $q = 1$ in (7) is the desired one and that the other $Q - 1$ users are co-channel interferers to be suppressed. In this case we have adopted the following cost function to be optimized:

$$J(\mathbf{w}, \mathbf{c}) = \frac{E\{|\mathbf{c}^H\mathbf{s}_1(k)|^2\}}{E\{|\mathbf{w}^H\mathbf{x}(k) - \mathbf{c}^H\mathbf{s}_1(k)|^2\}}. \tag{10}$$

This cost function represents a modified signal-to-interference plus noise ratio (SINR) at the input of the temporal equalizer, where the “signal” is represented by the the desired symbol sequence $\mathbf{s}_1(k)$ convolved with the ECIR vector $\mathbf{c}$. The maximization of (10) can be interpreted as an optimization of the following MMSE cost function

$$J_1(\mathbf{w}, \mathbf{c}) = E\{|\mathbf{w}^H\mathbf{x}(k) - \mathbf{c}^H\mathbf{s}_1(k)|^2\}, \tag{11}$$

subject to some constraint in $\mathbf{w}$ or $\mathbf{c}$ to avoid the trivial solution. Int this work we consider the linear constraint $\mathbf{b}^T\mathbf{c} = 1$ imposed on vector $\mathbf{c}$, which turns out into the following Lagrangian optimization problem:

$$\widetilde{J} = J_1 - \lambda\left(\mathbf{b}^T\mathbf{c} - 1\right), \tag{12}$$

with

$$\mathbf{b} = [\,\underbrace{0\ \ldots 0}_{d}\ 1\ \underbrace{0\ \ldots 0}_{K-d-1}\,], \tag{13}$$

where $\mathbf{c}$, is an $K \times 1$ vector representing the constraint and d is a time-delay. Thus, we restrict the $(d+1)$-th coefficient of $\mathbf{c}$ to be equal to one, where $1 \leq d \leq K$. By using the orthogonality principle [8], expanding (11) and taking the partial derivative with respect to $\mathbf{c}$, the Lagrange coefficient is found as

$$\lambda = \frac{1}{\mathbf{b}^T\mathbf{R_{ee}}^{-1}\mathbf{b}}, \tag{14}$$

where

$$\mathbf{R_{ee}} = \mathbf{R_{ss}} - \mathbf{R_{xs}}^H\mathbf{R_{xx}}^{-1}\mathbf{R_{xs}}, \tag{15}$$

is an *error matrix* and $\mathbf{R}_{ss} = E\{\mathbf{s}_1(k)\mathbf{s}_1^H(k)\} = \sigma_s^2\mathbf{I}$. By using the solution for λ, it can be shown [9] that the optimum ECIR is given by the following expression

$$\mathbf{c}_{opt} = \mathbf{R_{ee}}^{-1}\mathbf{b}\,(\mathbf{b}^H\mathbf{R_{ee}}^{-1}\mathbf{b})^{-1}. \tag{16}$$

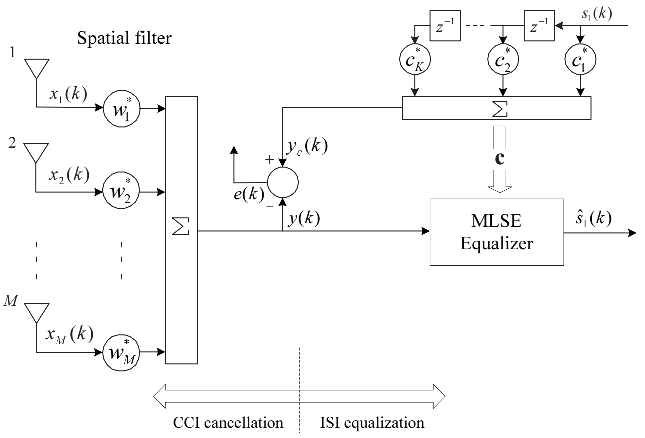

Fig. 1. A decoupled space-time single-user (D-ST) receiver. The spatial filter is dedicated to CCI cancellation and the temporal MLSE equalizer for ISI suppression.

Finally, by taking the partial derivative of (11) w.r.t. vector $\mathbf{w}$ and using (16) we find the optimum spatial filter coefficients:

$$\mathbf{w}_{opt} = (\mathbf{R_{xx}})^{-1}\,\mathbf{R_{xs}}\mathbf{c}_{opt}, \tag{17}$$

where $\mathbf{R_{xx}} = E\{\mathbf{x}(k)\mathbf{x}^H(k)\}$ and $\mathbf{R_{xs}} = E\{\mathbf{x}(k)\mathbf{s}_1^H(k)\}$ are correlation and cross-correlation matrices, respectively.

IV. A DECOUPLED SPACE-TIME MULTI-USER DETECTOR (D-ST-MUD)

One possible realization of the proposed receiver is illustrated in Figure 2, for multi-user detection of two co-channel signals. Similarly to the single-user D-ST receiver, here we distinguish two processing stages. The spatial filtering stage is dedicated to *interference cancellation* of long-delayed paths of users. This means that only those paths arriving with a delay superior to a pre-selected threshold value should be cancelled by the antenna array. Short-delayed paths are passed to the MLSE that performs sub-optimum ML *multi-user detection*, exploiting the equivalent (shortened) channel responses (ECIRs) of all users simultaneously.

As mentioned in Section I, the use of spatial filtering and ML multiuser detection via decoupled processing has two main motivations that come from propagation situations (3) and (4). As will be shown lately, the D-ST-MUD overcomes the limitations of single-user D-ST when (3) the number of interference paths exceeds the degrees of freedom of the antenna array and (4) interference paths are spatially correlated with desired ones.

The optimization of the D-ST-MUD receiver follows that of the single-user receiver with some key manipulations of entities involved in the optimization procedure. The idea is to group the ECIRs of all users to be detected in a unique “multi-user” vector. Without loss of generality, we assume that the ECIRs of all users to be detected have equal length L. We first define a multiuser ECIR matrix by organizing the ECIRs of the Q users in its columns:

$$\mathbf{C} = \begin{bmatrix} c_1(1) & c_1(2) & \ldots & c_1(L) \\ c_2(1) & c_2(2) & \ldots & c_2(L) \\ \vdots & \vdots & \ddots & \vdots \\ c_Q(1) & c_Q(2) & \ldots & c_Q(L) \end{bmatrix} = \begin{bmatrix} \mathbf{c_1}^T \\ \mathbf{c_2}^T \\ \vdots \\ \mathbf{c_Q}^T \end{bmatrix}. \tag{18}$$

We define the vec$(\cdot)$ operator that stacks all columns of a matrix in a unique “extended” column vector. A multiuser

ECIR vector $\mathbf{c}$ can thus be defined as

$$\mathbf{c} = \text{vec}\left(\mathbf{C}\right). \tag{19}$$

Recalling the idea of the D-ST-MUD receiver, which is to spatially suppress long-delayed user paths, we define K_0 as the maximum tolerated delay in symbol periods (threshold value). This means that channel impulse response components falling outside the interval $[0\,,\,K_0T]$ should be suppressed by the spatial filter and those falling inside this interval are passed to the ML multi-user detector. In terms of the multiuser ECIR vector we must optimize the receiver in order to obtain

$$\mathbf{c} = [\,\tilde{\mathbf{c}}^T\,,\,\mathbf{0}_{(K-K_0)Q}\,]^T \tag{20}$$

where

$$\tilde{\mathbf{c}} = [\,\underbrace{c_1(1)\ldots c_Q(1)\ldots c_1(K_0)\ldots c_Q(K_0)}_{K_0\times}\,]^T. \tag{21}$$

Thus, the multi-user ECIR vector should be optimized to have its last $(K-K_0)\times Q$ elements equals to zero. Its first $K_0\times Q$ elements constitutes the *shortened* multi-user channel response vector that is passed to the ML multi-user detector, as indicated in Figure 2.

The cost function (15) used in the previous section for the D-ST receiver still applies here. Following (10)-(15) we arrive at a similar formulation for the error matrix $\mathbf{R_{ee}}$. From this point, instead of finding the optimum $\mathbf{c}$ from $\mathbf{R_{ee}}$ we opted to find directly the shortened ECIR $\tilde{\mathbf{c}}$ in order to reduce the dimensionality as well as the complexity of the optimization problem. We thus define an auxiliary matrix $\mathbf{\Phi}$ as:

$$\mathbf{\Phi}\ = \text{diag}\left(\mathbf{1}_{K_0Q}\,,\,\mathbf{0}_{(K-K_0)Q}\right), \tag{22}$$

where $\mathbf{1}_{K_0Q}$ is a $1\times K_0Q$ vector of 1's, $\mathbf{0}_{(K-K_0)Q}$ is a $1\times(K-K_0)Q$ vector of 0's and operator diag$(\cdot)$ construct a diagonal matrix from its vector argument. With the aid of matrix $\mathbf{\Phi}$, the error matrix $\mathbf{R_{ee}}$ of (15) is rewritten as

$$\mathbf{R_{ee}}\ = \sigma_s^2\mathbf{\Phi} - \mathbf{\Phi}[\mathbf{R_{xs}}^H\mathbf{R_{xx}}^{-1}\mathbf{R_{xs}}]\mathbf{\Phi}, \tag{23}$$

where

$$\mathbf{R_{xs}} = E\{\mathbf{x}(k)\cdot\text{vec}\left([\mathbf{s}_1(k)\ldots\mathbf{s}_Q(k)]^H\right)\} \tag{24}$$

is a multiuser cross-correlation matrix of dimension $M\times KQ$.

The role of the auxiliary matrix $\mathbf{\Phi}$ is to null out cross-correlations of all Q users symbols that exceed the delay K_0. By ignoring the $K-K_0$ most delayed cross-correlations in the composition of matrix $\mathbf{R_{ee}}$, we carry out the optimization based on a reduced-dimension K_0Q square error matrix $\mathbf{R}_\Phi$, which is easily found as an upper-left sub-matrix of $\mathbf{R_{ee}}$. This matrix can be viewed as a result of the projection of the first K_0 symbols of each user onto a vector space that is orthogonal to the received signal vector $\mathbf{x}(k)$.

Similarly defining the constraint vector $\mathbf{b}$ and following the optimization steps, the optimum spatial filter and shortened ECIR coefficients are found as:

$$\tilde{\mathbf{c}}_{opt} = \frac{\mathbf{R}_\Phi^{-1}\mathbf{b}}{\mathbf{b}^T\mathbf{R}_\Phi^{-1}\mathbf{b}} = \left(\mathbf{b}^T\mathbf{R}_\Phi\mathbf{b}\right)^{-1}\mathbf{R}_\Phi^{-1}\mathbf{b}, \tag{25}$$

and

$$\mathbf{w}_{opt} = \mathbf{R_{xx}}^{-1}\left(\mathbf{R_{xs}}\mathbf{\Phi}\right)\mathbf{c}_{opt}, \tag{26}$$

where $\mathbf{c}_{opt} = [\,\tilde{\mathbf{c}}_{opt}^T\,,\,\mathbf{0}_{(K-K_0)Q}\,]^T$.

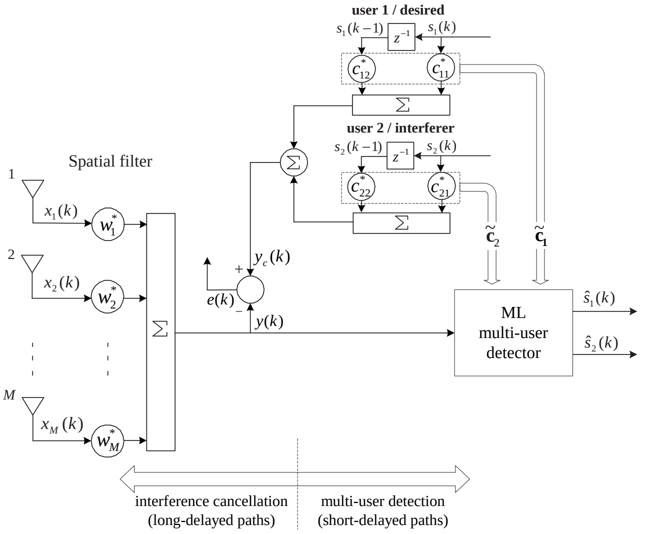

Fig. 2. A possible realization of a decoupled space-time multi-user detector (D-ST-MUD), with $Q = 2$ users to be detected and $K_0 = 2$. Spatial filtering for interference cancellation of long-delayed paths and multi-user ML detection based on ECIRs of users.

V. SIMULATION RESULTS

The performance of the D-ST-MUD receiver is illustrated by a set of results from computer simulations. Results are analyzed either from the directional response of the antenna array pattern or from the bit-error-rate (BER) *versus* SNR curves. We assume binary-phase-shift-keying (BPSK) modulation and perfect estimation of parameters for all simulated receivers. Fading is time-invariant over one transmitted block of 140 symbols, from which BER is computed. The BER curves were averaged over a total of 5000 independent Monte-Carlo runs. In order to simplify the exposition of our results we consider $Q = 2$ equal-power users. In all simulations of this paper, the path delay threshold is assumed to be equal to one-symbol period, i.e., $K_0 = 2$. This implies a ML multi-user detector of $2^{(K_0\cdot Q)} = 2^4 = 16$ trellis states. For the single-user D-ST we have $2^{(K_0-1)} = 2^1 = 2$ trellis states.

Concerning the frequency-selective channel model, a multipath Rayleigh fading model was assumed and the complex envelop of each propagation path follows a complex Gaussian distribution. All propagation paths have delays that are integer multiples of a symbol period, have equal average powers and are statistically independent. Channel impulse responses are normalized to unity.

In the first part of our simulation results we evaluate the the directional response pattern of the antenna array for the D-ST-MUD and single-user D-ST receivers in the absence of fading and for SNR = 30dB. Two propagation scenarios are considered in order to illustrate the comportment of the proposed receiver in situations (3) and (4) as compared to the single-user D-ST receiver.

We first consider the propagation scenario of Table I. Delays and direction-of-arrival (DOA) of paths are indicated. Both receivers employ a 3-element antenna array. We should mention that this is a scenario belonging to situation (3), where the total number of paths (3 from user 1 and 3 from user 2 = 6 paths) exceeds the degrees of freedom of the antenna array.

According to Figure 3, the proposed receiver effectively produces spatial nulls towards -40 and 80 degrees, which correspond to those paths with propagation delays greater

TABLE I
MULTIPATH PARAMETERS FOR SCENARIO 1

User	Delay	DOA (degrees)
Desired	0, T, 2T	0, 20, -40
Interferer	0, T, 2T	30, -70, 80

TABLE II
MULTIPATH PARAMETERS FOR SCENARIO 2

User	Delay	DOA (degrees)
Desired	0, T	0, 30
Interferer	0, T	-5, 35

than one symbol period (remember that $K_0 = 2$). The short-delayed paths of both users are preserved by the spatial filter to be passed to the ML multi-user detector. For the single-user D-ST receiver, it is worth noting that the interferers paths at 30, -70 and 80 degrees and the desired one at -40 degrees are not nulled out due to the lack of degrees of freedom of the antenna array (i.e., 4 interferer paths against $M - 1 = 2$ degrees of freedom). This poor array performance will certainly degrade performance of the MLSE equalizer, due to considerable residual CCI at the spatial filter output.

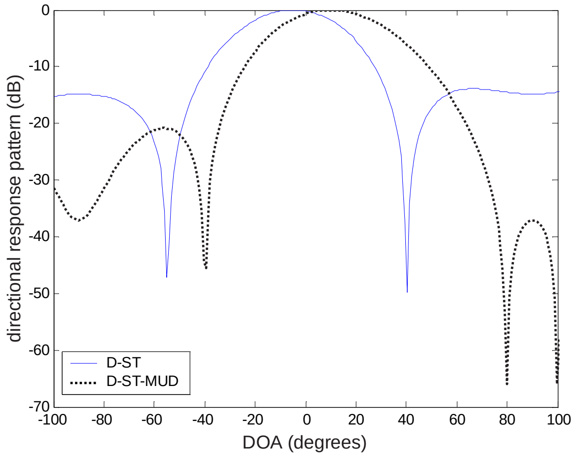

Fig. 3. Directional response pattern of the antenna array for D-ST-MUD and single-user D-ST receivers in scenario 1. 3-element antenna array

Now we consider the propagation scenario of Table II, where each user has two paths (zero-delayed and one-symbol-delayed). This is a scenario belonging to propagation situation (4), where the paths of desired and interferer users are spatially correlated (angular separation of 5 degrees for zero-delayed and one-symbol-delayed paths). Both receivers employ a 3-element antenna array.

Figure 4 shows that the D-ST-MUD receiver well preserves the zero-delayed and one-symbol delayed paths of both users (not only those from the desired one) as expected, accommodating them in the main lobe of the array pattern. The preserved paths will then be passed to the ML multi-user detector to be exploited in the temporal domain. The single-user D-ST receiver, in an attempt to null out the two interferer paths at -5 and 35 degrees, causes attenuations in the direction of the two desired paths that should be preserved for the MLSE equalizer. As a consequence of this undesirable attenuation, the SNR at the equalizer input will be low and the equalizer may not compensate for this loss of SNR. In this scenario, ML multi-user detection is a preferable solution to deal with CCI and ISI than spatial filtering.

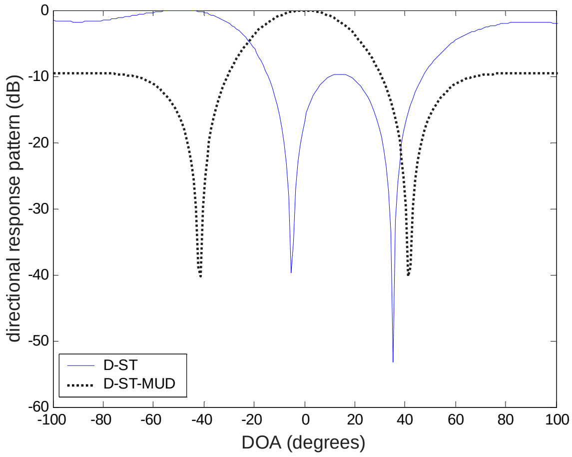

Fig. 4. Directional response pattern of the antenna array for D-ST-MUD and single-user D-ST receivers in scenario 2. 3-element antenna array

Now we evaluate the BER *versus* SNR performance of the proposed multi-user detector receiver in the presence of frequency-selective fading. As references for comparisons we consider two types of multi-user receiver structures. The first is a natural extension of the single-user D-ST receiver of Section III to the multi-user case. It consists of Q parallel single-user D-ST structures of Figure 1, each one supposed to detect one target user, considering the other $Q - 1$ users as interferers. We call this receiver "multi-user D-ST". The second one is a classical multi-user spatial processing receiver composed of a bank of Q MMSE spatial filters (see [11] and references therein). This receiver is called here "multi-user spatial". In our results, we also consider that these two conventional receivers may optionally employ serial interference subtraction.

We first consider the propagation scenario 1 (Table I). Figure 5 shows that the two conventional receivers with $M = 4$ receive antennas offer a very poor performance with a no BER improvement as SNR increases. In contrast, the D-ST-MUD receiver with just $M = 3$ antennas is largely superior and offers satisfactory performance. The faster decaying of the BER vs. SNR curve for the D-ST-MUD receiver indicates that it really has a higher diversity gain than the other ones. Such a diversity gain comes from temporal (path) diversity gain at the ML multi-user detector, which efficiently combines short-delayed paths of both users.

In Figure 6 the performance of the proposed D-ST-MUD receiver in scenario 2 (Table II) is shown. The multi-user D-ST and multi-user spatial employ $M = 4$ antennas and interference subtraction strategy is considered here. Perfect subtraction of interference is assumed. For the proposed receiver we have plotted its performance results considering $M = 3$ antennas. It can be seen that the multi-user spatial receiver has the worst performance. The multi-user D-ST offers some performance improvement over the first, due some path diversity gain at the MLSE equalizer. However, strong spatial correlation between the two pairs of desired and interferer paths still limits the performance of this receiver, explaining its slow BER improvement with SNR. In contrast, the proposed receiver with $M = 3$ offers a remarkable performance improvement over the two first ones due to efficient use of path diversity of both users. When interference subtraction is used, the two conventional multi-user receivers

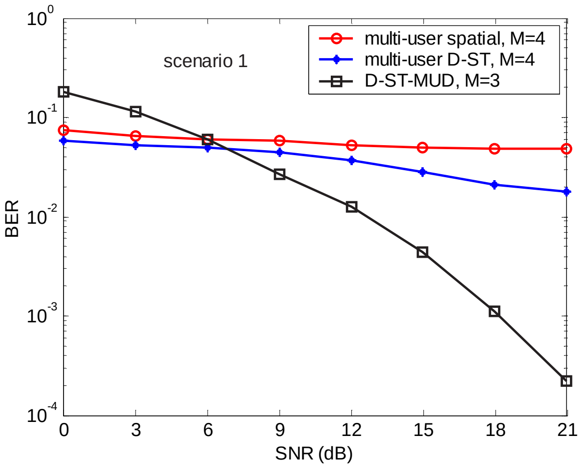

Fig. 5. BER performance of the D-ST-MUD receiver according to the SNR per receive antenna for scenario 1. As reference for comparisons, we plotted the performances of the multi-user extension of the conventional D-ST receiver and of the multi-user MMSE spatial receiver.

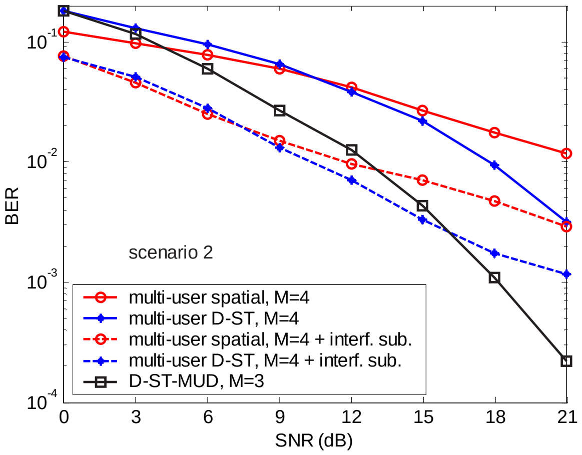

Fig. 6. BER performance of the D-ST-MUD receiver in scenario 2 with $M = 3$ antennas. The multi-user spatial and D-ST receivers employ $M = 4$ antennas and interference subtraction is considered.

exhibit an important performance improvement, being better than the D-ST-MUD at the low-to-medium SNR region. However, it is still clear that the BER of the proposed receiver decays faster with increasing SNR, thanks to the use of path diversity at the ML detector stage.

VI. CONCLUSIONS

In this paper a new space-time multi-user receiver with decoupled interference cancellation and multi-user detection has been proposed for wireless (mobile) communications. The proposed multi-user receiver utilizes spatial filtering for interference cancellation of long-delayed paths and maximum likelihood (ML) multi-user detection for joint demodulation of user signals based on short-delayed paths. This receiver has been called a *decoupled space-time multi-user detector* (D-ST-MUD).

The advantage of the D-ST-MUD receiver over the single-user D-ST one is its robustness to situations where the number of interference paths exceeds the degrees of freedom of the antenna array as well as situations where interference paths are spatially correlated with desired ones. In these situations, the joint use of spatial filtering and ML multi-user detection via decoupled processing is a promise solution that exploits path diversity of all users signals to obtain performance gains. The proposed receiver can be also seen as a low complexity ML multi-user detector, which is attractive from a computational point of view.

Computer simulation results assuming frequency-selective multipath fading scenarios were presented. It has been shown that the proposed D-ST-MUD receiver outperforms the multi-user version of the single-user D-ST receiver as well as the classical multi-user spatial detector, even with a smaller number of receive antennas.

The extension of the decoupled processing approach to multi-user multi-input multi-output (MIMO) antenna receivers is under development.

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