New Space Time coding for Joint Blind Channel Estimation and Data Detection through Time Varying MIMO Channels

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Abstract

Channel estimation based on a training sequence limits spectral efficiency. In this paper a new Orthogonal Space-Time Block Coder (OSTBC) is proposed for estimating an unknown Multiple Input Multiple Output (MIMO) channel without the need of a training sequence. Also, the orthogonal propriety of this code is taken into account to reduce the complexity of the maximum likelihood detector (MLD). Since the Steady State Kalman filter (SS-KF) has a lower complexity and nearly the same performance, compared to the standard Kalman Filter (KF), it is used to track the MIMO channel' variations.
The performance of the proposed coder is evaluated by means of Monte Carlo simulations and compared to that of optimal detection and some other coders proposed in the literature.

Keywords: *MIMO systems, Orthogonal Space-Time Block Codes, Steady State Kalman Filter, Maximum Likelihood Detector*.

1. Introduction

The demand of high data rates in wireless networks is continuously increasing. Multiple Input Multiple Output (MIMO) systems have been introduced as solution to rise up the spectral efficiency and capacity that this demand requires [1,2]. Space-time coding (STC) techniques can exploit spatial and temporal transmit diversity [3,6].
Among the existing space-time coding schemes, orthogonal space-time block codes (OSTBCs) [3,7] are of particular interest, because they achieve full diversity at a low receiver complexity. More specifically, the Maximum Likelihood (ML) receiver for OSTBCs consists of a linear receiver followed by a symbol-by-symbol decoder. In order to correctly decode the received signals, the ML decoder for OSTBCs must have perfect channel knowledge. Unfortunately, this channel information is usually not available to the receiver.

In a number of cases, the Channel State Information (CSI) can be estimated reliably by transmitting pilot signals [8,10]. However this results in a loss of spectral efficiency and capacity. To avoid this, there has been much interest in developing blind detection methods for space-time block codes [11,14]. In this work, we consider a "quasi-static" fading channel, where the channel is assumed to be static over multiple space-time code blocks but where pilot-assisted CSI acquisition is inefficient [15]. Blind detection methods may achieve near coherent detection performance, particularly when there is a sufficiently large data length, or number of blocks, in which quasi-static fading remains valid [15].

In [8] a cyclic minimization method for blind ML OSTBC detection is proposed. However, cyclic ML requires initialization of either the channel estimate or the symbol decisions. Simulation results revealed that the cyclic ML performance can be unsatisfactory given a mediocre initialization. A blind closed-form method to jointly estimate the channel and symbols was proposed by Stoica et al. [12] to initialize the cyclic ML. That blind closed-form method is also based on the special characteristics of OSTBCs. Interestingly, the closed-form method is functionally equivalent to the blind subspace OSTBC channel estimator in [15,16]

However, the channel may be time-varying due to the mobility of the transmitter and/or receiver, to changes in the environment, or to carrier frequency mismatch between the transmitter and the receiver. In these cases, the estimation algorithm must be able to track the channel variations. One of the most widely known approaches to channel tracking is Kalman filtering [10,17,20]. For example, a Kalman Filter (KF) is used to estimate channels in space-time trellis coded MIMO systems in [21]. The use of Kalman filter to estimate channels in space-time block coded systems is also proposed in the literature. In [17], a KF is used to estimate fast flat fading MIMO channels in Alamouti-based schemes. However, it is limited to the case of two transmit antennas. An extension of this work for any type of OSTBCs is

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presented in [20]. It is also shown in [20] that the KF can be significantly simplified due to the orthogonal propriety of OSTBC codewords. However to achieve this complexity reduction, it is assumed, both in [17] and [20], that the channel coefficients are uncorrelated. In [10] this assumption is disregarded and a reduced complexity Kalman Channel Estimator (KCE) is derived that works even in the case of correlated coefficients. Moreover a further reduction of the complexity is obtained by using the Steady State version of the KCE (SS-KCE). This is achieved without a noticeable degradation in the performance. This fact has also been discovered by Simon [18] who pointed out that the steady-state filter often performs nearly as well as the optimal time-varying filter.
In this paper a blind receiver, for a fast fading frequency-nonselective MIMO channel, is proposed. This receiver achieves joint blind channel estimation and data recovery by using the SS-KCE and a Reduced Complexity ML Detector (RCMLD). For this purpose a modified Alamouti OSTBC is proposed.
The remainder of the paper is organized as follows: In section II the proposed OSTBC is described. Section III presents an autoregressive model of the considered time varying MIMO channel. In section IV the proposed receiver structure, for joint blind channel estimation and sequence detection, is detailed. Simulation results are presented and discussed in section V. Finally, section VI concludes the paper.
In the following, the notations $(.)^{\mathcal{H}}$, $(.)^T$ and $(.)^*$ stand for conjugate transpose, transpose, and complex conjugate, respectively, $E\{.\}$ denotes the expectation, and $\otimes$ the Kronecker product.

2. The Proposed New OSTBC

We consider a MIMO system with two transmitting and two receiving antennas, $(N_T, N_R) = (2,2)$, sending at each time (k) a data block of length $T = 4$. The channel is assumed to be flat and constant during the transmission of each data block and can change between consecutive blocks. By using OSTBC with $(N_T, N_R) = (2,2)$ and ignoring the noise effect, it is very simple to obtain an estimation of the MIMO channel matrix. However, due to symmetry, the solution is not unique. So, as illustrated in Figure 1, a new OSTBC, based on the Alamouti one [3], is proposed in order to eliminate the ambiguity in the channel matrix estimation.
The k^{th} block delivered by the new coder is composed of two codewords. The first one is a simple Alamouti OSTBC and the second codeword is an Alamouti's OSTBC multiplied by a phase factor, p_k. This phase factor avoids the problem of equidistance (ambiguity) during the channel estimation process. It is chosen as $p_k = exp(j\varphi_k)$, where φ_k belongs to a predetermined set of size 2^m, m being the number of constellation points. φ_k depends on the pair $\begin{bmatrix} s_{k,1} \\ s_{k,2} \end{bmatrix}$, $s_{k,1}$ being the first symbol of block (k) and $s_{k,2}$ the second one. The proper choice of p_k will be discussed in section IV.

According to [4] and [7], this code is orthogonal, since:

$$S^{(k)} \times S^{(k)\mathcal{H}} = \alpha_k \times I_{N_T},$$

With $\alpha_k = \|s_{k,1}\|^2 + \|s_{k,2}\|^2 + \|s_{k,3}\|^2 + \|s_{k,4}\|^2$,

I_{N_T} being the identity matrix and $S^{(k)}$ defined as:

$$S^{(k)} = \begin{bmatrix} s_{k,1} & -s_{k,2}{}^* & p_k \times s_{k,3} & -p_k \times s_{k,4}{}^* \\ s_{k,2} & s_{k,1}{}^* & p_k \times s_{k,4} & p_k \times s_{k,3}{}^* \end{bmatrix} \quad (1)$$

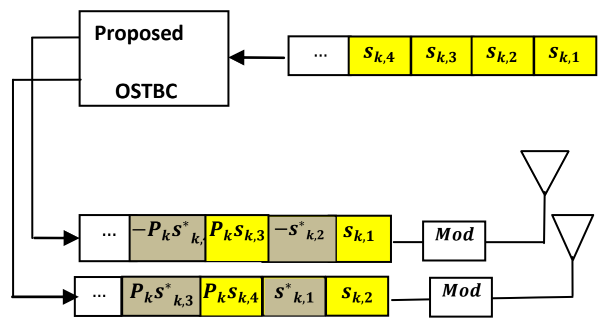

Fig. 1 Proposed Orthogonal Space-Time Coding.

3. Channel Model

In this work consider a frequency-flat fading channel is considered. It is also assume that the channel is invariant during the transmission of a space-time codeword block, but can change between consecutive ones.

As in [20,21], the MIMO channel variations are approximated by a first order AR process. The time evolution of the channel is thus expressed by:

$$h^{(k)} = Fh^{(k-1)} + Aw^{(k)}, \quad (2)$$

Where $h^{(k)} = vec(H^{(k)})$, $vec(.)$ being the operator that stacks the columns of a matrix on top of each other, $H^{(k)}$, called the channel matrix, is defined as:

$$H^{(k)} = \begin{pmatrix} {h_{11}}^{(k)} & \cdots & {h_{1N_T}}^{(k)} \\ \vdots & \ddots & \vdots \\ {h_{N_R1}}^{(k)} & \cdots & {h_{N_RN_T}}^{(k)} \end{pmatrix},$$

and $w^{(k)}$ is a vector of length $N_R \times N_T$ containing independent samples of circularly symmetric, zero-mean, Gaussian noise with covariance matrix $R_w = I_{N_RN_T}$. According to the widely used Wide-Sense Stationary Uncorrelated Scattering (WSSUS) model [22], the channel coefficients are modeled as independent, zero-mean, complex Gaussian random variables, with a time autocorrelation matrix given by:

$$E\left[h^{(k)}h^{(k+1)^{\mathcal{H}}}\right] \approx F^{\mathcal{H}} \quad , \qquad (3)$$

Where $F = \beta I_{N_RN_T}$ is a transition diagonal matrix, with coefficient $\beta = J_0(2\pi f_D T_s)$, J_0 being the zero-order Bessel function of the first kind, $f_D T_s$ the normalized Doppler rate (assumed to be the same for all transmitting-receiving antenna pairs), and T_s the baud duration [23].

From Eq.(2) it can be seen that the rate of the channel variations is fixed by the transition matrix F. The amplitude of all channel's coefficients $h^{(k)}$ is controlled by the diagonal matrix A. To ensure that the correlation matrix of $h^{(k)}$ is unitary, matrix A should be taken as $A = \sqrt{1-\beta^2} I_{N_RN_T}$ [24].
The speed of channel variations, quantified by β in Eq.(3), depends on the Doppler shift or, equivalently, the relative velocity between the N_T transmitting and the N_R receiving antennas. The greater the value of $f_D T_s$ (the smaller the value of β) the faster are the channel variations.

4. Data Recovery

The proposed blind receiver structure, for a fast fading frequency-nonselective MIMO channel, is shown in Fig. 2 Besides the demodulators; it consists mainly of three blocks: an initial channel estimator, a SS-KF channel tracker and a RMLD. The first block is run only for the first data bloc. The second and third blocks are run sequentially for each data bloc. The SS-KF serves to track the variations of the channels coefficients, which are used by the RMLD to recover the transmitted data.

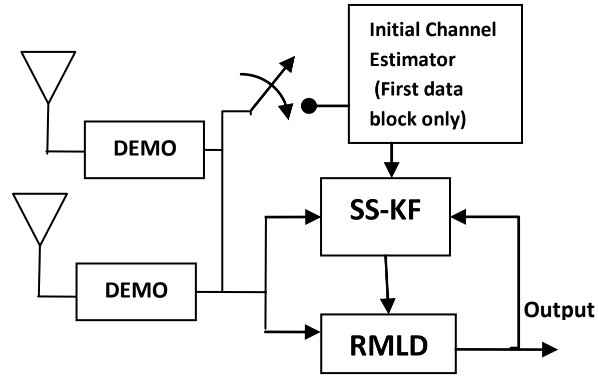

Fig. 2 Proposed receiver for a time varying MIMO Channel.

The relationship between transmitted and received signals for a data block (k) can be expressed as [8].

$$Y^{(k)} = H^{(k)}S^{(k)} + N^{(k)} \, , \qquad (4)$$

Where $Y^{(k)}$ is 2×4 matrix

$$Y^{(k)} = \begin{bmatrix} y_{k,11} & y_{k,12} & y_{k,13} & y_{k,14} \\ y_{k,21} & y_{k,22} & y_{k,23} & y_{k,24} \end{bmatrix} = [Y_1^{(k)}\ Y_2^{(k)}],$$

$y_{k,jn}$ being the channel output of antenna j at slot time n of time block k, $j = 1,2$ and $n = 1,..,4$.

Where $S^{(k)}$, defined in Eq.(1), is a 2×4 matrix containing the transmitted symbols of block (k), the 2×4 matrix $N^{(k)}$ contains samples of independent, zero mean, circularly symmetric, white Gaussian noise with covariance σ_n^2, and $H^{(k)}$ represents the 2×2 channel matrix. In space-time block coding, the matrix $S^{(k)}$ represents a transformation block of complex symbols $[s_{k,1}\ s_{k,2} \ldots s_{k,4}]$.

The space-time codeword $S^{(k)}$ is then used to transmit these $M = 4$ symbols in $T = 4$ time slots, achieving a rate of M/T.

4.1 Initial Channel Estimation

To obtain an initial estimate of the channel matrix we use the first received data block $(k = 1)$. Neglecting the noise effect, all possible channel matrix estimates can be obtained by using the signals received during the first two time slots $n = 1,2$:

$$\widehat{H}_\ell = \begin{bmatrix} \hat{\mathrm{h}}_{11\,\ell} & \hat{\mathrm{h}}_{12\,\ell} \\ \hat{\mathrm{h}}_{21\,\ell} & \hat{\mathrm{h}}_{22\,\ell} \end{bmatrix} \Big/ (\|\mathrm{s}_{\ell 1}\|^2 + \|\mathrm{s}_{\ell 2}\|^2) \qquad (5)$$

$$\hat{h}_{11\,\ell} = [s_{\ell 1}^* y_{1,11} - s_{\ell 2} y_{1,12}]$$
$$\hat{h}_{12\,\ell} = [s_{\ell 2}^* y_{1,11} + s_{\ell 1} y_{1,12}]$$
$$\hat{h}_{21\,\ell} = [s_{\ell 1}^* y_{1,21} - s_{\ell 2} y_{1,22}]$$
$$\hat{h}_{22\,\ell} = [s_{\ell 2}^* y_{1,21} + s_{\ell 1} y_{1,22}]$$

Where $\{s_{\ell 1}, s_{\ell 2}\} \in \{G\}$, with $\{G\}$ being the m points constellation set, and $\ell = 1, \ldots, 2^m$.

To select the appropriate channel matrix and the corresponding sequence, one may use the criterion:

$$< \widehat{H}^{(1)}, \hat{S}_1^{\ (1)} >= argmin_{(\widehat{H}_\ell, S_\ell)} \left\| Y_1^{(1)} - \widehat{H}_\ell S_\ell \right\|^2, \qquad (6)$$

With: $S_\ell = \begin{bmatrix} s_{\ell,1} & -s_{\ell,2}^{\ *} \\ s_{\ell,2} & s_{\ell,1}^{\ *} \end{bmatrix}$.

However, due to symmetry, the solution is not unique. To get the right solution, we propose to apply this criterion to the second received block $Y_2^{(1)} = \begin{bmatrix} y_{1,13} & y_{1,14} \\ y_{1,23} & y_{1,24} \end{bmatrix}$:

$$< \widehat{H}^{(1)}, \hat{S}_2^{\ (1)} >= argmin_{(\widehat{H}_\ell, B_{\ell,q})} \left\| Y_2^{(1)} - \widehat{H}_\ell B_{\ell,q} \right\|^2 , \qquad (7)$$

$$B_{\ell,q} = \begin{bmatrix} p_\ell s_{q,3} & -p_\ell s_{q,4}^{\ *} \\ p_\ell s_{q,4} & p_\ell s_{q,3}^{\ *} \end{bmatrix}.$$

Having determined the indices ℓ and q that minimize Eq.(7) one can get an initial estimate, $\widehat{H}^{(1)}$, of the channel matrix and estimates of the symbols $[s_{1,1}, s_{1,2}]$, and $[s_{1,3}\ s_{1,4}]$.
To guarantee the uniqueness of the solution of Eq.(7), the factors p_ℓ should be chosen such that:

$$\left\| \widehat{H}_\ell B_{\ell,q} - \widehat{H}_r B_{r,q} \right\|^2 > 0 \ \ \text{, for } \ell \neq r \qquad (8)$$

4.2 Channel Tracking

Channel tracking may be formulated as a state estimation problem. So we need to define the two equations, named the process and the measurement equations, respectively [18,25,26]. The process equation describes the dynamic behavior of the state variables to be estimated, while the measurement equation represents the relationship between the state variables and the observed system output. Since in our case we are interested in channel tracking, Eq.(2) may be considered as the process equation, with $h^{(k)}$ as the state vector. The system output, in our case, is the channel output $Y^{(k)}$ in Eq.(4). By stacking the columns of matrices $Y^{(k)}$, $H^{(k)}$ and $N^{(k)}$ in Eq.(4), the following measurement equation can be obtained:

$$y^{(k)} = \mathcal{S}^{(k)} h^{(k)} + n^{(k)} \ , \qquad (9)$$

Where $\mathcal{S}^{(k)} = S^{(k)^T} \otimes I_{N_R}$ and $R_n = \sigma_n^2 I$ is the covariance matrix of the measurement noise $n^{(k)}$.
Eq.(2) and Eq.(9) represent then the state-space formulation of the problem of estimating flat, time-varying MIMO channels. As both of these equations are linear functions of the state vector $h^{(k)}$ and the noises $w^{(k)}$ and $n^{(k)}$ are independent, white and Gaussian, the Kalman filter provides the optimal recursive estimates, in the MMSE sense, for the channel coefficients [18,24]. The SS-KF proposed by [10] is used in the present work to track the channel variations, since it performs nearly as well as the optimal time-varying one, with a reduced complexity. In this filter, the channel coefficients are updated by using the following equations.

$$\hat{h}_{k/k} = \beta B_\infty \hat{h}_{k-1/k-1} + \frac{1}{\alpha_k} A_\infty \mathcal{S}^{(k)^{\mathcal{H}}} y^{(k)} \ , \qquad (10)$$

Where:

$$A_\infty = P_\infty \left(\frac{\sigma_n^2}{\alpha_k} I_{N_R N_T} + P_\infty \right)^{-1}$$

$$B_\infty = I_{N_R N_T} - A_\infty$$

The steady-state value of the estimation error covariance matrix P_∞ may be obtained by solving the following discrete algebraic Riccati equation (DARE) [18, 24].

$$P_\infty = \beta^2 P_\infty - \beta^2 P_\infty \left(P_\infty + \frac{\sigma_n^2}{n_s} I_{N_R N_T} \right)^{-1} P_\infty + \sigma_w^2 I_{N_R N_T} \ , \qquad (11)$$

Where n_s corresponds to the energy of each encoded data block, assumed to be a constant.

4.3 Reduced Maximum Likelihood Detector (RMLD)

The MLD is an optimum detector in the sense that it minimizes the probability of error. Since the additive noise terms at the N_R receiving antennas are statistically independent and identically distributed (*i,i,d*), zero mean

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Gaussian random variables, the joint conditional probability density function $p(Y^{(k)}/S^{(k)})$ is Gaussian. Therefore The MLD selects the symbol vector $S^{(k)}$ that minimizes the Euclidean distance metric [27]:

$$\mu(S) = \sum_{j=1}^{N_R} \left| y_j^{(n)} - \sum_{i=1}^{N_T} h_{ji}{}^{(n)} s^{(n)} \right|^2 , \qquad (12)$$

Where $y_j^{(k)}$ is the output of the channel at the received antenna j, at time (n).

In our case, the maximum-likelihood detector for OSTBC [28] yields the decoupled estimates $\hat{s}_{k,1}$ and $\hat{s}_{k,2}$, obtained from the following equation:

$$\begin{bmatrix} \hat{s}_{k,1} \\ \hat{s}_{k,2} \end{bmatrix} = \begin{bmatrix} \hat{h}_{11}^* & \hat{h}_{21}^* & \hat{h}_{12} & \hat{h}_{22} \\ \hat{h}_{12}^* & \hat{h}_{22}^* & -\hat{h}_{11} & -\hat{h}_{21} \end{bmatrix} \times [y_{k,11} \quad y_{k,21} \quad y_{k,12}{}^* \quad y_{k,22}{}^*]^T, \qquad (13)$$

From these estimates we can deduce p_k in order to get estimates $\begin{bmatrix} \hat{s}_{k,3} \\ \hat{s}_{k,4} \end{bmatrix}$:

$$\begin{bmatrix} \hat{s}_{k,3} \\ \hat{s}_{k,4} \end{bmatrix} = p_k^{-1} \times \begin{bmatrix} \hat{h}_{11}^* & \hat{h}_{21}^* & \hat{h}_{12} & \hat{h}_{22} \\ \hat{h}_{12}^* & \hat{h}_{22}^* & -\hat{h}_{11} & -\hat{h}_{21} \end{bmatrix} \times [y_{k,13} \quad y_{k,23} \quad y_{k,14}{}^* \quad y_{k,24}{}^*]^T, \qquad (14)$$

5. Simulation Results

In this section, we present some simulation results to illustrate the performance of the proposed data recovery and channel estimation algorithm. In all simulations presented in this section, a block of $n = 512$ BPSK information symbols was transmitted, using the predetermined group for $p_k = exp(j\varphi_k), \varphi_k \in \left\{0, \frac{\pi}{3}, \frac{\pi}{2}, \frac{2\pi}{3}\right\}$, through a (2,2) Rayleigh flat fading MIMO channel, with different values of $f_D T_s$. The results averaged over 10.000 Monte Carlo runs are presented in Figures 3 to 7. Figure 3 presents the Bit Error Rates (BER) of the proposed blind algorithm, the coherent detector and the semi blind detector, using the RMLD, for $f_D T_s = 0.0015$. The performances of the proposed blind receiver, for different values of the parameter $f_D T_s$, are presented in Figure 4. It can be observed from this Figure that the performance does not depend on this parameter for a low SNR, and that for a high SNR the performance degrades as this parameter increases. Figure 5 shows that the SS-KF manages to well track the channel coefficients, for $f_D T_s = 0.0025$ and SNR = 20 dB. The results presented so far were obtained by assuming that the channel coefficients are uncorrelated, however, spatial correlation between transmit and/or receive antennas usually exists in practical scenarios [29]. This can occur, for instance, if the separation of adjacent antennas is not sufficient [10]. The proposed receiver works even when the channel coefficients are correlated as illustrated in Figure 6, where it is shown that the results obtained with an uncorrelated coefficients channel are approximately the same as those obtained with $R_T{}^{1/2} = [1 \ 0.4; 0.4 \ 1]$ as correlation matrix for the transmitted antennas and $R_R{}^{1/2} = [1\ 0; 0\ 1]$ as correlation matrix for the received antennas.
Finally, from Figure 7 it can be seen that the proposed blind receiver outperforms other blind receivers, from the specialized literature [11,12,30,31].

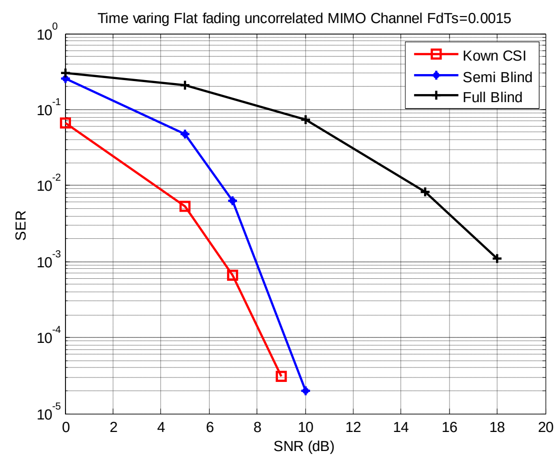

Fig.3 Performance of the RMLD with known channel, using known CSI, semi blind detection and the proposed blind algorithm, for $f_D T_s = 0.0015$.

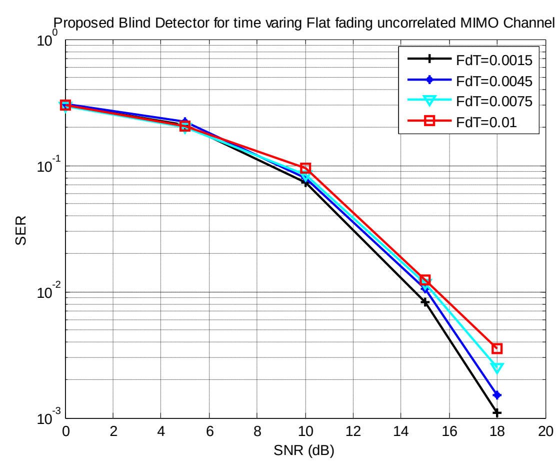

Fig. 4 The Performance of the proposed blind algorithm for different values of $f_D T_s$.

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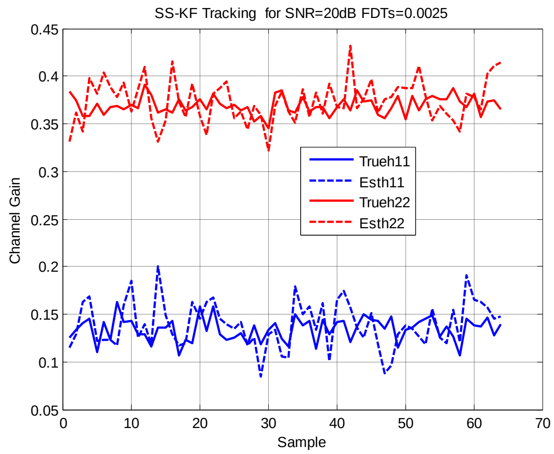

Fig.5 Tracking of channel coefficients h_{11} and h_{22} with SS-KF, for $RSB = 20\ dB$ and $f_D T_S = 0.0025$.

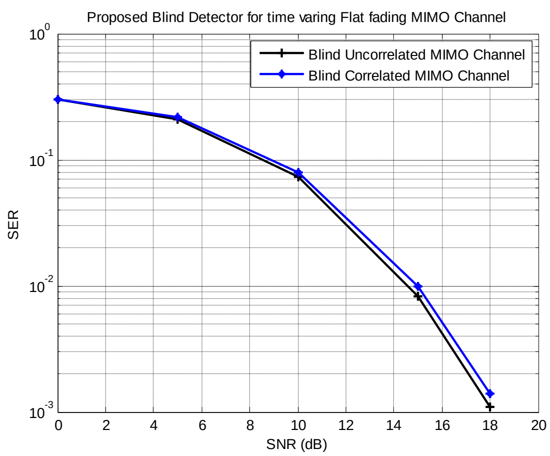

Fig.6 Performance of the proposed blind algorithm with correlated and uncorrelated time selective channels, for $f_D T_s = 0.0015$.

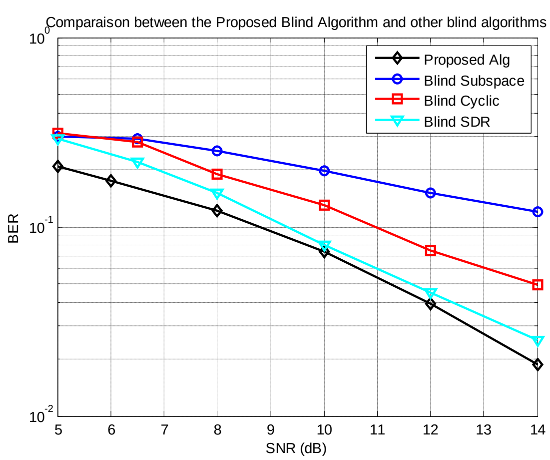

Fig.7: Comparison between the proposed algorithm and different other blind algorithms, using BPSK over a time selective channel with $f_D T_s = 0.02$.

Conclusion

In this paper, a blind receiver for spatial multiplex MIMO channels is proposed. It combines the SS-KF and the MLD to jointly estimate the coefficients of a Rayleigh flat-fading channel and the transmitted data.

A new modified Alamouti OSTBC is proposed for a proper initialization of the SS-KF. The orthogonal propriety of this coder allows reducing the complexity of the ML detector. The choice of the SS-KF for tracking the channel coefficients contributes to a further reduction of the receiver complexity.

Simulation results show that our proposed reduced complexity blind receiver achieves better performance than other blind receivers proposed in the literature. It has also the advantage of working even if the channel coefficients are correlated.

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