A Two-Stage Receiver for Co-channel Interference Cancellation in Space-Time Block-Coded Systems over Frequency Selective Channels

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***Abstract*— In this work we propose a new receiver structure for space-time block-coded systems that decouples the tasks of CCI cancellation and space-time decoding in two processing stages. The two-stage receiver consists of a multiple-input multiple-output (MIMO) minimum mean square error (MMSE) spatial filter for CCI cancellation connected to a modified time-reversal space-time decoder that is matched to the combined response of the channel of the desired user plus the MIMO-MMSE filter. A prefiltered MLSE detector is used for equalization. The two-stage receiver is compared to the one proposed in [10] for flat-fading channels. We show via computer simulation that the two-stage receiver effectively cancels CCI signals and still provides transmit diversity gain under frequency-selective fading.**

***Keywords*— STBC, CCI, ISI, wireless communications**

I. Introduction

Multiple-input multiple-output (MIMO) wireless channels are known 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]–[5] where the idea is to obtain diversity and coding gains at the receiver with simplified processing. In mobile communication systems, STBC is being considered as an attractive solution to provide diversity gain on downlink path, i.e., at the mobile terminal.

In [3], a very simple STBC scheme was proposed, denoted here by Alamouti's STBC or simply ASTBC, for transmission with two antennas over flat fading channels. In [4], Tarokh proposed new STBC schemes for 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 likely to be frequency-selective and the orthogonality between the transmitted symbols that is needed for this schemes to work does not hold. In [6], Lindskog and Paulraj generalized the ASTBC 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). In [7], the TR-STBC was evaluated under the physical layer of the Enhanced Data Rates for Global Evolution (EDGE).

It is known that one of the limiting factors in mobile communication links is co-channel interference (CCI). The use of spatial processing at the receiver is the classical solution to combat CCI signals and obtain diversity gains, thus increasing system capacity [8]. In [9], an STBC scheme with interference suppression was proposed. More recently, an adaptive CCI cancellation strategy employing the ASTBC scheme was proposed in [10]. However, all of these works have assumed flat-Rayleigh fading channels in the design of the receivers. It is known that receiver design for upcoming mobile communications systems such as EDGE should take into account the presence of both ISI and CCI. In [11] and [12] we proposed a decoupled space-time receiver strategy for CCI and ISI suppression in the reverse link of EDGE for a single transmit antenna.

Here, we propose a new receiver structure for space-time block-coded systems that decouples the tasks of CCI cancellation and space-time decoding in two processing stages. The two-stage receiver consists of a multiple-input multiple-output (MIMO) minimum mean square error (MMSE) spatial filter for CCI cancellation connected to a modified TR-STBC decoder that is matched to the combined response of the channel of the desired user plus the MIMO-MMSE filter. A prefiltered MLSE equalizer is used for signal detection. This receiver is a refinement of those presented in [10]–[12] to a TR-STBC system with ISI and CCI. We show via computer simulation that the two-stage receiver effectively cancels CCI signals and still provides transmit diversity gain under frequency-selective fading.

The remainder of this paper is organized as follows. Section II describes the system model. In Section III, we formulate the two-stage receiver. In Section IV, the performance of the two-stage receiver is shown via computer simulation results. In Section V, we evaluate the performance of the new receiver under the EDGE system context. The conclusions are presented in Section VI.

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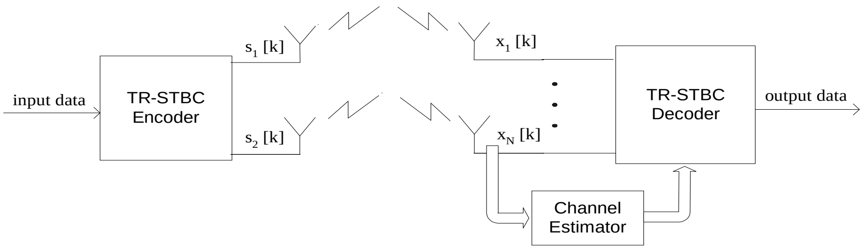

Fig. 1. System model for space-time coding employing the TR-STBC scheme, suitable for frequency-selective channels.

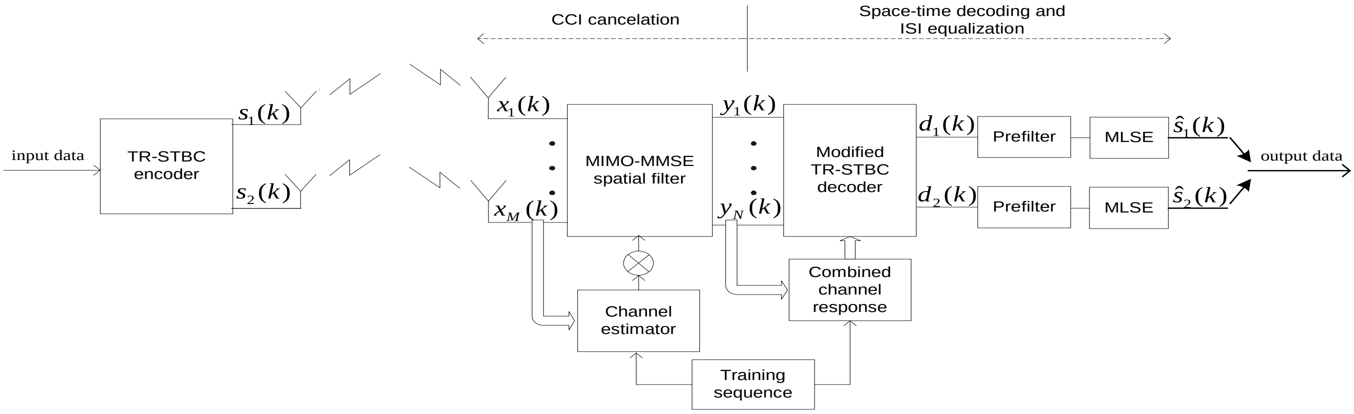

Fig. 2. Structure of the Two-Stage receiver with CCI cancellation, TR-STBC decoding and ISI equalization over frequency-selective channels.

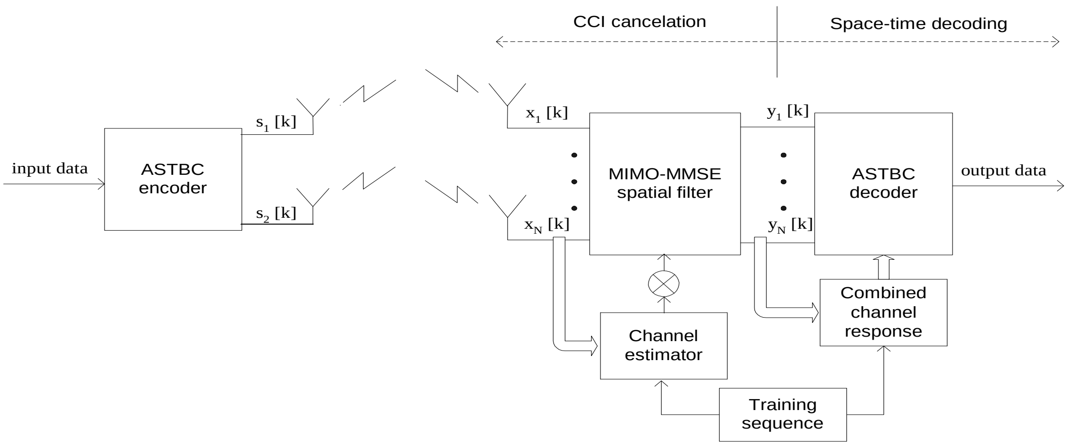

Fig. 3. Structure of the STBC receiver proposed in [10] for CCI cancellation over flat fading channels.

II. SYSTEM MODEL

A high-level block diagram of a space-time coding system with 2 transmit antennas and M receive antennas 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 M 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 also consider that the channel impulse response has length L and that the fading is quasi-static. For the sake of simplicity we consider a single space-time coded co-channel interferer. At any time-instant k, the received signal can be expressed as

$$\mathbf{x}(k) = \mathbf{H}\mathbf{s}(k) + \mathbf{G}\mathbf{z}(k) + \mathbf{n}(k) \quad (1)$$

where $\mathbf{H} = [\mathbf{H}_1 \;\; \mathbf{H}_2]$ and $\mathbf{s}(k) = [\mathbf{s}_1^T(k) \;\; \mathbf{s}_2^T(k)]^T$ have length $M \times 2L$ 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 $\mathbf{z}(k)$ are similarly defined for the co-channel interferer. The $M \times 1$ vector $\mathbf{n}(k)$ is an additive white Gaussian noise (AWGN).

III. Two-Stage Receiver

The two-stage receiver is shown in Fig. 2. It consists of a multiple-input multiple-output (MIMO) minimum mean square error (MMSE) spatial filter connected to a modified TR-STBC decoder and a prefiltered MLSE equalizer. The MIMO-MMSE filter should employ all its degrees of freedom to cancel CCI signals, preserving the space-time structure of the space-time block-code at its output signal. After the MIMO-MMSE filter, the modified TR-STBC decoder employs a modified channel impulse response to extract transmit diversity from the received signal. The modified TR-STBC decoder has this denomination because it is matched to the original space-time channel of the desired user modified by the coefficients of the MIMO-MMSE spatial filter. At the output of the decoder, prefilters are used to reshape the channel impulse response to a desired number of taps such that the complexity of the MLSE equalizer is reduced. Assuming that CCI is sufficiently minimized by the MIMO-MMSE filter, the orthogonality of the space-time code still holds and independent MLSE equalizers can be used to individually detect the transmitted sequences.

The proposed receiver is compared here to the one presented in [10] (Fig. 3), designed for flat-fading channels. Both receivers follow the same optimization criterion for CCI cancellation. The main difference is that the proposed one is designed to perform CCI cancellation under the assumption of a frequency-selective channel, thus offering the possibility of exploiting the channel impulse response to provide path diversity in addition to space diversity. At any time-instant k, the *m*th output signal of the MIMO-MMSE spatial filter is given by

$$y_m(k) = \mathbf{w}_m^H \mathbf{x}(k), \quad 1 \leq m \leq M \tag{2}$$

where the vector $\mathbf{W}_m = [w_{m,1} w_{m,2} \dots w_{m,M}]^T$ denotes the coefficients of the *m*th spatial filter. An error vector is formed from the difference between the output of the MIMO-MMSE filter and a target signal as

$$\mathbf{e}(k) = \mathbf{W}^H \mathbf{x}(k) - \mathbf{H}\mathbf{s}(k) = \mathbf{W}^H \mathbf{x}(k) - \mathbf{x}_d(k) \tag{3}$$

where $\mathbf{x}_d(k) = \mathbf{H}\mathbf{s}(k)$ represents the desired transmitted sequence at instant k convolved with the desired channel impulse response and $\mathbf{W} = [\mathbf{w}_1\, \mathbf{w}_2\, \dots\, \mathbf{w}_M]$. Thus, the MMSE cost function is expressed as follows

$$J = E\{\|\mathbf{W}^H \mathbf{x}(k) - \mathbf{x}_d(k)\|^2\}. \tag{4}$$

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

$$\mathbf{W} = \mathbf{R}_{\mathbf{xx}}^{-1} \mathbf{R}_{\mathbf{xx}_d} \tag{5}$$

where $\mathbf{R}_{\mathbf{xx}} = E\{\mathbf{x}(k)\mathbf{x}^H(k)\}$ is the input covariance matrix while $\mathbf{R}_{\mathbf{xx}_d} = E\{\mathbf{x}(k)\mathbf{x}_d^H(k)\}$ is a cross-correlation matrix where the desired signal is represented by $\mathbf{x}_d(k)$. The coefficients of the MIMO-MMSE spatial filter can be computed adaptively using classical adaptive algorithms such as the recursive least squares (RLS) [10]. In this work we focus on the optimized performance of the considered receivers, assuming perfect channel knowledge at the receiver.

Assuming residual CCI signal is negligible, the output signal of the MIMO-MMSE spatial filter can be written as

$$\mathbf{y}(k) = \mathbf{H}_d\, \mathbf{s}(k) + \mathbf{n}^{'}(k) \tag{6}$$

where $\mathbf{H}_d = \mathbf{W}^H \mathbf{H}$ is the modified channel matrix consisting of the original space-time coded channel combined by the coefficients of the MIMO-MMSE filter. This modified channel represents the effective channel that is handled by the TR-STBC decoder and can be interpreted as a *virtual* channel from the 2 transmit antennas to the M outputs of the MIMO-MMSE filter. The term $\mathbf{n}^{'}(k)$ is a spatially-colored noise vector containing filtered Gaussian noise and residual CCI, and its covariance matrix is $\mathbf{R}_{\mathbf{n}'\mathbf{n}'} = \sigma^2_{\mathbf{n}'} \mathbf{W}^H \mathbf{W}$. Since the modified TR-STBC decoder is matched to $\mathbf{H}_d$, its coefficients are given by $\widetilde{\mathbf{H}}_d^*$, i.e., a time-reversed complex-conjugated version of the desired space-time coded channel matrix $\mathbf{H}_d$. Each output signal of the TR-STBC decoder $d_1(k)$ and $d_2(k)$ should contain the ISI structure associated to the transmitted substreams $\mathbf{s}_1(k)$ and $\mathbf{s}_1(k)$ that are estimated by the MLSE equalizers, respectively.

The operations of prefiltering and MLSE equalization are based on the orthogonality of the modified channel matrix $\mathbf{H}_d$, assumption that holds if residual CCI at the output of the MIMO-MMSE filter is negligible. The prefilter is optimized to provide a shortened channel impulse response to the MLSE equalizer. In this work we employ the feedfoward filter of an MMSE decision-feedback equalizer (DFE) as a simple prefilter. More sophisticated solutions for the perfilter can be found in [14].

From Figs. 2 and 3, we observe that the two-stage receiver can be interpreted as combination of the conventional TR-STBC system of Fig. 1 and the STBC receiver with CCI canecellation of Fig. 3 and proposed in [10], with the addition of the prefilters to reduce complexity of the MLSE equalizer. We will employ these receivers as references for comparisons in the next section.

IV. Simulation Results

The performance of the two-stage 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. The frequency-selective channel follows a two-ray Rayleigh fading model with uncorrelated and equal-power paths. The time-delay of the second path is one symbol period. For simplicity, we assume a single space-time coded flat-fading co-channel interferer signal in the system. For the TR-STBC and the two-stage receivers, we employ a prefilter with 2 taps pior to the MLSE to shorten the channel impulse response towards $L = 1$, reducing equalization complexity.

Figure 4 shows the bit-error-rate (BER) performance of the two-stage receiver. We also plotted the performance of conventional Alamouti's STBC (ASTBC) for a flat-fading

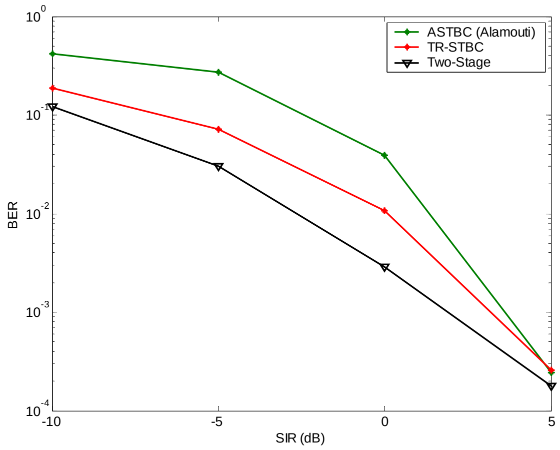

Fig. 4. Performance of the Two-Stage receiver (ISI, L=2) compared to those of the conventional ASTBC (flat-fading, L=1) and TR-STBC (ISI, L=2) in the absence of AWGN. The BER is plotted as a function of the SIR.

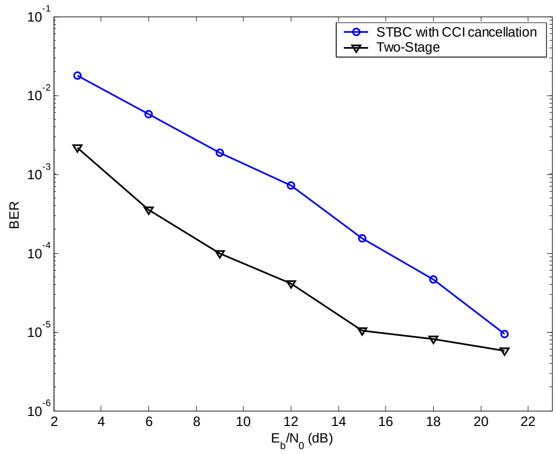

Fig. 5. Performance of the Two-Stage receiver with CCI and ISI compared to that of the STBC receiver of [10] with no ISI.

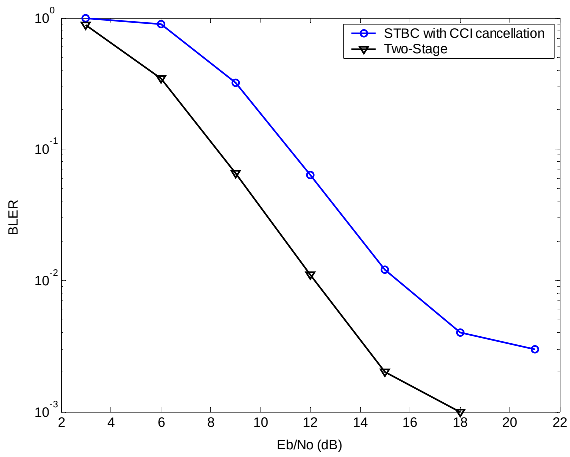

Fig. 6. BLER performance of the Two-Stage receiver for MCS-5 (8-PSK) under the TU channel and SIR=0dB.

channel ($L = 1$) as well as the performance of conventional TR-STBC with ISI ($L = 2$). The BER results are plotted according to average the signal-to-interference-ratio (SIR) in the absence of AWGN. The number of receive antennas for all three systems is $M = 2$. The worst performance is observed for ASTBC over flat-fading since it does not perform CCI cancellation and there is not path diversity to be exploited. Improved performance is offered by the TR-STBC receiver since it exploits ISI to provide diversity gains. However, the diversity gain of TR-STBC are not maximized because CCI compromises the orthogonality of the space-time code. The two-stage receiver outperforms both ASTBC and TR-STBC since it attempts to cancel CCI previously to space-time decoding, maximizing the diversity gain of the space-time code.

In Fig. 5 the performance of the two-stage receiver with CCI and ISI is compared to that of the STBC receiver with CCI cancellation (Fig. 3) with no ISI ($L = 1$). Here we employ $M = 3$ receive antennas. The SIR is fixed at 0dB and the BER is plotted as a function of the average input E_b/N_0. The best performance is obtained with the two-stage receiver, indicating that it successfully cancels CCI and exploits ISI structure to maximize the diversity gain of the space-time code. For higher E_b/N_0 values, where ISI is the dominant perturbation, we observe that the performance of both receivers approximates. This is caused by some temporal coloring that is present at the input signal of the MLSE, due to sub-optimum design of the prefilter.

V. Performance Evaluation under the EDGE System Context

The packet service of the EDGE system is called Enhanced General Packet Radio System (EGPRS), employing nine modulation and coding schemes (MCS) composed of two types of modulation: the GMSK (common to the GSM) and the new 8-PSK scheme. To reach the advantages introduced by this new modulation scheme, a link quality control (LQC) is necessary, since that the GMSK outperforms 8-PSK scheme in the bit error rate (BER). In the physical layer of EGPRS nine MCS are defined, say MCS-1, MCS-2,..., MCS-9. Four of them employ GMSK modulation (MCS-1 up to MCS-4) and five employ 8-PSK modulation (MCS-5 up to MCS-9). The performance of conventional ASTBC under the EDGE context was assessed in [15] by assuming a flat-Rayleigh fading channel with CCI. In the following results we evaluate the performance of the two-stage receiver over a frequency-selective channel, focusing on MCS-5.

The results are averaged over 2000 RLC radio blocks with ideal frequency hopping. A single co-channel interferer with SIR=0 dB is assumed. The typical urban (TU) channel model [16] is considered for both the desired user and the co-channel interferer signals, where $L = 5$. In order to reduce equalization complexity we employ a DDFSE equalizer [13] instead of an MLSE. We assume M=4 receive antennas. 6 shows the performance of the STBC receiver with CCI cancellation in the absence of ISI against the two-stage receiver with ISI. It can be seen that the new receiver presents the best results, providing an E_b/N_0 gain of 3dB at 1% target block error rate (BLER). Note that the superior performance of the two-stage receiver can be translated into a higher throughput for the user, since the throughput is related with BLER by *Throughput* $= (1 - BLER)R_{max}$, where R_{max} is the user data rate for a given MCS.

VI. CONCLUSIONS

We have proposed a two-stage receiver for space-time block-coded systems that decouples the tasks of CCI cancellation and space-time decoding in two processing stages. The receiver is designed for either flat or frequency-selective fading channels and consists of a MIMO-MMSE spatial filter for CCI cancellation and a modified TR-STBC decoder connected to a prefiltered MLSE equalizer for ISI equalization. We have showed via computer simulations that the two-stage receiver effectively cancels CCI and maximize the diversity gain of the space-time code. The two-stage receiver outperformed both ASTBC and TR-STBC receivers, as well as another STBC receiver proposed in [10]. The proposed receiver was also evaluated at the link-level of EDGE on the TU channel with CCI, showing excellent results in terms of BLER.

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