Joint Beamformer Estimation and Co-Antenna Interference Cancelation for TURBO-BLAST

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Abstract— **TURBO-BLAST is a novel multi-transmit multi-receive (MTMR) antenna scheme for high-throughput wireless communications. It exploits a novel space-time coding scheme based on the independent block forward error correction (FEC) codes and space-time interleaving, and a near optimal iterative decoder, for decoding a new generation of space-time codes. The proposed iterative decoder has two decoding stages: a soft interference cancelation detector and a set of soft-in soft-out decoders. In this paper, we focus on designing a robust parallel interference cancelation scheme that jointly estimates the soft interference and the linear beamformer weights to minimize the mean-square error (MMSE) between the true and estimated signals. Using simulation results, we show that the proposed scheme outperform the previously proposed soft interference cancelation receivers based on maximum ratio combining (MRC) principle.**

I. INTRODUCTION

Recently, there has been growing interest in designing multi-transmit and multi-receive (MTMR) antenna schemes to increase single-user capacity in wireless communications systems. In particular, the MTMR communications structures popularized as *Bell-Labs Layered Space-Time (BLAST) architectures [1]* have received considerable attention as they could provide very high data-rate communication over wireless channels without increasing the total transmit power and channel bandwidth.

To achieve the enormous capacity available in multi-in multi-out (MIMO) matrix channels, it is well known that the MTMR scheme has to be designed with an appropriate precoder and decoder which decouple the parallel sub-channels. The current generation of cellular systems support only multi-antenna elements at the base station. In this scenario, when the receiver has knowledge of the matrix channel, the optimal way of coding to decouple the sub-channels efficiently is through the use of space-time block coding proposed in [2]. However, the achievable data rate using this class of space-time codes is only the size of the constellations used. Therefore, they are not well suited for the future generation of wireless communications, where the focus will be on increasing the transmission rate. Moreover, in the wireless local area networks (WLAN), both the mobile, usually Lap-Top Computers, and the base station can be equipped with multi-element array antennas. This motivates the designing a high-rate space-time coding scheme for MTMR systems that employ advanced signal processing techniques to decouple the parallel sub-channels.

In this paper, we introduce a *robust* receiver for the space-time coding scheme obtained by combining the traditional channel coding of independent substreams and space-time interleaving. The combination of independent coding and space-time interleavers can be viewed as "random" space-time codes. We use independent encoding of each substream for two reasons. First, we use fixed-rate codes; thereby, we increase the transmission rate of the system with the increased number of transmitters. Second, the codes can be simply designed using traditional FEC coding schemes in Galois-field for any number of transmit antennas. Moreover, the structure of these codes leads to an iterative "turbo-like" receiver for jointly decoding the simultaneously transmitted substreams with low complexity.

In [3] and [4], we introduced two iterative receiver schemes for Turbo-BLAST (T-BLAST) architecture: (1) an optimum maximum *a posteriori* (MAP) receiver with a computational complexity exponential in the number of transmitting antennas, and (2) a suboptimal parallel soft-interference cancelation receiver with an implementation complexity linear in the number of transmitting antennas. The goal of this paper is to optimize the interference estimate and the linear beamformer weights in the suboptimal (second) receiver that minimizes the mean-square error (MMSE) of the estimates. The MMSE criterion is used because it is robust with respect to channel estimation errors and external co-channel interferences.

II. TURBO-BLAST ARCHITECTURE

We consider a MTMR system that has n_T transmitting and n_R receiving antennas, with $n_R \geq n_T$. Throughout this paper, we assume that the n_T transmitters operate with synchronized symbol timing at a rate of $1/T$ symbols per second and the sampling times of n_R receivers are symbol-synchronous. The channel variation is assumed to be negligible over L symbol periods comprising a packet of symbols (non-ergodic process).

Figure 1 shows a high-level description of the T-BLAST architecture. A user's data stream is demultiplexed into n_T data substreams $\{\mathbf{B}_k\}_{k=1}^{n_T}$ of equal rate. The data substreams are block-encoded using the same predetermined forward error correction (FEC) block code $\{\mathbf{C}_k\}_{k=1}^{n_T}$. The encoded substreams are bit-interleaved using an off-line designed space-time random permuter. We use $\{\tilde{\mathbf{C}}_k\}_{k=1}^{n_T}$ to denote the permuted substreams. Then the space-time interleaved substreams are independently mapped into QPSK symbols $\{\mathbf{A}_k\}_{k=1}^{n_T}$.

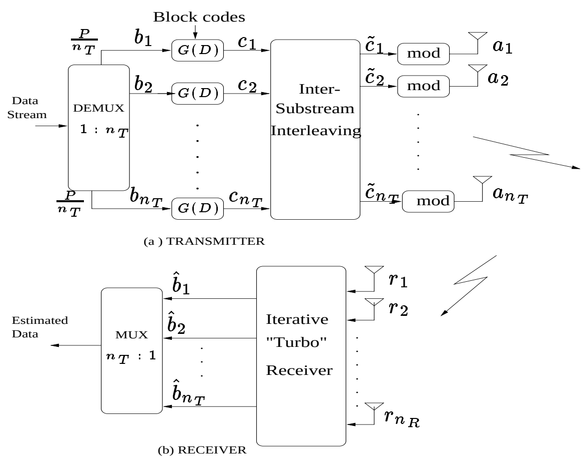

Fig. 1. TURBO-BLAST ARCHITECTURE

A block diagram of the iterative receiver is shown in Figure 2. The receiver has two stages:
• *Stage I (detector):* The soft interference-cancelation detector.
• *Stage II (decoders):* The set of n_T parallel soft-input/soft-output (SISO) channel decoders.
The detector and decoder stages are separated by space-time interleavers and de-interleavers. The interleavers and de-interleavers are used to compensate for the interleaving operation used in the transmitter as well as to decorrelate the correlated outputs before feeding them to the next stage.

III. Data Model

With no delay spread, the discrete-time model of the received signal vector at the ith signaling interval is given by:

$$\mathbf{r}(i) = \mathbf{H}\mathbf{a}(i) + \mathbf{v}(i) \qquad (1)$$

where $\mathbf{H} \in \mathcal{C}^{n_R \times n_T}$ is the channel impulse response matrix, vector $\mathbf{a}(i) \in \mathcal{C}^{n_T \times 1}$ is the transmitted information,

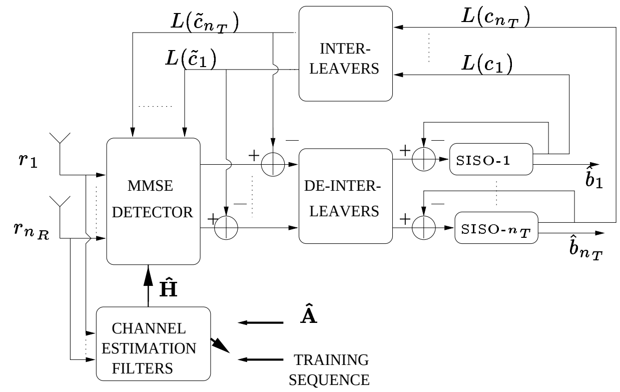

Fig. 2. ITERATIVE RECEIVER

$\mathbf{r}(i) \in \mathcal{C}^{n_R \times 1}$ is the received vector, and the Gaussian noise vector $\mathbf{v}(i) \in \mathcal{C}^{n_R \times 1}$. The components of the noise vector are uncorrelated zero-mean complex white Gaussian random variables with zero mean and variance σ^2. The channel matrix $\mathbf{H}$ is assumed to be constant during a frame, but it may vary from one frame to another. Moreover, we assume that the rank of $\mathbf{H} = \min(n_T, n_R)$. In a rich scattering environment, this condition is almost always met for large transmit and receive antennas.

IV. Iterative receivers

Let $a_k(i)$ be the desired signal. We may write (1) as:

$$\mathbf{r}(i) \quad = \quad \mathbf{h}_k a_k(i) + \mathbf{H}_k \mathbf{a}_k(i) + \mathbf{v}(i) \qquad (2)$$

where $\mathbf{H}_k = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{k-1}, \mathbf{h}_{k+1}, \ldots, \mathbf{h}_n] \in \mathcal{C}^{n_R \times n_T - 1}$ and $\mathbf{a}_k(i) = [a_1(i), a_2(i), \ldots, a_{k-1}(i), a_{k+1}(i), \ldots, a_n(i)]^T$ are the interfering channel matrix and the vector of interfering substreams for the kth substream, respectively. The vector channel $\mathbf{h}_k = [h_{k1}, h_{k2}, \ldots, h_{kn_R}]^T$ is an $n_R \times 1$ vector that represents the complex gains of the n_R different paths pertaining to the kth transmit-antenna signal.

A. Linear Detector

For a linear detector designed to extract the desired signal, the decision statistic of the kth substream at the ith sampling instant is:

$$x_k(i) \quad = \quad \underbrace{\mathbf{w}_k^H \mathbf{h}_k a_k(i)}_{d_k} + \underbrace{\mathbf{w}_k^H \mathbf{H}_k \mathbf{a}_k(i)}_{u_k} + \underbrace{\mathbf{w}_k^H \mathbf{v}(i)}_{\bar{v}_k} \quad (3)$$

The terms corresponding to d_k, u_k and $\bar{v}_k$ are the desired response obtained by the linear beamformer, the CAI, and phase-rotated noise, respectively.

B. Soft interference canceler (Stage I):

To overcome the CAI, we propose a multi-substream receiver based on the combined use of a detector and soft interference canceler, which optimizes the interference estimate and the weights of the linear detector jointly by using the MMSE criterion. In the interference cancelation receiver, we remove CAI from the linear beamformer output x_k:

$$y_k = \mathbf{w}_k^H \mathbf{r} - u_k \quad (4)$$

where u_k is a linear combination of interfering substreams: $u_k = \mathbf{w}_2^H \hat{\mathbf{a}}_k$. For brevity, we omit the sampling index (i). The performance of the estimator is measured by the error $e_k = (a_k - y_k)$. We need to minimize $\mathcal{E}[e_k e_k^*]$, where $\mathcal{E}$ is the expectation operator. The weights $\mathbf{w}_k \in \mathcal{C}^{n_T \times 1}$ and interference estimate u_k are optimized by minimizing the mean-square value of the error between each substream and its estimate.

Problem 1: Given (2) and (4), find the weight vectors $\mathbf{w}_k$ and u_k by minimizing the following cost function:

$$(\hat{\mathbf{w}}_k, \hat{u}_k) = \arg \min_{(\mathbf{w}_k, u_k)} \mathcal{E}\left[\|a_k - y_k\|^2\right] \quad (5)$$

where the expectation is over noise and the statistics of the data sequence.

□

Solution 1: A Solution to **Problem 1** is given by

$$\hat{\mathbf{w}}_k = (\mathbf{P} + \mathbf{Q} + \mathbf{R_{nn}})^{-1}\mathbf{h}_k \quad (6)$$

$$\hat{u}_k = \mathbf{w}_k^H \mathbf{T} \quad (7)$$

Where

$$\begin{array}{ll} \mathbf{P} = \mathbf{h}_k \mathbf{h}_k^H & \in \mathcal{C}^{n_R} \\ \mathbf{Q} = \mathbf{H}_k \left[\mathbf{I}_{(n_T-1)} - \mathrm{Diag}(\mathcal{E}\{\mathbf{a}_k\}\mathcal{E}\{\mathbf{a}_k\}^H)\right] \mathbf{H}_k^H & \in \mathcal{C}^{n_R} \\ \mathbf{R}_{nn} = \sigma^2 \mathbf{I}_{n_R} & \in \mathcal{C}^{n_R} \\ \mathbf{T} = \mathbf{H}_k \mathcal{E}(\mathbf{a}_k) & \in \mathcal{C}^{n_R \times 1} \end{array}$$

□

We used standard minimization techniques to solve the optimization problem formulated in (1). In arriving at this solution we used:

$$\mathcal{E}\{\mathbf{av}\} = \mathbf{0}; \quad \mathcal{E}\{a_i a_j\} = \mathcal{E}\{a_i\}\mathcal{E}\{a_j\} \ \ \forall i \neq j \quad (8)$$

These conditions are achieved by the independent and different space interleaving and time interleaving applied at the transmit end.

- For the first iteration, we assume $\mathcal{E}\{\mathbf{a}_k\} = \mathbf{0}$, in which case (4) reduces to the linear MMSE receiver for substream k:

$$y_k(i) = \mathbf{h}_k^H (\mathbf{H}^H \mathbf{H} + \sigma^2 \mathbf{I})^{-1} \mathbf{r}(i) \quad (9)$$

- On the limit of $\mathcal{E}[\mathbf{a}_k] \to \mathbf{a}_k$, (4) simplifies to a perfect interference canceler:

$$y_k(i) = (\mathbf{h}^H \mathbf{h} + \sigma^2)^{-1} \mathbf{h}_k^H (\mathbf{r}(i) - \mathbf{H}_k \mathbf{a}_k) \quad (10)$$

Solution 2: The MMSE solution to the weight vector $\mathbf{w}_k$ requires matrix inversion of $n_R \times n_R$ matrices. A sub-optimum solution to **Problem 1** is obtained by ignoring the matrix $\mathbf{Q}$ in $\mathbf{w}_k$, as follows:

$$\begin{aligned} y_k &= \mathbf{h}_k^H ((\mathbf{h}_k \mathbf{h}_k^H + \sigma^2 \mathbf{I})^H)^{-1} (\mathbf{r}(i) - \mathbf{H}_k \mathcal{E}\{\mathbf{a}_k\}) \\ &= ((\mathbf{h}_k^H \mathbf{h}_k + \sigma^2)^{-1} \mathbf{h}_k^H (\mathbf{r}(i) - \mathbf{H}_k \mathcal{E}\{\mathbf{a}_k\}) \quad (11) \end{aligned}$$

□

This solution requires a scalar inversion only. Note that the matrix $\mathbf{Q}$ represents the variances and co-variances of the residual interferences.

C. SISO Decoders (Stage II):

To acquire the expectations of interfering substreams, we use n_T-parallel SISO decoders to provide the *a priori* probabilities of the transmitted substreams. The n_T-parallel SISO decoders operate identically to the BCJR algorithm used in TURBO decoding [6]. The *a priori* probabilities are obtained from the decoder soft outputs of the previous iterations using the following relationship:

$$P(a_{jr} = +1) = 1 - P(a_{jr} = -1) = \frac{\exp(L(a_{jr}))}{1 + \exp(L(a_{jr}))} \quad (12)$$

where $L(a_{jr})$ is the soft output (formalized as a log-likelihood ratio) of symbol a_{jr} provided by the SISO decoder. The expectation of a_{jr} is

$$\begin{aligned} \mathcal{E}[a_{jr}] &= \frac{(+1)\exp(L(a_{jr}))}{1 + \exp(L(a_{jr}))} + \frac{(-1)}{1 + \exp(L(a_{jr}))} \\ &= \tanh(L(a_{jr})/2), \qquad j = 1, 2, \ldots, n_T \quad (13) \end{aligned}$$

where $a_j = a_{jr} + i a_{ji}$.

The interference estimation is based on block-based "extrinsic information" provided by SISO decoders; i.e, information about a_j is gleaned from the prior information about the other symbols $\{L(a_m)\}_{m \neq j}$.

Note 1: This receiver is also applicable to the case where the MIMO channel has delay spread. If the MIMO channel has a finite delay spread that spans l symbol periods, then by stacking l successive samples of received data vector we can define: $\bar{\mathbf{r}}(i) = vec[\mathbf{r}(i), \ldots, \mathbf{r}(i + l - 1)] \in \mathcal{C}^{n_R l \times 1}$, $\bar{\mathbf{a}}(i) = vec[\mathbf{a}(i - l + 1), \ldots, \mathbf{a}(i + l - 1)] \in \mathcal{C}^{n_T(2l-1) \times 1}$, $\bar{\mathbf{v}}(i) = vec[\mathbf{v}(i - l + 1) and \ldots, \mathbf{v}(i + l - 1)] \in \mathcal{C}^{n_R l \times 1}$. Hence the system equation for the ith signaling interval is

$$\bar{\mathbf{r}}(i) = \bar{\mathbf{H}}\bar{\mathbf{a}}(i) + \bar{\mathbf{v}}(i) \quad (14)$$

where $\bar{\mathbf{H}} \in \mathcal{C}^{n_R l \times n_T(2l-1)}$ is given by

$$\bar{\mathbf{H}} = \begin{bmatrix} \mathbf{H}[l-1] & \ldots & \mathbf{H}[0] & \ldots & \mathbf{0} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \mathbf{0} & \ldots & \mathbf{H}[l-1] & \ldots & \mathbf{H}[0] \end{bmatrix} \quad (15)$$

where $\mathbf{H}[j], 0 \leq j \leq l - 1$, denotes the jth tap of the MIMO channel impulse response matrix. The iterative receiver is applicable for this case, but the dimensionality of the MMSE receiver will change according to (14).

V. SIMULATION EXAMPLES

We consider a BLAST scheme with 16 transmitters and 16 receivers. The packet length of each substream is 100 symbols with an additional 20-symbol training sequence. Each substream is independently encoded using a rate 1/2 convolutional code generator (7,5) and then interleaved using space-time interleavers. The interleaved substreams are QPSK-modulated. The space-time interleavers are chosen randomly and no attempt is made to optimize their design. For all the Monte-Carlo simulations presented herein, we use a flat fading matrix channel generated using a modified one-ring scattering channel model [7]. For each run (packet), a new realization of $\mathbf{H}$ is chosen. Computer simulations were performed on the following BLAST configurations: (1) D-BLAST (MMSE based) designed with no edge waste [1], (2) T-BLAST-MMSE as proposed in Solution 1, and (3) T-BLAST-MRC receiver 2 in [4].

A. Example 1: Time-invariant channel

Figure 3 shows the BER performance versus SNR for D-BLAST and T-BLAST receivers for iterations 1,2,4 and 5. As expected, the performances of both D-BLAST and T-BLAST improve with increasing SNR. The performance of both T-BLAST receivers improves with increasing iterations and exceeds that of D-BLAST in 2 iterations. A significant gain (7dB) is achieved by the T-BLAST scheme over the D-BLAST. The T-BLAST-MMSE performs around 0.75 dB better than T-BLAST-MRC.

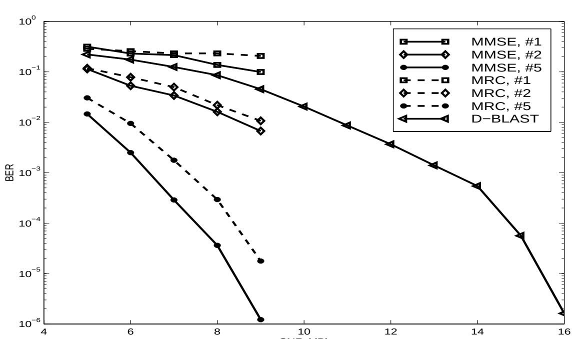

Fig. 3. BER Vs. SNR for time-invariant channel

B. Example 2: Time-varying channel

The maximum Doppler frequency considered here is 20Hz. Figure 4 shows the BER performance after 5 iterations versus SNR for T-BLAST-MMSE and T-BLAST-MRC. From figure we note that the performance of both T-BLAST receivers improves with SNR, with T-BLAST-MMSE outperforming T-BLAST-MRC by a wide margin (2dB). This illustrates the robustness of the MMSE receiver for channel estimation errors. Moreover, a performance decrement of about 6dB is observed from Figure 3 to Figure 4 due to possible channel estimation errors present in the time-varying channel.

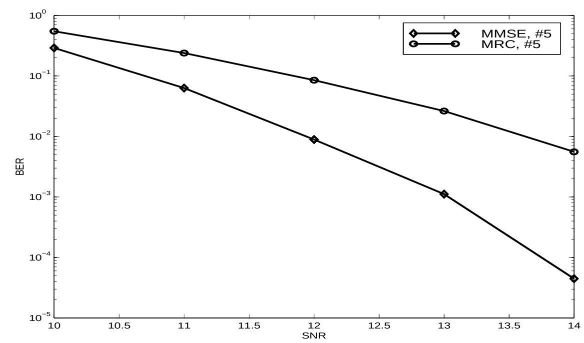

Fig. 4. BER Vs. SNR for time-varying channel

VI. CONCLUSIONS

We described a new iterative receiver based on MMSE and Turbo-decoding principle for decoding space-time codes that are based on independent FEC coding and space-time interleavers for MTMR schemes. The T-BLAST scheme, in general, was shown to have excellent performance, which significantly outperforms the D-BLAST architecture. Moreover, the proposed MMSE based iterative receiver for T-BLAST was shown to outperform the MRC-based soft interference cancelation receiver when channel estimation errors are present. The space-time codes and the iterative decoders proposed in this paper are suitable for both flat-fading and delay-spread channels.

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