Performance of Space-Time Processing Receivers for MIMO Antenna Systems

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Abstract – In this work we assess performance of multiple-input multiple-output (MIMO) antenna systems with space-time processing over a frequency-selective channel in presence of time-dispersive co-channel interference. We evaluate the performance of the conventional MIMO-decision-feedback equalizer (MIMO-DFE) receiver and also propose a low complexity receiver, based on the decoupled interference cancelling principle with a delayed decision-feedback sequence estimator (DDFSE) for equalization [7]. The proposed receiver, called decoupled interference cancelling MIMO-DDFSE (DIC-MIMO-DDFSE), shows satisfactory performance, outperforming the MIMO-DFE on an interference-limited scenario.

1 Introduction

Multiple-input-multiple-output channels are known for some time to offer very high spectral efficiencies and unprecedented data rates achieved on a wireless environment [1]. The V-BLAST architecture [2] is a well known application for the narrowband TDMA system. In current cellular (mobile) communication systems, the frequency-selectivity of the wireless channel and the presence of strong co-channel interference place a significant challenge to MIMO antenna systems. Thus, the use of MIMO space-time processing techniques has attracted significant attention of the researches. Recently, different receiver structures to cope with the frequency-selectivity of the wireless channel have been evaluated [3, 4]. However, most of the works have not considered the presence of co-channel interference (CCI), which may not be realistic in mobile communication systems.

In this work we assess performance of MIMO antenna systems over frequency-selective channels in presence of time-dispersive interference. Receiver space-time processing is used in order to effectively suppress intersymbol interference (ISI) and to provide more degrees of freedom to suppress multiple access interference (MAI), which is defined here as the sum of self interference between different data substreams and CCI due to frequency spectrum reuse. We evaluate the performance of the conventional MIMO-DFE receiver and propose a low complexity interference cancelling receiver, based on a delayed decision-feedback sequence estimator (DDFSE) [5]. The main idea behind the proposed receiver is to enhance the tasks of MAI and ISI suppression, while avoiding higher computational complexity. Essentially, the proposed receiver employs linear space-time processing at the front-end, primarily for MAI minimization. Following the front-end processing, separate non-linear temporal processing based on decision-feedback and maximum likelihood sequence detection is used to effectively suppress ISI. The proposed receiver, called decoupled interference cancelling MIMO-DDFSE (DIC-MIMO-DDFSE), shows satisfactory performance, outperforming the MIMO-DFE on interference-limited scenarios.

This paper is organized as follows. Channel and system-model is established on Section II. The two considered space-time receivers are formulated in section III. In section IV numerical results are presented. Finally section V presents the conclusions of this work.

2 Channel and System Models

A high-level system block diagram is shown in Fig. 1 in its equivalent baseband model, concerning a single-user link. All transmitters (1 to M) operate co-channel at the same symbol rate with synchronized symbol timing. Transmission data is split into M sub-streams and independently transmitted by transmit antennas 1 to M. The total transmitted power P_T is fixed and normalized to P_T/M. At the receiver side, each antenna element receives a superposition of faded versions of all M transmitted substreams. The N-element receive array ($N \geq M$) is connected to a signal processing block for the recovery of each data sub-stream. After detection, the data sub-streams are re-ordered and converted to the serial unique stream that constitutes the estimated transmitted data. We can represent the discrete-time channel impulse response from the transmit antenna m to the receiving antenna n as follows

$$\mathbf{h}_{nm} = [h_{nm}(0)\; h_{nm}(1)\; \ldots\; h_{nm}(L)]^T, \tag{1}$$

where $L+1$ is the number of taps in the channel impulse response. the space-time channel matrix for m-th transmit antenna is obtained by assembling the $\mathbf{h}_{nm}$ vectors into an $N \times (L+1)$ matrix as follows

$$\mathbf{H}_m = [\mathbf{h}_{1m}\, \mathbf{h}_{2m}\, \ldots\, \mathbf{h}_{Nm}]^T, \tag{2}$$

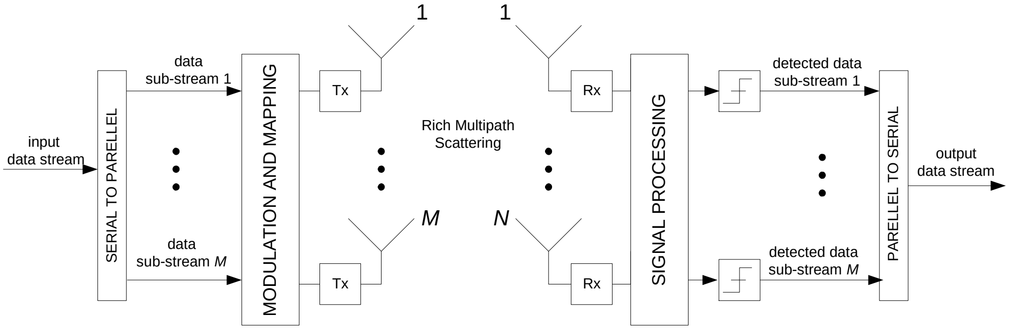

FIG. 1: Block diagram of a MIMO antena system.

where $m = 1, 2, \ldots, M$. Thus, the N-dimensional received signal vector $\mathbf{x}(k)$ can be expressed as

$$\mathbf{x}(k) = \sum_{m=1}^{M} \mathbf{H}_m \mathbf{s}_m(k) + \mathbf{n}(k), \tag{3}$$

with the $L+1$ sequence of symbols transmitted by the m-th antenna denoted by

$$\mathbf{s}_m(k) = [s_m(k)\, s_m(k-1) \,\ldots\, s_m(k-L)]^T. \tag{4}$$

The $N \times 1$ vector $\mathbf{n}(k)$ denotes the temporally and spatially additive white Gaussian noise (AWGN).

3 Space-Time Receivers

3.1 MIMO-DFE

The MIMO-DFE [6] is shown in Fig. 2. It consists of a bank of M linear space-time feedfoward filters $\mathbf{w}_m$ of N branches and $K_f + 1$ taps per branch, followed by M multiple-input-single-output (MISO) feedback filters $\mathbf{b}_m$ of K_b taps. In the detection of a particular substream, the MISO feedback filter is used to subtract interference due to other substreams by assuming that the training or the decision-directed sequence from all transmitted substreams are available at all detection branches. In this work we consider the parallel interference cancelling (PIC) approach, where all M sub-streams are simultaneously detected. The N-dimensional received signal vector can be stacked up into an $N(K_f+1) \times 1$ equivalent representation as follows

$$\mathbf{x}'(k) = [\mathbf{x}^T(k)\, \mathbf{x}^T(k-1) \,\ldots\, \mathbf{x}^T(k-K_f)]^T, \tag{5}$$

so that the signal vector at the input of the feedfoward filter can be written as

$$\mathbf{x}'(k) = \sum_{m=1}^{M} \mathcal{H}_m \mathbf{s}'_m(k) + \mathbf{n}(k), \tag{6}$$

where

$$\mathbf{s}'_m(k) = [s_m(k)\, s_m(k-1) \,\ldots\, s_m(k-L-K_f)]^T, \tag{7}$$

is the extended sequence of symbols from the m-th transmit antenna and

$$\mathcal{H}_m = \begin{bmatrix} \mathbf{H}_m & 0 & \ldots & 0 \\ 0 & \mathbf{H}_m & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \ldots & 0 & \mathbf{H}_m \end{bmatrix}, \tag{8}$$

is a block Toeplitz matrix with $N(K_f+1) \times 1$ rows and $L + K_f + 1$ columns. The sequence of K_b most recent decisions produced by every detection branch is given by

$$\widehat{\mathbf{s}}_m(k-\delta-1) = [s_m(k-\delta-1) \,\ldots\, s_m(k-\delta-K_b)]^T, \tag{9}$$

where the parameter δ denotes the detection delay, which will be assumed identical for all detection branches. At time instant k, the m-th output signal $y_m(k)$ of the the MIMO-DFE is expressed as follows

$$y_m(k) = \mathbf{w}_m^H \mathbf{x}'(k) - \mathbf{b}_m^H \widehat{\mathbf{s}}(k-\delta-1), \tag{10}$$

with $\mathbf{w}_m^H$ and $\mathbf{b}_m^H$ being $N(K_f+1) \times 1$ and $K_b \times 1$ vectors, respectively. The MMSE solution for the MIMO-DFE is similar to that of a classical DFE (see [3]).

On frequency-selective propagation scenarios, the feedfoward and feedback filters of the MIMO-DFE must minimize MAI and equalize ISI. In severe ISI channels with a limited number of receive antennas, insufficient degrees of freedom of the space-time front-end may cause error propagation and degrade performance, requiring a large number of receive antenas and time taps to cope with such worst-case situations.

3.2 DIC-MIMO-DDFSE

In this work we present a low complexity MIMO receiver, called decoupled interference canceller MIMO-DDFSE (DIC-MIMO-DDFSE). The receiver structure, depicted in Fig. 3, is based on a maximum signal-to-interference-plus-noise (MSINR) criterion. Each space-time feedfoward filter for a particular substream is optimized to maximize its post-detection SINR, thus minimizing interference originated from the other substreams as well as interference from co-channel users. Following each space-time filter, a prefiltered DDFSE equalizer is employed to effectively suppress ISI. Therefore, this receiver "decouples" the tasks of MAI and ISI minimization in two processing stages. The decoupled processing concept with DDFSE equalization has been applied in [7] for separate CCI and ISI suppression with multiple receive antenas under the EDGE context. We derive the solution for the detection branch associated to transmit antena 1. The solution for the other detection branches is similar. The output signal $y_1(k)$ can be interpreted as the sum of a desired and an error component as follows

$$y_1(k) = \mathbf{w}_1^H \mathbf{x}'(k) = \mathbf{g}_1^H \mathbf{s}'_1(k) + e_1(k), \tag{11}$$

where $\mathbf{g}_1$ is the overall channel impulse response at the output of the space-time interference cancelling filter for transmit antenna 1 and

$$e_1(k) = \sum_{m=2}^{M} \mathbf{g}_m^H \mathbf{x}'(k) + \mathbf{w}_1^H \mathbf{n}(k), \qquad (12)$$

is an error signal accounting for residual interference plus filtered noise. In our signal model we assume that $\mathbf{g}_1$ and $e_1(k)$ are uncorrelated processes. We adopt the following cost function to be optimized [8]

$$\mathrm{SINR}_1 = \frac{E\{|\mathbf{g}^H \mathbf{s}'_1(k)|^2\}}{E\{e_1(k)e_1^*(k)\}}. \qquad (13)$$

This cost function represents the equalization SINR. We want to determine the best solution for vector $\mathbf{g}_1$ such that a temporal equivalent of the space-time ISI channel is maximized over interference plus noise. The maximization of (13) is equivalent to the minimization of its denominator subject to a constraint imposed on $\mathbf{g}_1$. We select the constraint $\mathbf{g}_1^H \mathbf{g}_1 = 1$ and define the equivalent MMSE cost function as

$$J_1(\mathbf{w}_1, \mathbf{g}_1) = E\{|\mathbf{w}_1^H \mathbf{x}'(k) - \mathbf{g}_1^H \mathbf{s}'_1(k)|^2\}. \qquad (14)$$

It is shown in [9] that the solution of the above equation is easily obtained from a generalized eigenvalue problem to the following error covariance matrix

$$\mathbf{R}_{ee} = \mathbf{R}_{ss} - \mathbf{R}_{xs}^H \mathbf{R}_{xx}^{-1} \mathbf{R}_{xs}. \qquad (15)$$

The optimum channel impulse response $\mathbf{g}_{opt}$ for a particular detection branch is given by is the minimum eigenvector to $\mathbf{R}_{ee}$ and the optimum coefficients for the space-time interference cancelling filter are given by

$$\mathbf{w}_{opt} = (\mathbf{R}_{xx})^{-1} \mathbf{R}_{xs}\, \mathbf{g}_{opt}. \qquad (16)$$

Given that the error signal $e_m(k)$, $m = 1, 2 \ldots M$ is sufficiently small, the M DDFSEs can operate independently. This means that, for each transmitted sub-stream, the maximum likelihood sequence estimation (MLSE) portion of DDFSE does not deal with channel state information associated to other sub-streams, resulting in a scalar DDFSE for detection of each sub-stream. As a consequence, the complexity of the sequence detector is only linear on the number of transmit antenas. The prefilters prior to DDFSE are used to whiten the temporally-colored noise due to space-time filtering as well as to provide a minimum-phase channel for the DDFSE. In this work we consider a feedfoward filter of the classical DFE as the prefilter. The overall channel impulse response $\mathbf{g}$ is employed to directly calculate the coefficients of the prefilter and those of the feedback filter of the DDFSE. In [10], a similar optimization criterion for the receiver and prefilter structures is developed.

4 Numerical Results

The performance of MIMO-DFE and DIC-MIMO-DDFSE are compared by means of numerical simulations. First, performance is evaluated on a pure ISI scenario. The frequency-selective channel follows a two-ray Rayleigh fading model. The channel impulse response taps are generated as complex zero-mean uncorrelated Gaussian random variables. We consider two degrees of channel frequency-selectivity, say $\tau = 0.25$T (less distortive) and $\tau =$T (highly distortive), where τ is the time-delay of the second path and T is the symbol period. In order to simplify comparisons, we assume perfect channel knowledge for both receivers.

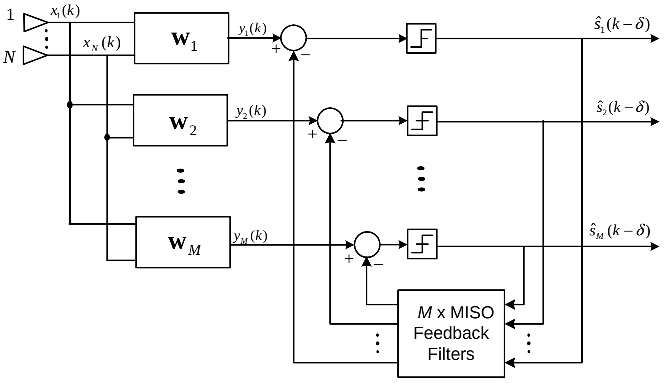

FIG. 2: MIMO-DFE structure.

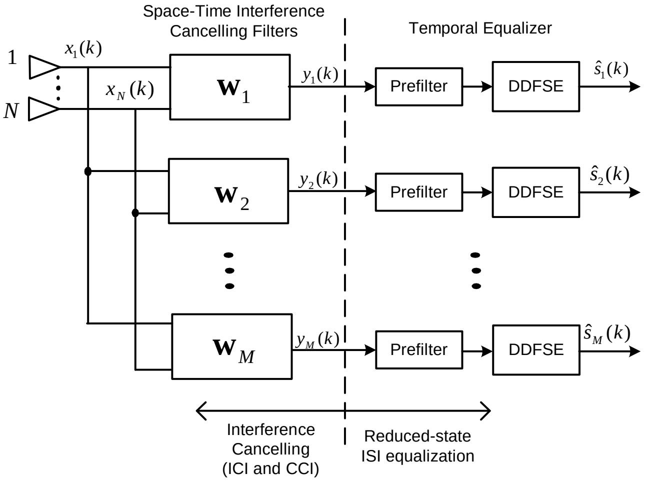

FIG. 3: DIC-MIMO-DDFSE structure.

Figure 4 depicts the bit-error-rate (BER) as a function of the input SNR. It is observed that the MIMO-DFE performs better than the DIC-MIMO-DDFSE when ISI delay spread is low. An inversion in the performances is observed for the worst-case, where the proposed receiver exhibits exhibits the best result. Note that the performance degradation of DIC-MIMO-DDFSE due to increased ISI is not significant as it is for the MIMO-DFE. This is explained by the fact that the DIC-MIMO-DDFSE treats the MAI in the spatial-domain and ISI in the temporal-domain, making a better use of path diversity to suppress ISI. The MIMO-DFE receiver attempts to cancel MAI also in the temporal-domain by means of decision-feedback and error propagation is determinant for the performance lost of MIMO-DFE against the DIC-MIMO-DDFSE.

Now we consider the presence of a time-dispersive single-antenna co-channel user with $\tau =$T. The SNR is

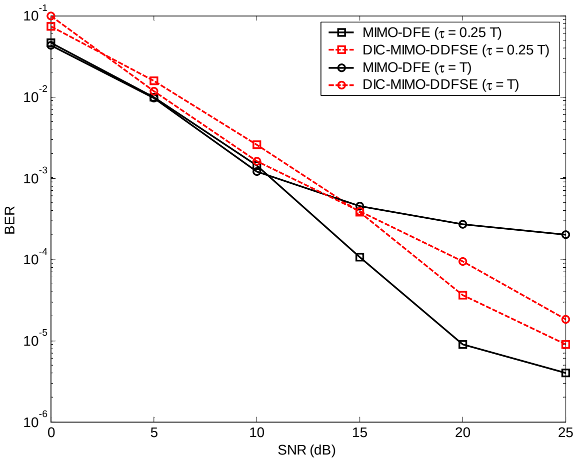

FIG. 4: Numerical results for MIMO-DFE and DIC-MIMO-DDFSE over time-dispersive channels with $\tau = 0.25$T and $\tau =$T.

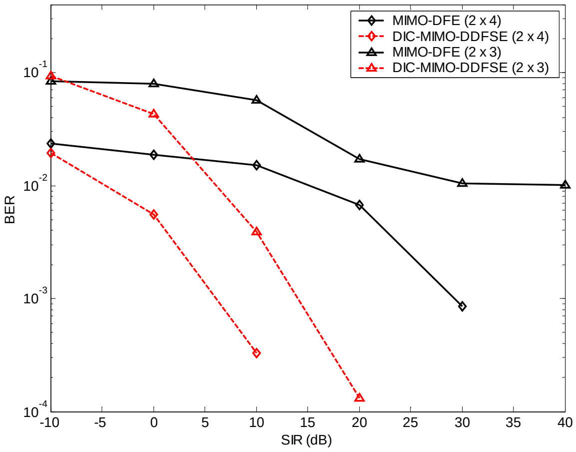

FIG. 5: Performance of MIMO-DFE and DIC-MIMO-DDFSE as a function of the SIR of a single co-channel user.

fixed at 40dB and the SIR is varied from -10 to 40dB. We also consider two $M \times N$ system configurations. The parameters of the feedfoward and feedback filters of MIMO-DFE are $K_f + 1 = 5$ and $K_b = 3$, respectively. For the DIC-MIMO-DDFSE, pure spatial front-end filters $(K_f + 1 = 1)$ are employed and the DDFSE is characterized by $\mu = 1$ and $K_b - \mu = 1$. For the 2×4 case, it is observed in Fig. 5 that the BER of the MIMO-DFE decrease at a slower pace than that of the DIC-MIMO-DDFSE. For the 2×3 case, the performance of MIMO-DFE saturates at around 1% BER while the performance of the DIC-MIMO-DDFSE exhibits the same improvement with SIR, indicating that the MAI and ISI are effectively suppressed. Note that the 2×3 DIC-MIMO-DDFSE outperforms the 2×4 MIMO-DFE for most of the SIR range.

5 Conclusions

In this work, we have evaluated the performance of MIMO antenna systems with space-time processing receivers. We developed a decoupled interference cancelling receiver to enhance performance of MIMO receivers on interference-limited frequency-selective channels. The proposed DIC-MIMO-DDFSE demonstrated excellent results on a severe ISI channel with time-dispersive MAI, outperforming the MIMO-DFE. Further comparisons between both receivers should take into account the successive interference detection technique.

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