Turbo Coded MMSE Algorithms for W-CDMA MIMO-BLAST Systems

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***Abstract*—This paper focuses on the use of an equalization-based receiver for WCDMA (Wideband Code-Division Multiple Access) MIMO (Multiple Input, Multiple Output) BLAST (Bell Labs Layered Space Time)-type systems. The receiver is based on the MMSE (Minimum Mean Square Error) algorithm and is tested using the UMTS (Universal Mobile Telecommunications System) HSDPA (High Speed Downlink Packet Access) standard as a basis, including the reference UMTS environments**

Keywords- MMSE, MIMO, BLAST, turbo coding.

I. Introduction

MIMO systems have been considered to be one of the most significant technical breakthroughs in modern communications, since they can augment significantly the system capacity, by increasing the number of both transmit and receive antennas [1]. Just a few years after its invention the technology is already part of the standards for wireless local area networks (WLAN), third-generation (3G) networks and beyond.

The receiver for such a scheme is obviously complex; due to the number of antennas, users and multipath components, the performance of a simple RAKE/ MF (Matched Filter) receiver (or enhanced schemes based on the MF) has a severe interference canceling limitation, that does not allow for the system to perform at full capacity. Therefore, a MMSE receiver [2], adapted for multipath MIMO, was developed for such cases acting as an equalizer, yielding interesting results. In order to further augment the MMSE performance, an additional MF-PIC scheme was added to the receiver. The MF-PIC scheme is a PIC (Parallel Interference Canceling) scheme that operates with the MF results, which is useful for use between turbo iterations. It basically cancels all interference, previously estimated by the MMSE algorithm and turbo decoder, from the MF results such that all cross-correlations between symbols after the MF are dissolved. Such a scheme produces a performance improvement with little added complexity, when compared to the simple MMSE decoder.

The structure of the paper is as follows. In section II, the MMSE receiver for MIMO with multipath is introduced, and the MF-PIC scheme is explained in section III. The turbo codec for use alongside the receiver schemes is described in section IV, and simulation results are described in section V. Conclusions are drawn in section VI.

II. MMSE Receivers

A standard model for a DS-CDMA system with K users (assuming 1 user per physical channel) and L propagation paths is considered. The modulated symbols are spread by a Walsh-Hadamard code with length equal to the Spreading Factor (*SF*).

Assuming that the transmitted signal on a given antenna is of the form

$$\boldsymbol{e}(t)_{tx=1} = \sum_{n=1}^{N}\sum_{k=1}^{K} \boldsymbol{A}_{k,tx}\boldsymbol{b}_{k,tx}^{(n)}\boldsymbol{s}_k(t-nT), \tag{1}$$

where N is the number of received symbols, $\boldsymbol{A}_{k,tx}=\sqrt{E_k}$, E_k is the energy per symbol, $\boldsymbol{b}_{k,tx}^{(n)}$ is the n^{th} transmitted data symbol of user k and transmit antenna tx, $\boldsymbol{s}_k(t)$ is the k^{th} user's signature signal (equal for all antennas) and T denotes the symbol interval.

The received signals of a MIMO system with N_{TX} transmit and N_{RX} receive antennas, on one of the receiver's antennas can be expressed as:

$$\boldsymbol{r}_{v_{rx=1}}(t) = \sum_{tx=1}^{N_{TX}} \boldsymbol{e}_{tx}(t) * \boldsymbol{c}_{tx,rx}(t) + \boldsymbol{n}(t) \tag{2}$$

where $\boldsymbol{n}(t)$ is a complex zero-mean AWGN (Additive White Gaussian Noise) with variance σ^2, $\boldsymbol{c}_{tx,rx}(t) = \sum_{l=1}^{L} \boldsymbol{c}_{tx,rx,l}^{(n)} \delta(t-\tau_l)$ is the impulse response of the radio link between the antenna tx and rx (assumed equal for all users using this link), $\boldsymbol{c}_{tx,rx,l}$ is the complex attenuation factor of the l^{th} path of the link, τ_l is the propagation delay (assumed equal for all antennas) and * denotes convolution. The received signal on can also be expressed as:

$$\boldsymbol{r}_{v_{rx=1}}(t) = \sum_{n=1}^{N}\sum_{tx=1}^{N_{TX}}\sum_{k=1}^{K}\sum_{l=1}^{L} \boldsymbol{A}_{k,tx}\boldsymbol{b}_{k,tx}^{(n)}\boldsymbol{c}_{tx,rx}(t)\boldsymbol{s}_k(t-nT-\tau_l) + \boldsymbol{n}(t) \tag{3}$$

Using matrix algebra, the received signal can be represented as

$$\boldsymbol{r}_v = \boldsymbol{SCAb} + \boldsymbol{n}, \qquad (4)$$

where $\boldsymbol{S}$, $\boldsymbol{C}$ and $\boldsymbol{A}$ are the spreading, channel and amplitude matrices respectively. The structure of the matrices is explained in detail in [3].

Vector $\boldsymbol{b}$ represents the information symbols. It has length $\left(K \cdot N_{TX} \cdot N\right)$, and has the following structure

$$\boldsymbol{b}=\left[\mathrm{b}_{1,1,1},\cdots,\mathrm{b}_{\mathrm{N_{TX}},1,1},\cdots,\mathrm{b}_{1,\mathrm{K},1},\cdots,\mathrm{b}_{\mathrm{N_{TX}},\mathrm{K},1},\cdots,\mathrm{b}_{\mathrm{N_{TX}},\mathrm{K},\mathrm{N}}\right]^T. \qquad (5)$$

Note that the bits of each transmit antenna are grouped together in the first level, and the bits of other interferers in the second level. This is to guarantee that the resulting matrix to be inverted has all its non-zeros values as close to the diagonal as possible. Also note that there is usually a higher correlation between bits from different antennas using the same spreading code, than between bits with different spreading codes.

The $\boldsymbol{n}$ vector is a $\left(N \cdot SF \cdot N_{RX} + N_{RX} \cdot \psi_{MAX}\right)$ vector with noise components to be added to the received vector $\boldsymbol{r_v}$, which is partitioned by N_{RX} antennas,

$$\boldsymbol{r}_v=\left[\boldsymbol{r}_{1,1,1},\cdots,\boldsymbol{r}_{1,SF,1},\cdots,\boldsymbol{r}_{N,1,1},\cdots,\boldsymbol{r}_{N,SF+\psi_{MAX},1},\cdots,\boldsymbol{r}_{N,1,N_{RX}},\cdots,\boldsymbol{r}_{N,SF+\psi_{MAX},N_{RX}}\right]^T. \qquad (6)$$

Equalization-based receivers compensate for all effects that the symbols are subject to in the transmission chain, namely the MAI (Multiple Access Interference), ISI (Inter-Symbolic Interference) and the channel effect. Thus being, only the thermal noise cannot be compensated for, since only its power level can be effectively estimated.

The equalization receiver used as basis in this works makes use of the MMSE algorithm, as is based on the Matched Filter output,

$$\boldsymbol{y}_{MF} = \left(\boldsymbol{SCA}\right)^H \boldsymbol{r}_v \qquad (7)$$

The MMSE estimate aims to minimize $E\left(\left|\boldsymbol{b} - \hat{\boldsymbol{b}}\right|^2\right)$, where

$$\hat{b} = \boldsymbol{L}^H \boldsymbol{r}_v \qquad (8)$$

is the MMSE estimate. From [4], the EM (Equalization Matrix) includes the estimated noise power σ^2, and is represented by

$$\boldsymbol{E}_{M,MMSE} = \boldsymbol{R} + \sigma^2 \boldsymbol{I}. \qquad (9)$$

$$\boldsymbol{R} = A \cdot C^H \cdot S^H \cdot S \cdot C \cdot A \qquad (10)$$

The MMSE estimate is thus

$$\boldsymbol{y}_{MMSE} = \left(\boldsymbol{E}_{M,MMSE}\right)^{-1} \boldsymbol{y}_{MF}, \qquad (11)$$

with

$$\boldsymbol{L} = \boldsymbol{SCA} \cdot \left(\boldsymbol{R} + \sigma^2 \boldsymbol{I}\right)^{-1}. \qquad (12)$$

III. MF-PIC ALGORITHM

The MMSE receiver can be coupled with a MF-PIC, in order to improve the results. The estimates obtained with the receiver (receiver processing in Figure 1) are passed through a SDD (Soft Decision Device) before the interference cancellation. The SDD can be composed of CSD (Clipped Soft Decision), or by an optimum decision function admitting that the estimates suffer from noise with a Gaussian distribution (which holds nearly true for the case of the Equalization-Based receivers) [7]. The estimated symbols will act as the first estimate for the interference cancellation,

$$\hat{b}_1 = SDD\left(\boldsymbol{y}_{estim}, \sigma^2_{estim}\right), \qquad (13)$$

where σ^2_{estim} is the noise variance of $\boldsymbol{y}_{estim}$. The cancelling operates on the MF result, and is simply the simultaneous removal of all influences that the symbols have on each other, throughout the transmission and receiver operations, in the absence of noise (accomplished with the removal of the main diagonal of $\boldsymbol{R}$)

$$\hat{\boldsymbol{c}}_{n+1} = \boldsymbol{y}_{MF} - \left(\boldsymbol{R} - diag\left(\boldsymbol{R}\right)\right)\hat{b}_n. \qquad (14)$$

The result is then normalized and passed through the SDD, becoming the estimate for the next iteration

$$\hat{b}_{n+1} = SDD\left(\hat{c}_{n+1} \odot \boldsymbol{C}_{NORM}, \sigma^2_{estim}\right), \qquad (15)$$

where $\odot$ represents element-wise multiplication. The normalization consists simply of inverting the main diagonal of $\boldsymbol{R}$,

$$\boldsymbol{C}_{NORM} = diag\left(\boldsymbol{R}\right)^{-1}, \qquad (16)$$

so as to compensate for the amplitude offset resultant of the spreading and channel power. Figure 1 illustrates the MF-PIC. The added complexity to the MMSE algorithm is negligible since the main system matrices ($\boldsymbol{S}$,$\boldsymbol{C}$,$\boldsymbol{A}$,$\boldsymbol{R}$) required by the MF-PIC have already been computed for the MMSE operation. The iterative algorithm only needs to multiply the current estimated symbol by pre-defined matrices, while performing the SDD. The main difference from the MF-PIC structure shown to conventional PIC schemes is the fact that this new scheme makes use of the MMSE's structure and thus is able to correctly estimate the interference caused by ISI (Inter-Symbolic Interference) and MAI (Multiple Access Interference), aside the thermal noise component. Also, the used normalization factor is improved since, besides containing the effect of spreading and channel power, it also contains the cross-correlation effects caused by multipath, which in conventional receivers isn't used.

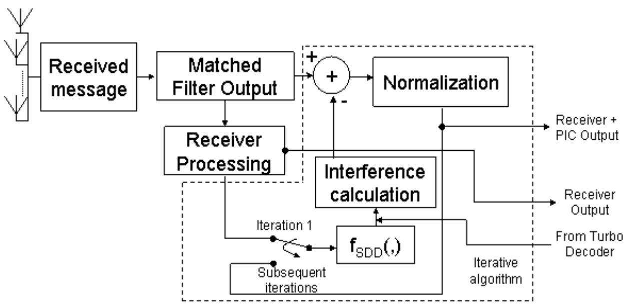

Figure 1 – MF-PIC Structure

IV. TURBO CODEC

The turbo decoder scheme is portrayed in Figure 2. It uses the MAP decoder [5] as the basis algorithm and performs 9 iterations for the turbo decoding stage.

Two types of decoding arrangements were considered; with and without feedback. The case without feedback is straightforward; the bit estimates are simply output from the turbo decoder. The case with feedback is different; instead of outputting the bit estimates, the decoder will output the LLRs (Log Likelihood Ratios) of the coded bits, obtained during the decoding process. These coded bits will then be used as the estimates of the interference, in order to obtain better results.

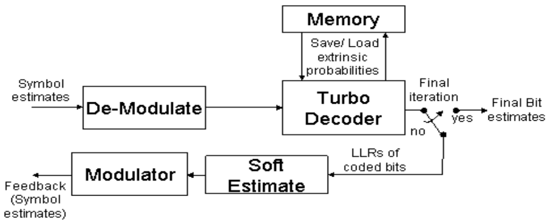

Figure 2– Turbo decoder scheme

The soft estimate of the coded bits' LLR is given by the expected value of each coded bit. This is given by

$$
\begin{aligned}
E(x_n) &= P(x_n = 1)\cdot 1 + P(x_n = -1)\cdot(-1) = \\
&= \frac{P(x_n = 1) - P(x_n = -1)}{P(x_n = 1) + P(x_n = -1)} = \\
&= \frac{\frac{P(x_n = 1)}{P(x_n = -1)} - 1}{\frac{P(x_n = 1)}{P(x_n = -1)} + 1} = \frac{e^{\log\left[\frac{P(x_n=1)}{P(x_n=-1)}\right]} - 1}{e^{\log\left[\frac{P(x_n=1)}{P(x_n=-1)}\right]} + 1} = \tanh\left(\frac{\Lambda(x_n)}{2}\right).
\end{aligned} \tag{17}
$$

The corresponding soft estimate is then modulated back into a coded symbol, and is input into the MF-PIC block as the feedback from the turbo decoder. For subsequent iterations, note that the turbo code has a memory for the extrinsic probabilities of the previous iteration. This allows for more effective ways of decoding, since the turbo decoder can make use of the extrinsic information from the previous iteration, as the intrinsic information of the current iteration (if no memory was used, there would be no intrinsic information at the beginning of the iterations). In the final iteration, the final bit estimates are output from the turbo decoder, and a decision is taken.

V. RESULTS

All results assume that SF=16 and that each user has one physical channel, and a block size of 512 bits. The Pedestrian A and Vehicular A channels were used as reference channels [6]. Different types of results will be shown; with and without turbo coding, in order to quantize the coding effect.

The results without coding encompass the MMSE decoder alongside the MMSE coupled with a MF-PIC scheme of 2 iterations. This will show that the MF-PIC alone allows for a substantial performance gain.

The coded results are also divided into those with and without feedback. The results without feedback will reveal the code's performance gain, whereas the results with feedback will enhance the performance of the MF-PIC, due to more precise estimates, and hence improved cancelling. In order to ensure fair comparisons, the total number of turbo decoding operations was kept the same (total of 9 iterations) for both topologies with and without feedback.

In Figure 3, the MMSE receiver algorithm is compared to the MMSE+MF-PIC. Notice that there are substantial performance when the PIC is introduced; especially in a MIMO 2x2 environment (gain of 6dBs), due to the exploitation of interference cancelling alongside the increased receive diversity, yielding final results with better performance levels than for the single user SISO case.

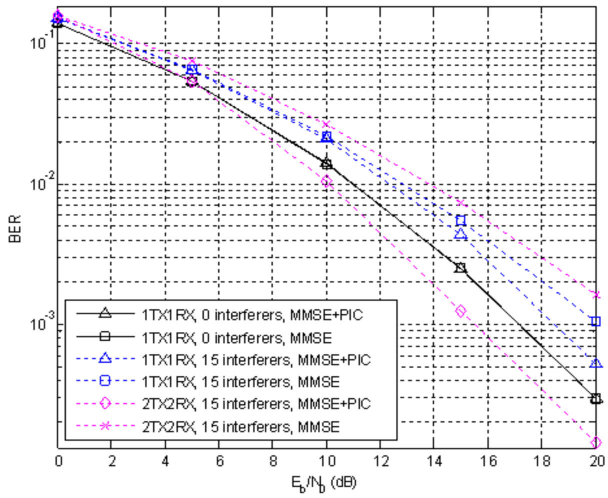

Figure 3– Uncoded BER performance for the MMSE and MMSE+PIC scheme, in the Pedestrian A channel.

Figure 4 displays the BER performance for the MMSE algorithm coupled with the turbo codec of R=1/2. Notice that the results with coding are completely different than the ones without coding, due to the impressive coding gain gleamed from the UMTS turbo code. Notice also that the turbo codec allows for the cases with higher orders of diversity (in terms of multipath and receive antennas) to yield the best performance results, due to the iterative nature of the decoding algorithm, exploiting the correct estimation and increases diversity, as did the MF-PIC previously.

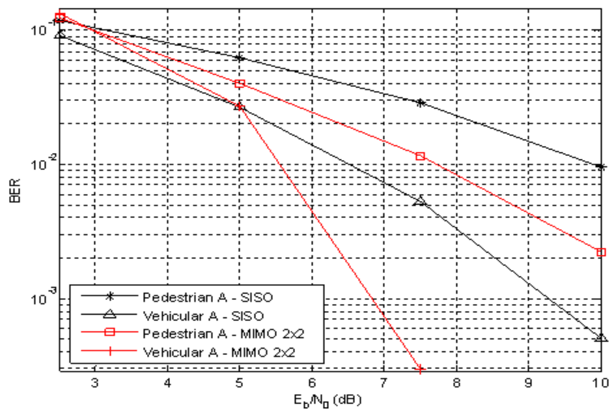

Figure 4 – BER performance of the MMSE+turbocode, for a fully loaded scenario.

Figure 5 displays the results of using a MMSE+MF-PIC coupled with the turbo codec. It can be seen that the performance gain to the similar case without the MF-PIC is significant, with gains of over 1dB for the MIMO 2x2 case.

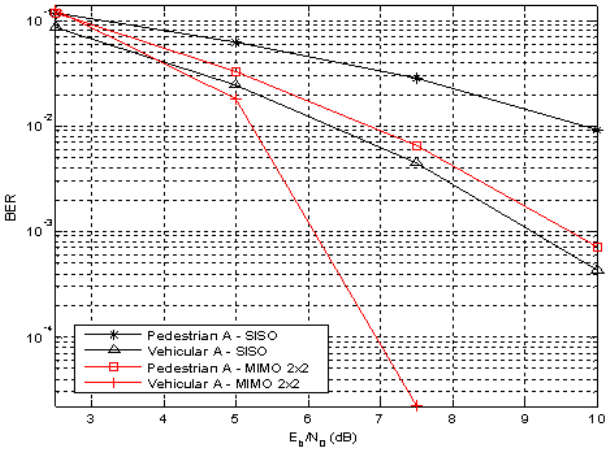

Figure 5– BER performance of the MMSE+PIC+turbocode, for a fully loaded scenario.

When turbo feedback is employed, the results are better. From Figure 6, it can be seen that the cases using MIMO 2x2 are substantially improved from the case without feedback, and that the SISO results are only slight better. Notice the case for the MIMO 2x2 in the Vehicular A channel, where the BER was reduced by one order of magnitude, for a received E_b/N_0=5dB. As before, the iterative nature of the scheme is exploited with few propagation errors, therefore making use of the receive diversity of the MIMO 2x2. It was assumed that the feedback loop was activated twice, and that each turbo decoder operation used only 3 iterations (providing a total of 9 iterations, as for the other cases).

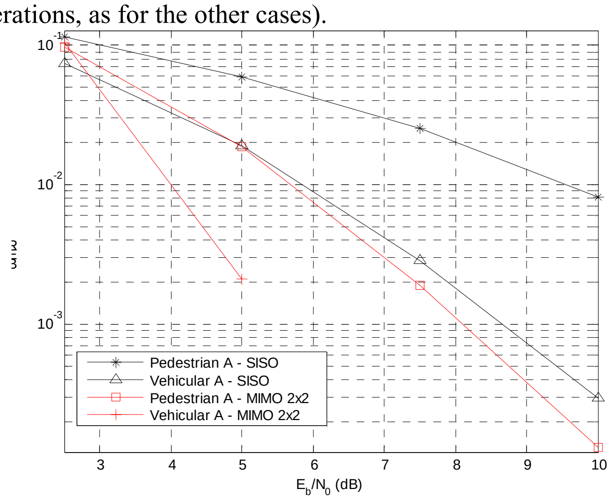

Figure 6– BER performance of the MMSE+PIC+turbocode with feedback, for a fully loaded scenario.

Before concluding this paper, it should be mentioned that similar results were previously obtained for the downlink turbo codec with feedback (with slight design modifications, alongside a turbo decoder with some shortcomings, such as the absence of memory to retain the symbol's LLR between iterations), by Jia Shen ([8][9]). This work however, considers only medium loading (with *k*/SF≈0.5) and flat-fading for the channel model, using the well known block-fading channel model (in which it is assumed that the channel remains stationary for the duration of one block of symbols, taking a new set of uncorrelated values for the next block).

VI. CONCLUSIONS

In this paper, the MMSE-based receiver algorithm was coupled with a MF-PIC and a turbo codec, in order to ensure the best results. It was possible to see that the MF-PIC aids both the uncoded and coded transmissions, and is most effective when the turbo coded is exploited in the iterative structure of the MF-PIC, providing extremely important feedback to cancel most of the estimates correctly. From the results, it can be seen that BER values under 10^{-4} can be obtained for E_b/N_0 values as low as 7dB, for a fully loaded (*k*=SF) MIMO 2x2 scenarios in the Vehicular A channel.

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