Interference Cancellation Receiver for Multiple-Access Space-Time Block-Coded Systems over Frequency Selective Channels

Walter Freitas Jr., Rodrigo Cavalcanti and André de Almeida

Abstract— **Transmit diversity schemes have emerged in wireless systems as an attractive solution to obtain diversity gains at the mobile terminals. An efficient way of achieving transmit diversity is the use of space-time block-coding (STBC). In high-data rate mobile communication systems with tight reuse configurations, inter-symbol interference (ISI) as well as co-channel interference (CCI) due to user multiple access must be considered in the design of STBC systems. In this work we propose an effective receiver structure for multiple-access space-time block-coded systems capable of performing CCI cancellation and ISI equalization in a two-stage approach. The receiver is based on a cascade connection of i) a multiple-input- multiple-output (MIMO) minimum mean square error (MMSE) spatial filter for CCI cancellation, ii) a modified space-time decoder and iii) a non-linear sequence-detector equalizer for ISI equalization. The non-linear equalizer is a prefiltered delayed decision-feedback sequence estimator (DDFSE). Simulation results demonstrate that the proposed receiver offers remarkable results while being interference-resistant and having a reduced complexity detector.**

Index Terms— **Space-time codes, MIMO, ISI and CCI**

I. Introduction

Multiple-input multiple-output (MIMO) wireless channels are known for some time to offer better link and/or capacity gains, which can be exploited by employing antenna arrays at both ends of the link [1]. An efficient way of exploiting the MIMO channel is the use of spatial multiplexing or V-BLAST (Vertical Bell Labs Layered Space-Time) that aims at providing higher data rates with no sacrifice in bandwidth [2]. Another approach that benefits from exploiting the MIMO channel is the use transmit diversity by means of space-time block-coding [3], [4], [5] where the idea is to obtain diversity and coding gains at the receiver with simple linear processing. In mobile communication systems, STBC is being considered as an attractive solution to provide diversity gain on downlink, i.e., at the mobile terminal.

In [3] a remarkable STBC scheme was proposed, denoted here by Alamouti's STBC, or simply ASTBC, for transmission with two antennas over flat fading channels. Due to the very simple structure of ASTBC, a modified version of this STBC is considered in UMTS standards. In [4], Tarokh proposed new STBC schemes with more than two transmit antennas. The STBC schemes developed in these works are valid under the assumption of a flat-fading channel only. However, in high-data rate wireless communications systems the channel is frequency-selective and the orthogonality between the transmitted symbols that is needed for this schemes to work does not hold. In [6], ASTBC transmission was generalized for channels with inter-symbol interference (ISI), where the transmitted signals are coded on a block-by-block basis instead of a symbol-by symbol basis. This scheme has been called time-reversal STBC (TR-STBC).

The spectral bandwidth is an expensive and limited resource. Therefore, such resource is shared among several users and this sharing leads to multiple access interference. It is known that one of the limiting factors in mobile communication links is co-channel interference (CCI) caused by user multiple access. The use of adaptive antenna array processing at the receiver is the classical solution to combat CCI signals and obtain diversity gains, thus increasing the capacity [7]. In [8] an STBC scheme with interference suppression was proposed. In [9] an adaptive CCI cancellation strategy in STBC systems was presented. However, these works have assumed flat-Rayleigh fading channels. The design of STBC schemes in upcoming mobile communications systems should take into account the presence of both ISI and CCI. In [10] we proposed an effective space-time receiver strategy for ISI/CCI suppression with a single transmit antenna. In this work we propose another effective receiver structure for STBC systems capable of performing co-channel interference cancellation and inter-symbol interference equalization in a two-stage approach. The proposed receiver is a generalization of those presented in [9], [10] to cope with both ISI and CCI in a multiple-access system. The receiver is based on a minimum mean square error (MMSE) filtering for CCI cancellation and a modified space-time decoder that is connected to a non-linear equalizer for ISI equalization. The non-linear equalizer is a prefiltered delayed decision-feedback sequence estimator (DDFSE) [11]. The proposed receiver has shown to be interference-resistant and yet reduced-complexity with excellent results.

The remainder of this paper is organized as follows. We first describe the system model. Afterwards, we formulate the proposed STBC receiver. Then, link performance results are shown by means of computer simulations. The paper finishes with some conclusions.

II. System Model

A high-level block diagram of a space-time coding system with two transmit antennas and N receive antennas denoted

The authors are with the Wireless Telecom Research Group (GTEL), Fortaleza-CE, Brazil, emails:{walter,rodrigo,andre}@gtel.ufc.br

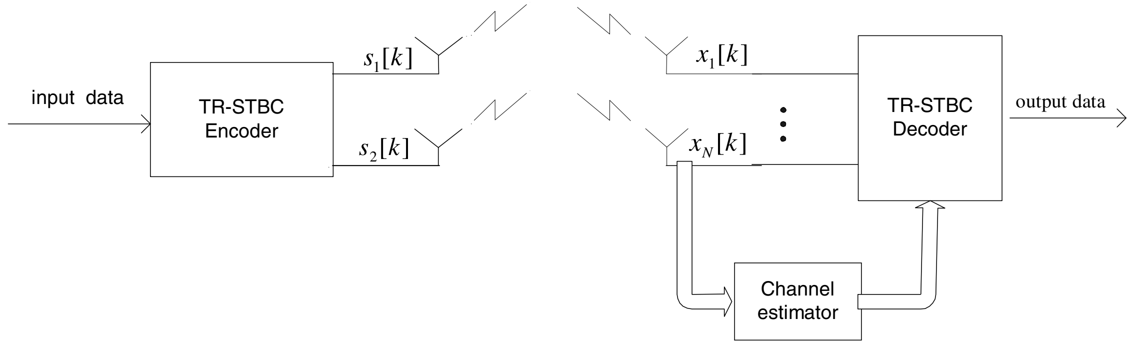

Fig. 1. Conventional TR-STBC scheme for ISI channels.

generically as (2Tx-NRx) is shown in Fig. 1, where TR-STBC is employed. The transmission data is split into two sub-streams and encoded by the TR-STBC encoder. Each code symbol is transmitted, simultaneously, from a different antenna. These code symbols are designed to maximize the diversity gain at the receiver under the assumption of a flat or frequency-selective channel. The received signals undergo independent fading so that the signal at each of the N receive antennas is a superposition of delayed and faded versions of the two transmitted signals plus noise.

We assume that the total transmitted power is fixed and normalized to 1. Ideal symbol timing is assumed. We assume that the channel impulse response has length L and that the fading is quasi-static. In other words, the channel matrix $\mathbf{H}$ is randomly generated, but remains constant during the transmission of one space-time code word. A new random channel matrix, independent of the previous one, is then generated for each new space-time code word. For the sake of simplicity we consider a single space-time coded co-channel interferer. At any time-instant k, the received signal vector on the MIMO-MMSE spatial filter can be expressed as

$$\mathbf{x}[k] = \mathbf{H} \cdot \mathbf{s}[k] + \mathbf{G} \cdot \mathbf{z}[k] + \mathbf{n}[k], \tag{1}$$

where $\mathbf{H} = [\ \mathbf{H}^{(1)} \quad \mathbf{H}^{(2)}\ ]$ and $\mathbf{s}[k] = [\ \mathbf{s}_1^T[k] \quad \mathbf{s}_2^T[k]\ ]^T$ have length $N \times 2L$ and $2L \times 1$, representing the space-time coded matrix channel and the space-time coded symbol vector, respectively. The matrix $\mathbf{G}$ and the vector $\mathbf{z}$ are similarly defined for co-channel interferer signal. The $N \times 1$ vector $\mathbf{n}[k]$ is an additive white Gaussian noise (AWGN).

III. Multiple-Access and Inter-symbol Interference Cancellation Approaches

We propose a novel interference-resistant and reduced-complexity space-time block-coded receiver for MIMO antenna systems over frequency-selective channels. The proposed receiver (Fig. 3) is compared here to the one presented in [9] (Fig. 2), designed for flat-fading channels. Both approaches follow the same criterion for CCI cancellation. The most important difference is that the proposed one is capable of performing both co-channel interference cancellation and inter-symbol interference equalization. This is achieved by employing TR-STBC scheme in conjunction with a DDFSE equalizer, as shown in Fig. 3. The MIMO-MMSE spatial filter is designed to minimize CCI signals only, while preserving the space-time structure of the space-time code. At the output of the MIMO-MMSE spatial filter, the channel-modified matched filter recovers the transmitted sequence that is still corrupted by ISI. Then, a prefiltered DDFSE performs ISI equalization and produces decisions on the original sequence.

At any time-instant k, the output signal vector of the MIMO-MMSE spatial filter can be expressed as

$$\mathbf{y}[k] = \mathbf{W}^H \cdot \mathbf{x}[k], \tag{2}$$

$\mathbf{W} = [\ \mathbf{w}_1 \quad \mathbf{w}_2 \ldots \mathbf{w}_N\ ]$ with $\mathbf{w}_n = [\ w_1 \quad w_2 \ldots w_N\ ]^T$, $1 \le n \le N$ is an $N \times N$ matrix for the coefficients of the spatial filter. The error signal is formed from the difference between the output of the spatial filter and a target signal that is composed of the desired transmitted sequence convolved with the desired matrix channel impulse response as

$$\mathbf{e}[k] = \mathbf{W}^H \cdot \mathbf{x}[k] - \mathbf{H} \cdot \mathbf{s}[k] = \mathbf{W}^H \cdot \mathbf{x}[k] - \mathbf{x}_0[k], \tag{3}$$

where $\mathbf{x}_0[k] = \mathbf{H} \cdot \mathbf{s}[k]$. Thus, the MMSE cost function is expressed as follows

$$J = E\{\|\mathbf{W}^H \cdot \mathbf{x}[k] - \mathbf{x}_0[k]\|^2\}. \tag{4}$$

The optimal weights are found by minimizing the above cost function. The solution is given by

$$\mathbf{W} = \mathbf{R}_{\mathrm{xx}}^{-1}\mathbf{R}_{\mathrm{xx}_0}, \tag{5}$$

where $\mathbf{R}_{\mathrm{xx}} = E\{\mathbf{x}[k]\mathbf{x}^H[k]\}$ is the input covariance matrix while $\mathbf{R}_{\mathrm{xx}_0} = E\{\mathbf{x}[k]\mathbf{x}_0^H[k]\}$ is a cross-correlation matrix where the desired signal is represented by $\mathrm{x}_0[k]$. The coefficients of the MIMO-MMSE spatial filter can be computed adaptively by using classical adaptive algorithms such as the recursive least squares (RLS) [9]. Without loss of generality in this work we assume perfect channel state information at the receiver. Assuming CCI signal is minimized, the output signal of the MIMO-MMSE spatial filter can be written as

$$\mathbf{y}[k] = \mathbf{H}^{'} \cdot \mathbf{s}[k] + \mathbf{n}^{'}[k], \tag{6}$$

where $\mathbf{H}^{'} = \mathbf{W}^H\mathbf{H}$ is the modified matrix channel consisting of the spatial filter weights combined with the original matrix channel. This modified channel represents the effective channel that is fed to the TR-STBC decoder. The term $\mathbf{n}^{'}[k]$ is an additive spatially colored Gaussian noise vector with covariance matrix $\mathbf{R}_{\mathrm{n}'\mathrm{n}'} = \sigma^2\mathbf{W}^H\mathbf{W}$. The performance of the receiver can be maximized by taking $\mathbf{R}_{\mathrm{n}'\mathrm{n}'}$ into account in the metric computations of the Viterbi algorithm in the

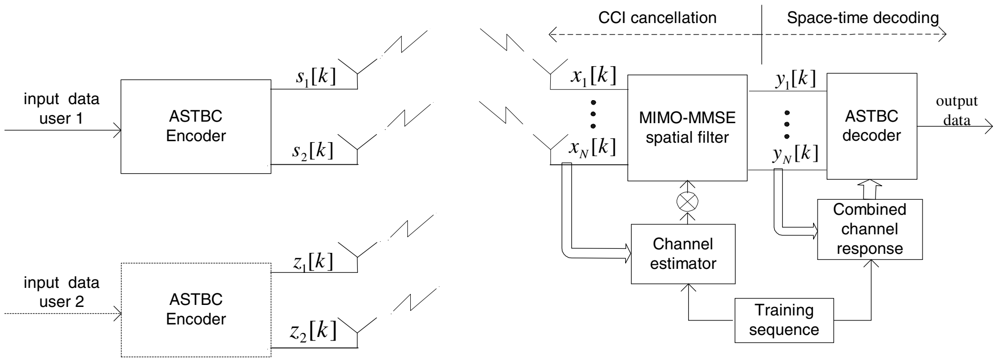

Fig. 2. STBC receiver for CCI cancellation in flat fading channels.

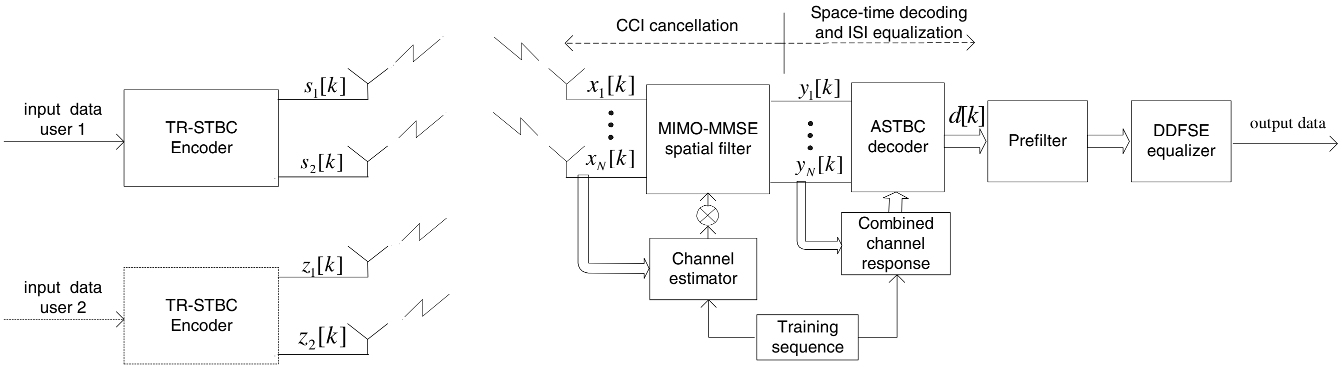

Fig. 3. The proposed receiver with combined interference cancellation and ISI equalization.

MLSE [9], at the expense of the an increased computational complexity. The receiver process is based on the assumption of orthogonality of the modified channel matrix $\mathbf{H}^{'}$. Therefore, we can express the output of the channel-modified matched filter as

$$\mathbf{d}[k] = \mathbf{H}^{'H} \cdot \mathbf{y}[k]. \quad (7)$$

The signal vector $\mathbf{d}[k]$ goes to the prefilter that is used to provide a minimum-phase channel impulse response to the DDFSE equalizer. In this work we employ the feedforward filter of an MMSE decision-feedback equalizer (DFE) as the prefilter while the feedback filter is used to cancel the tail of the ISI in the DDFSE. It can be seen that the proposed receiver is a combination of the TR-STBC scheme shown in Fig. 1 and the one shown in Fig. 2, with the addition of a DDFSE equalizer. Therefore we will include the schemes of Fig. 1 and Fig. 2 as a reference of comparison in the following section.

Delayed-decision feedback sequence estimator (DDFSE) is a sequence detector equalizer that couples a maximum likelihood sequence estimation (MLSE) with a decision feedback filter. The use of the feedback filter is to shorten the channel impulse response memory at the input of the MLSE so that the number of trellis states can be reduced decreasing the complexity. The use of suboptimal DDFSE in place of MLSE is particularly important an in high-data rate systems with higher-order modulation, where the use of a full MLSE becomes impractical due to its large trellis complexity.

Here, we employ a prefiltered DDFSE at the output of the modified space-time decoder. The prefilter works as a sort of pre-equalizer, the function of which is to whiten the colored signal produced at ASTBC decoder output as well as to concentrate the ISI energy within the minimum number of channel taps, simplifying the DDFSE. The prefilter coefficients are directly calculated from the combined channel response, according to the solution for the feedforward filter of a MMSE decision feedback equalizer (DFE). The choice of a prefiltered DDFSE for the proposed interference cancellation receiver is motivated by the good performance-complexity trade-off that it offers.

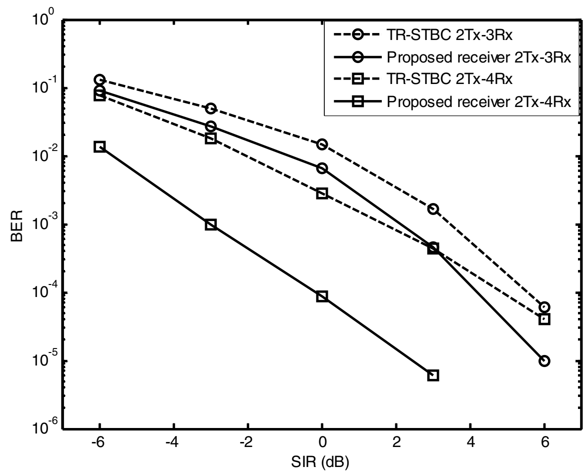

Fig. 4. BER performance of the proposed interference cancellation receiver, compared to that of conventional TR-STBC as a function of the SIR.

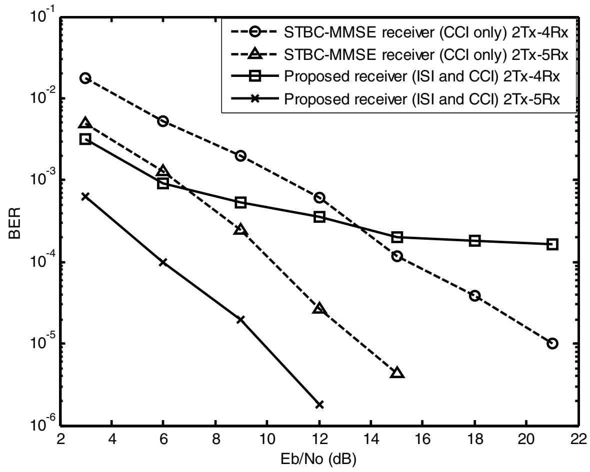

Fig. 5. BER performance of the proposed interference cancellation receiver under CCI and ISI compared to that of STBC-MMSE receiver in the absence of ISI.

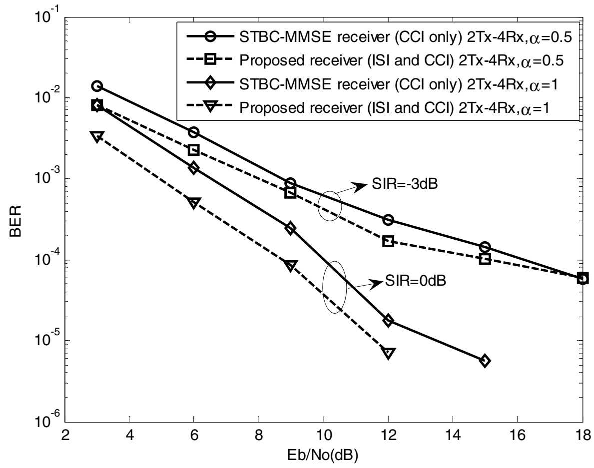

Fig. 6. BER performance for the 2-ray channel, varying the gain of the one-symbol delayed path (α), SIR=0 and -3dB.

IV. Simulation Results and Conclusions

The performance of the proposed receiver is illustrated in this section by means of Monte Carlo simulations. We employ binary phase-shift keying (BPSK) modulated symbols and each run represents a transmitted time-slot of 140 payload symbols. For simplicity, we assume a single space-time coded co-channel interferer in the system.

Figure 4 shows the bit-error-rate (BER) performance of the proposed receiver as compared to the conventional TR-STBC scheme, in the absence of noise. The BER results are plotted according to the signal-to-interference-ratio (SIR) for the 2Tx-3Rx and the 2Tx-4Rx configurations. The proposed receiver shows superior performance considering in this interference-limited scenario, especially in the 2Tx-4Rx case, where it exhibits remarkable performance gains over all the simulated SIR range.

In Fig. 5 the performance of the proposed receiver under CCI and ISI is compared with that of Fig. 2 with no ISI (called here STBC-MMSE). In this case, 2Tx-4Rx and the 2Tx-5Rx configurations are employed. Two equal power-users under the same channel/fading conditions are considered. The ISI model is based on a two-ray propagation model. A prefilter with memory equals to 5 is employed. For the 2Tx-4Rx case, the proposed receiver presents the best results for low to medium $\mathrm{Eb/No}$ range. Some error floor is observed for large $\mathrm{Eb/No}$ values. This is due to sub-optimality of the prefilter/DDFSE part. We highlight, however, that such BER floor disappears as the memory of the prefilter is reduced while increasing the memory of the MLSE part. Our focus however is on the design of low complexity detectors and this comes with a price. For the 2Tx-5Rx case, the proposed receiver provides significant gains. These results show that, in addition to space diversity provided by the space-time code, the proposed interference cancellation receiver benefits from the path diversity available at the received signal to increase the diversity order and to cancel CCI signals, resulting in a superior performance.

Remark 1: For the proposed receiver, there is a performance-complexity tradeoff that depends on the memory of the prefilter. Such parameter defines the delayed paths that will be considered as interferer (which should be canceled in the spatial domain) as well as those of the desired user that will be combined in the MLSE part. Large prefilters and a DDFSE with small feedback, provide increased performance at the expense of an increased complexity.

In order to evaluate the path diversity gain offered by the DDFSE sequence detector of the proposed receiver, we consider the 2-ray channel profile and vary the gain of the second (one-symbol-delayed) path, i.e. $\alpha = 1$ (equal power paths) and $\alpha = 0.5$. We assume $N = 4$, with SIR=0 and -3dB. It can be verified from Fig. 6, that an increased path diversity gain is achieved for $\alpha = 1$. This confirms that our equalizer effectively combines the two paths of the desired user. This gain is smaller when SIR=-3dB, possibly, due to residual interference at the equalizer input.

Finally, we focus attention on more realistic propagation scenarios for performance evaluation. The COST207 Typical Urban (TU) and Hilly Terrain (HT) propagation models are now considered. For the TU case, the channel impulse response has length $L = 5$ while for HT we set $L = 8$. Figure 7 shows satisfactory performance of the proposed receiver, specially for the TU case. The performance degradation in the HT case is expected, since it is more frequency-selective than TU. We have observed that long delayed multipaths present in the HT case are not effectively handled by our 5-tap prefilter, which would need much more taps to effectively shorten the channel for the DDFSE. This is possibly one reason for such performance degradation.

We have proposed a new interference cancellation receiver for STBC systems, based on a MIMO-MMSE spatial filter for CCI cancellation and a modified space-time decoder connected to a prefiltered DDFSE equalizer for ISI equalization. The BER performance of the proposed receiver under ISI and CCI was compared to that of two other conventional STBC systems by means of computer simulations. The results indicated that this new STBC receiver is capable of minimizing space-time block-coded multiple-access interference, while extracting the spatial/path diversity gains of the space-time

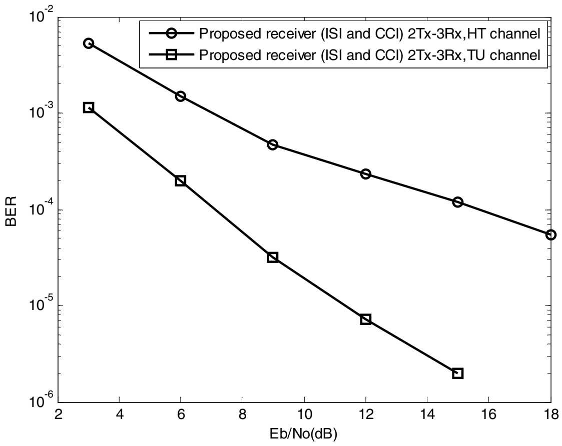

Fig. 7. BER performance as a function of the input Eb/No for COST207 TU and HT propagation models.

code. We have also evaluated the proposed receiver in hybrid MIMO transceiver structures (HMTS) [12]. In HMTS, we consider layers in a parallel way using STBC and V-BLAST so that parts of the data are space-time coded across some antennas, and these parts are combined in layers, using a V-BLAST approach. Since the spatially-multiplexed layers see each other as interferers, similar strategy employed in this paper is interesting to be considered. With this idea, HMTS arises as a solution to jointly achieve spatial multiplexing and diversity gains similar to the idea presented in [13].

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