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Description	

Iterative Receivers for STTrC-Coded MIMO Turbo Equalization

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***Abstract*— The problem of iterative mutiuser detection in single-carrier broadband multiple-input multiple-output (MIMO) system is studied in this paper. Two minimum mean squared error (MMSE) multiuser receivers are proposed for space-time trellis coded system in frequency selective channels. The first receiver uses MMSE criterion both for multiuser detection and equalization. The second one uses MMSE criterion only for multiuser detection, while the equalization part is an optimal maximum a posteriori (MAP) equalizer. The second receiver significantly outperforms the first one both in the presence and in the absence of the unknown co-channel interference, at the expense of increased complexity.**

I. Introduction

The scarcity of the frequency resources and ever growing demand for new broadband services imposes a need for the bandwidth efficient transceiver schemes. The concept of space-time codes (STC) [1] is addressing that problem by combining the benefits of transmit diversity and channel coding techniques. Since the system resources are usually shared by more than a single user, it is essential to find the effective receiver structures that will allow multiple users to access to the system, while pertaining the essential benefits of the space-time coding.

The space-time trellis coded (STTC) MIMO multiuser system was studied in [2]. There, however, a flat fading channel is considered. In this paper we propose two iterative receiver structures for the STTC coded system in frequency selective channels. The first one uses the minimum mean squared error (MMSE) criterion both to separate signals from different antennas and to combine multipath components. The second one uses MMSE criterion only to separate the signals from different antennas while the multipath combining is performed by the set of maximum *a posteriori* (MAP) equalizers. The unknown co-channel interference (UCCI) is suppressed by estimation of the covariance matrix of the UCCI-plus-noise [3]. The simulation results show that the latter receiver significantly outperforms the former one both in the presence and in the absence of the UCCI.

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This paper is organized as follows. Section II describes system model. Section III presents the two proposed receivers. Section IV presents numerical results. The paper is concluded in Section V.

II. System Model

Figure 1 shows the system model used in this paper. Each of $N + N_I$ users encodes bit information sequence $c_n(i)$, $n = 1, ..., N + N_I$, $i = 1, ..., Bk_0$ using the rate k_0/n_0 STTC code, where n_0 and B are the number of transmit antennas and frame length in symbols, respectively. The users indexed by $n = 1, ..., N$ are desired users and those indexed by $n = N + 1, .., N + N_I$ are assumed to be UCCI. The encoded sequences $b_n(k)$, $k = 1, ..., Bn_0$ are interleaved, and headed by the user-specific training sequences consisting of T symbols. The entire frame is then serial-to-parallel converted, resulting in the sequences $b_n^i(l) \in \mathcal{Q}$, $i = 1, .., n_0$, $l = 1, ..., B$ and transmitted with n_0 transmitted antennas. $\mathcal{Q}$ denotes the signal constellation set. The channel is frequency selective with L paths.

After coherent demodulation in the receiver, the signals from each of M receive antennas are sampled in time domain to capture the multipath components. Observing the signals from different transmit antennas of different users as the virtual users and arranging them in the vector form similarly as it was done in [4] we form the space-time representation of the received signal at time instant k given by

$$\mathbf{y}(k) = \mathbf{H}\mathbf{u}(k) + \mathbf{H}_I\mathbf{u}_I(k) + \mathbf{n}(k), \ k = 1, ..., T + B, \quad (1)$$

where $\mathbf{y}(k) \in \mathbb{C}^{LM \times 1}$ is space-time sampled received signal vector, $\mathbf{H} \in \mathbb{C}^{LM \times Nn_0(2L-1)}$ is desired signals' channel matrix of the form

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}(0) & \dots & \mathbf{H}(L-1) & \dots & \mathbf{0} \\ \vdots & \ddots & & \ddots & \vdots \\ \mathbf{0} & \dots & \mathbf{H}(0) & \dots & \mathbf{H}(L-1) \end{bmatrix}$$

with $[\mathbf{H}(l)]_{m,n}$ being the l-th path complex gain between $\lceil \frac{n}{n_0} \rceil$-th user's $\lfloor \frac{n}{n_0} \rfloor$-th transmit antenna and m-th receive antenna, where $\lceil \cdot \rceil$ and $\lfloor \cdot \rfloor$ denote the upper and lower closest integer. The matrix $\mathbf{H}_I \in \mathbb{C}^{LM \times N_I n_0(2L-1)}$ denotes the corresponding channel matrix for the UCCI with entries similarly defined as in $\mathbf{H}$. The vectors $\mathbf{u}(k) \in \mathbb{C}^{Nn_0(2L-1)\times 1}$, $\mathbf{u}_I(k) \in \mathbb{C}^{N_I n_0(2L-1)\times 1}$ and $\mathbf{n}(k) \in \mathbb{C}^{LM\times 1}$ contain desired users' signals from different transmit antennas, UCCI's signals and additive white Gaussian noise (AWGN) with covariance $E\{\mathbf{n}(k)\mathbf{n}^H(k)\} = \sigma^2\mathbf{I}$, respectively [3].

III. Turbo MIMO Equalizers

Assume without loss of generality that the 1st user's ith antenna's signal is the signal of interest. Let $\tilde{\mathbf{u}}(k)$, $k = T+1,...,T+B$ denote the soft feedback from the channel decoder, representing the estimate of all the users together with their inter-symbol interference components (ISI) [4].

A. Receiver #1

The first receiver is extension of the receiver from [2] to frequency selective channels. Let $\hat{\mathbf{u}}_1^i(k) = \tilde{\mathbf{u}}(k) - \tilde{\mathbf{u}}(k) \otimes \mathbf{e}_1^i$, where $\mathbf{e}_1^i = [\mathbf{0}_{1\times(L-1)Nn_0+i}\ 1\ \mathbf{0}_{1\times LNn_0-i-1}]^T \in \mathbb{R}^{Nn_0(2L-1)\times 1}$, and $\otimes$ is the elementwise vector product. The channel is first estimated based on the training sequence $\mathbf{u}(k)$, $k = 1,...,T$. In order to suppress the known and unknown CCI components as well as the ISI components of the desired signal, a linear filter with weighting factor $\mathbf{w}_1^i(k)$ is then applied to the signal $\hat{\mathbf{y}}_1^i(k) = \mathbf{y}(k) - \mathbf{H}\hat{\mathbf{u}}_1^i(k), k = T+1,...,B+T$. The weighting factor $\mathbf{w}_1^i(k)$ is obtained according to MMSE criterion

$$\mathbf{w}_1^i(k) = \arg\min_{\mathbf{w}(k)} ||\mathbf{w}^H(k)\hat{\mathbf{y}}_1(k) - b_1^i(k)||^2, \qquad (2)$$

resulting in

$$\mathbf{w}_1^i(k) = \mathbf{R}_{cov,1}^{-1}\mathbf{h}_1^i, \qquad (3)$$

with

$$\mathbf{R}_{cov,1} = \mathbf{H}\mathbf{\Lambda}_{1,1}^i(k)\mathbf{H}^H + \mathbf{U}, \qquad (4)$$

where $\Lambda_{1,1}^i(k) = \mathbf{I} - E\{\hat{\mathbf{u}}_1^i(k)\hat{\mathbf{u}}_1^i(k)^H\}$, $\mathbf{U} = \mathbf{H}_I\mathbf{H}_I^H + \sigma^2\mathbf{I}$ and $\mathbf{h}_1^i = \mathbf{H}\mathbf{e}_1^i$. In the first iteration the soft feedback is not available and $\hat{\mathbf{y}}_1^i(k)$ is replaced by $\mathbf{y}(k)$. The UCCI-plus-noise covariance matrix $\mathbf{U}$ can be estimated using training sequence only (first iteration) of using both training sequence and soft feedback (subsequent iterations), as in [3], [5]. Assuming Gaussian distribution of the outputs of the MMSE filter, we find conditional mean and variance as $\mu_1^i(k) = \mathbf{w}_1^{i\,H}\mathbf{h}_1^i$ and $\nu_1^i(k) = \mathbf{h}_1^{i\,H}\mathbf{R}_{cov,1}^{-1}\mathbf{h}_1^i - \mu_1^i(k)\mu_1^{i\,*}(k)$. After performing the same procedure for $i = 1,...,n_0$, the means $\mu_1^i(k)$, variances $\nu_1^i(k)$ and filter outputs $v_1^i(k) = \mathbf{w}_1^{i\,H}\mathbf{h}_1^i$ are used to make the extrinsic information to be supplied to the 1st user's space-time trellis decoder, as in [2].

B. Receiver #2

We propose a modification of the receiver #1 that preserves the degrees of freedom of the MMSE receiver by jointly detecting desired and part of the multipath signals. The channel is estimated first, as in the previous subsection. Let $\hat{\mathbf{u}}_1^i(k) = \tilde{\mathbf{u}}_1^i(k) - \tilde{\mathbf{u}}_1^i(k) \otimes \mathbf{e}_1^i$, where $\mathbf{e}_1^i = [\mathbf{0}_{1\times(L-1)Nn_0+i}\ 1\ \mathbf{0}_{1\times Nn_0-1}...1\ \mathbf{0}_{1\times Nn_0-i-1}]^T \in \mathbb{R}^{Nn_0(2L-1)\times 1}$. The desired signal $b_1^i(k)$ together with its past multipath components is estimated by applying the linear MMSE filter to the signal $\hat{\mathbf{y}}_1^i(k) = \mathbf{y}(k) - \mathbf{H}\hat{\mathbf{u}}_1^i(k)$, $k = T+1,...,B+T$, where the weighting vector $\mathbf{w}_1^i(k)$ satisfies the following MMSE criterion

$$\mathbf{w}_1^i(k) = \arg\min_{\mathbf{w}(k)} ||\mathbf{w}^H(k)\hat{\mathbf{y}}_1^i(k) - \mathbf{a}^H\mathbf{b}_1^i(k)||^2, \qquad (5)$$

subject to the constraint $||\mathbf{g}||^2 = 1$, where $g = [\mathbf{w}^T(k)\ \mathbf{a}^T]^T \in \mathbb{C}^{(L+1)M\times 1}$, $\mathbf{b}_1^i(k) = [b_1^i(k)...b_1^i(k-L+1)]^T$, and $\mathbf{a} \in \mathbb{C}^{L\times 1}$. Using the method of Lagrange multipliers the optimal solution for (5) can be found as

$$\mathbf{w}_1^i(k) = [[\mathbf{g}_{max}]_1, ..., [\mathbf{g}_{max}]_{LM}]^T, \qquad (6)$$

where $\mathbf{g}_{max}$ is the eigenvector that corresponds to the maximum eigenvalue of the matrix $\mathbf{R}_{gg}^{-1}$, with $\mathbf{R}_{gg}$ being defined as

$$\mathbf{R}_{gg} = \begin{bmatrix} \mathbf{R}_{cov,2} & \mathbf{H}_1^1 \\ \mathbf{H}_1^{1\,H} & \mathbf{I} \end{bmatrix},$$

where $\mathbf{R}_{cov,2} = \mathbf{H}\mathbf{\Lambda}_{1,2}^i(k)\mathbf{H}^H + \mathbf{U}$, $\mathbf{H}_1^i = [\mathbf{h}_L^{'}\ldots\mathbf{h}_1^{'}]$, with $\mathbf{h}_l^{'} = [\mathbf{0}_{(L-l)M\times 1}[\mathbf{h}_1^i]_1\cdots[\mathbf{h}_1^i]_{lM}]^T$, $l = 1,\ldots,L$. The matrix $\mathbf{\Lambda}_{1,2}^i(k)$ is defined as $\Lambda_{1,2}^i(k) = \mathbf{I} - E\{\hat{\mathbf{u}}_1^i(k)\hat{\mathbf{u}}_1^i(k)^H\}$, with $\hat{\mathbf{u}}_1^i(k)$ given in the beginning of this subsection.

Assuming Gaussian outputs of the MMSE filter, the equivalent conditional multipath channel coefficients are computed as

$$\mu_{1,l}^i(k) = \mathbf{w}_1^{i\,H}\mathbf{h}_l^{'}, l = 1,\ldots,L, \qquad (7)$$

and the conditional variance as

$$\nu_1^1(k) = \mathbf{w}_1{}^H\mathbf{R}_{cov,2}\mathbf{w}_1 - \sum_{l=1}^{L}\mu_{1,l}^1(k)\mu_{1,l}^{1\,*}(k). \qquad (8)$$

After repeating procedure for $i = 1,...,n_0$, the MMSE filter outputs $v_1^i(k) = \mathbf{w}_1^{i\,H}\hat{\mathbf{y}}_1^i(k)$, the means $\mu_{1,l}^i(k)$, $l = 1,\ldots,L$, variances $\nu_1^i(k)$ and *a priori* probabilities corresponding to the elements of the vector $\mathbf{b}_1^i(k)$ are fed to the ith MAP equalizer of the 1st user, which computes the extrinsic probability to be supplied to the 1st user's space-time trellis decoder, as shown in Fig. 1. The whole procedure is then repeated for the rest of desired users.

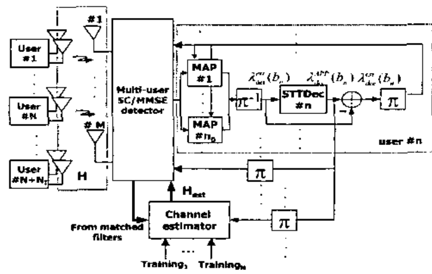

Fig. 1. Transmitter and iterative receiver block scheme

C. MAP Equalizer

The ith MAP equalizer of the 1st user calculates *a posteriori* probabilities for each of the transmitted symbols $b_1^i(k)$ and each of the symbols p_α belonging to the constellation set $\mathcal{Q}$, as follows

$$\lambda_{det,\alpha}^{app}(b_1^i(k)) = \log P[b_1^i(k) = p_\alpha | v_1^i(t), \mu_{1,l}^i(t), \nu_1^i(t)], \quad (9)$$

for $l = 1, ..., L$, $t = 1, ..., B$ and $\alpha = 1, ..., |\mathcal{Q}|$. After that the extrinsic information to be passed to the SISO channel decoder is calculated as

$$\lambda_{det,\alpha}^{ext}(b_1^i(k)) = \lambda_{det,\alpha}^{app}(b_1^i(k)) - \lambda_{dec,\alpha}^{ext}(b_1^i(k)), \qquad (10)$$

where $\lambda_{dec,\alpha}^{ext}(b_1^i(k))$ is the extrinsic information obtained after symbol-level [6] channel decoding, as in [2].

D. Computational Complexity

The complexity of the receiver #1 is dominated by the matrix inversion of the MMSE part, which is cubic in the product LM, i.e. $O(L^3M^3)$. The complexity of the reciever #2 is dominated by either MMSE part or the MAP equalization part of the receiver, i.e. it is roughly $O(\max\{L^3M^3, |\mathcal{Q}|^L\})$.

IV. Numerical Examples

Performance of the proposed receivers was tested through simulations. QPSK modulation was assumed with $B = 150$. Channel estimates are perfect. Fading is Rayleigh distributed, constant over each frame transmitted, and it changes independently frame by frame. The channel with $L = 2$ was used in all the numerical examples. The 4-state QPSK code from [1] was used for all MIMO users. The MAP space-time trellis decoder of [2] was used. The user specific random interleavers were assumed. The covariance matrix $\mathbf{U}$ of the UCCI-plus-noise is assumed to be perfectly estimated, but in practice the iterative estimation of [3] can be used.

In Fig. 2 the comparison of two receivers is presented for $(N, M) = (1, 1)$. It can be seen that the receiver #2 performs significantly better than the receiver #1. The receiver #1 is not able to properly separate the signals from the two transmit antennas due to the lack of receive antennas and low multipath diversity. The receiver #2, on the other hand, preserves the degrees of freedom of the MMSE receiver by jointly detecting desired signal and part of its multipath components.

In Figs. 3 and 4 the receivers' performance is compared in a multiuser scenarios with $(N, M) = (2, 2)$ and $(N, M) = (3, 3)$, respectively. The first receiver is not able of achieving the corresponding single-user bound, while that was possible with the latter receiver. By observing the single-user scenarios in Figs. 2-4 it can be noticed that the gain from receiver #2 becomes smaller for larger number of receive antennas available. This is due to the fact that in cases of smaller number of receive antennas the preserved degrees of freedom in the latter receiver contribute more to the receiver performance than in the case of large number of receive antennas.

In Figs. 5 and 6 the receivers' performance is compared in the presence of UCCI, for $(N, N_I, M) = (2, 1, 3)$. In Fig. 5 the result is presented when UCCI transmits using only one antenna corresponding to the signal-to-interference-ratio (SIR) SIR=3dB. In Fig. 6 both UCCI's antennas are used, corresponding to SIR=0dB (all transmit antennas of all the users have the same power). Again, it can be seen that the second receiver has the better interference suppression capability, due to the larger number of effective degrees of freedom.

V. Conclusions

Iterative multiuser detection and equalization in STTrC-coded system is studied in this paper. Two receiver structures are proposed based on soft interference cancellation (SC) and MMSE filtering. First receiver uses SC/MMSE filter both for ISI and CCI suppression while the second one uses SC/MMSE only for CCI cancelling and it jointly detects signal and its ISI components. Simulation studies show that the latter receiver significantly outperforms the former one both in the presence and in the absence of the UCCI. This is due to the preserved degrees of freedom, that improve the second receiver's interference suppression capability.

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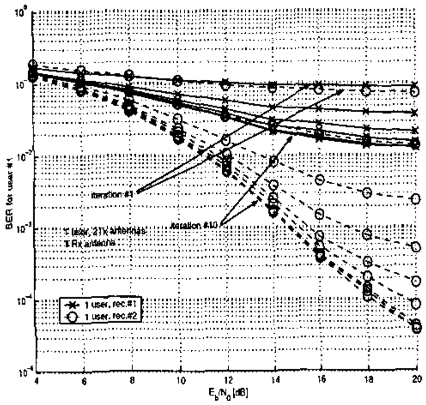

Fig. 2. Comparison of receivers, $(N, M) = (1, 1)$

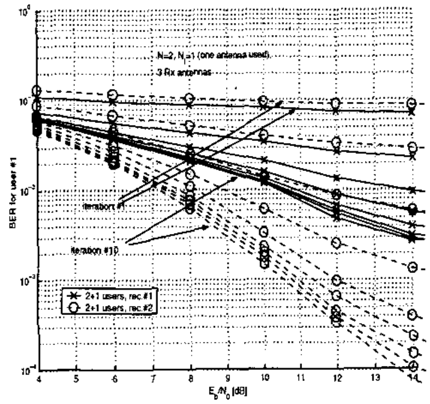

Fig. 5. Comparison of receivers, $(N, N_I, M) = (2, 1, 3)$, SIR=3dB (single antenna used by UCCI)

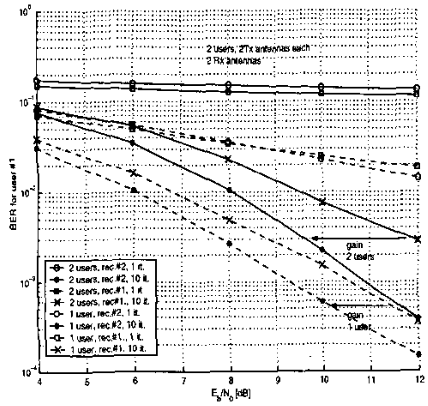

Fig. 3. Comparison of receivers, $(N, M) = (2, 2)$ and $(N, M) = (1, 2)$

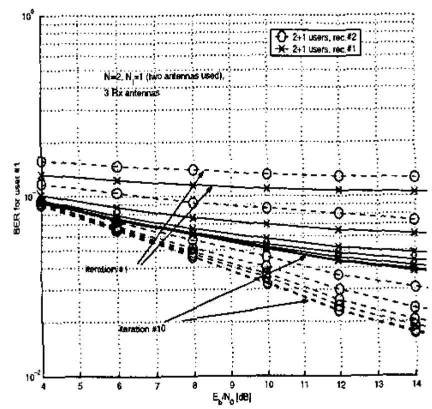

Fig. 6. Comparison of receivers, $(N, N_I, M) = (2, 1, 3)$, SIR=0dB (two antennas used by UCCI)

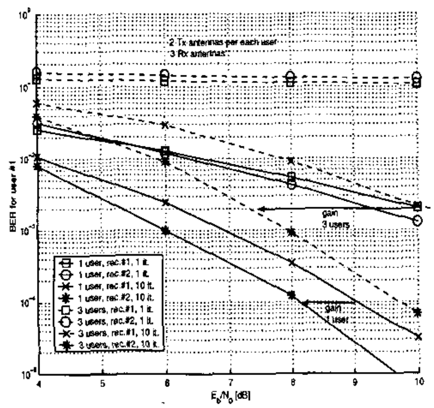

Fig. 4. Comparison of receivers, $(N, M) = (3, 3)$ and $(N, M) = (1, 3)$