Iterative Partial-Cancelling MMSE Algorithms for W-CDMA MIMO-BLAST Systems

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***Abstract*—This paper focuses on the usage of an enhanced 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 coupled with an IPC (Iterative Partial Cancellation) scheme. The scheme is tested in both an uncoded and coded setting, using the UMTS (Universal Mobile Telecommunications System) HSDPA (High Speed Downlink Packet Access) standard as a basis, and the reference UMTS environments**

Keywords- MIMO, BLAST, Iterative detection, Interference Cancellation.

INTRODUCTION

MIMO systems are 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 especially for WCDMA systems: 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][3], adapted for multipath MIMO, was developed for such cases acting as an equalizer, yielding interesting results. In order to further improve the performance, an additional IPC scheme was added to the receiver. The IPC scheme acts as a SIC (Successive Interference Canceling), which starts by canceling the most promising estimates, and performs subsequent canceling on the remaining estimates, during a pre-defined number of iterations. Such scheme can allow a significant 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 WCDMA MIMO schemes is introduced, and the IPC-MMSE scheme is described 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. A semi-analytical approach to both the MMSE and IPC-MMSE is given in section VI, and conclusions are drawn in section VII.

MMSE RECEIVERS

A standard model for a DS-CDMA system with K users (assuming one 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

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

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 antennas and N_{RX} receive antennas on one of the receiver's antennas can be expressed as

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

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

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

Using matrix algebra, the received signal can be represented as

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

where $\mathbf{S}$, $\mathbf{C}$ and $\mathbf{A}$ are the spreading, channel and amplitude matrices respectively. In this paper, equal power levels were considered for all users, and hence the $\mathbf{A}$ matrix is not necessary. The structure of the matrices is explained in detail in [3].

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

$$\mathbf{b}=\left[b_{1,1,1},\ldots,b_{N_{TX},1,1},\ldots,b_{1,K,1},\ldots,b_{N_{TX},K,1},\ldots,b_{N_{TX},K,N}\right]^T. \qquad (5)$$

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-zero values as close to the diagonal as possible. It should also be notted 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 $\mathbf{n}$ vector, with noise components to be added to the received vector r_v, has length $N\cdot SF\cdot N_{RX}+N_{RX}\cdot\psi_{MAX}$ ($\psi_{\max}$ is the maximum delay of the channel's impulse response, normalized to the number of chips, $\psi_{MAX}=\lceil\tau_{\max}/T_c\rceil$ where T_c is the chip period). The r_v vector is

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

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.

The equalization receiver used as basis in this work employs the MMSE algorithm and is based on the Matched Filter output,

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

From [4], the EM (Equalization Matrix) is

$$\mathbf{E}_{M,MMSE}=\mathbf{R}+\sigma^2\mathbf{I}\,, \qquad (8)$$

with

$$\mathbf{R}=A\cdot C^H\cdot S^H\cdot S\cdot C\cdot A\,. \qquad (9)$$

The MMSE estimate is thus

$$\mathbf{y}_{MMSE}=\hat{\mathbf{b}}=\mathbf{E}^{-1}_{M,MMSE}\,\mathbf{y}_{MF}\,. \qquad (10)$$

IPC-MMSE Algorithm

The IPC variant of the MMSE receiver is built on top of the MMSE scheme. From the MMSE estimates, a pre-defined number of the best symbols that are considered to be well-estimated (according to a decision function, which can be either the optimum *tanh* of (16) or the clipped soft decision [6]) are rounded to the nearest symbol in the constellation and taken out of the equation. This pre-defined number of symbols may vary from according to channel conditions and BER, but in our case we will always consider that only 50% of the symbols of each iteration are chosen for hard-decision. The partial-received message is then computed as

$$\mathbf{p}_{rv}=\mathbf{r}_v-\left(\mathbf{SCA}\right)\hat{\mathbf{p}}\,, \qquad (11)$$

where $\hat{\mathbf{p}}$ represents the symbols to be taken out of the equation (with "0"s inserted in the places of all other symbols). The new $\mathbf{p}_{MF}$ (partial MF) estimates are given by

$$\mathbf{y}_{p_{MF}}=\left(\mathbf{p}_{SCA}\right)^H\mathbf{p}_{rv}\,, \qquad (12)$$

where $\mathbf{p}_{SCA}$ denotes the $\mathbf{SCA}$ matrix result without the columns that belong to the symbols taken out of the equation. Next we just have to follow the MMSE algorithm, which becomes

$$\mathbf{p}_R=\left(\mathbf{p}_{SCA}\right)^H\left(\mathbf{p}_{SCA}\right), \qquad (13)$$

$$\mathbf{p}_{E_M}=\mathbf{p}_R+\sigma^2\mathbf{I} \qquad (14)$$

and

$$\mathbf{y}_{p_{MMSE}}=\left(\mathbf{p}_{E_M}\right)^{-1}\mathbf{y}_{p_{MF}}\,, \qquad (15)$$

where σ^2 is assumed to be invariant. The procedure is repeated until a stopping criterion is met, usually a specific number of iterations.

Figure 1 illustrates a simple chart of the IPC-MMSE scheme. Notice the connections for the turbo decoder (when turbo code is used at the transmitter).

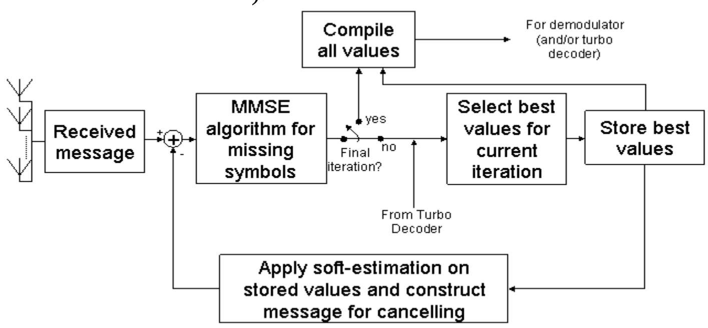

Figure 1 - IPC-MMSE Scheme

Turbo Codec

The turbo decoder scheme is portrayed in Figure 2. It uses the MAP decoder [5] as the basis algorithm and performs 8 iterations for the turbo decoding stage.

Two types of decoding arrangements were considered: one where the IPC scheme is run for a specific number of iterations, and the decoding is done only at the end; and the other with turbo decoding feedback, i.e., where the IPC scheme is run for several loops (each loop with a specific number of iterations), with the turbo decoding module being run every time the IPC loop ends. In the latter case, there is feedback from the turbo decoder, with the estimates for the coded bits (i.e., those for which the MMSE algorithm provides estimates).

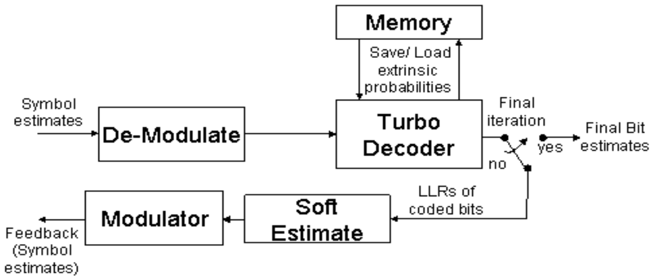

Figure 2– Turbo decoder scheme

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

$$E\left(x_n\right) = P\left(x_n = 1\right)\cdot 1 + P\left(x_n = -1\right)\cdot\left(-1\right) =$$

$$= \frac{P\left(x_n = 1\right) - P\left(x_n = -1\right)}{P\left(x_n = 1\right) + P\left(x_n = -1\right)} =$$

$$= \frac{\frac{P(x_n=1)}{P(x_n=-1)} - 1}{\frac{P(x_n=1)}{P(x_n=-1)} + 1} = \frac{e^{\log\left[\frac{P(x_n=1)}{P(x_n=-1)}\right]} - 1}{e^{\log\left[\frac{P(x_n=1)}{P(x_n=-1)}\right]} + 1} = \tanh\left(\frac{\Lambda(x_n)}{2}\right). \quad (16)$$

The corresponding soft estimate is then modulated back into a coded symbol, and is input into the IPC block as the feedback from the turbo decoder. It should be noted that, for subsequent iterations, the turbo decoder stores the extrinsic probabilities of the previous iteration. This allows 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 (otherwise, there would be no intrinsic information at the beginning of the iterations). In the final iteration, the final bit estimates are the output of the turbo decoder, and a decision is taken.

PERFORMANCE RESULTS

All results assume that *SF*=16, 3 iterations for the IPC scheme and one user per physical channel. Each user had a block size of 512 bits and equal power levels. The Pedestrian A and Vehicular A channels were used as reference channels [7].

Figure 3 compares some results of both the normal MMSE and the IPC-MMSE, where the gain obtained from using the IPC scheme is noticeable. It is also interesting to observe that the IPC scheme surpasses the SISO single user case in the fully-loaded MIMO 2x2 situation, due to correct estimation and cancelling, with the added receive diversity.

Figure 4 portrays the results for the MMSE coupled with a turbo decoder without feedback, for both the SISO and MIMO 2x2 using spatial multiplexing setting. Notice that now, due to turbo (iterative) decoder, the MIMO 2x2 setting provides better results than the SISO. Figure 5 shows the same performance results for the IPC-MMSE scheme. Major performance gains are observed: e.g., the BER of 10^{-4} is obtained for an E_b/N_0 of 7dB for the fully loaded Vehicular A 2x2, whereas in the uncoded case, this would only be attainable with E_b/N_0 over 20dB.

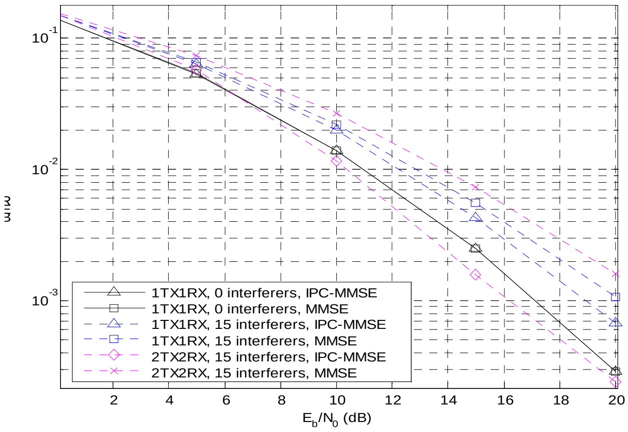

Figure 3– Uncoded BER performance of the IPC-MMSE and MMSE scheme, for the Pedestrian A channel.

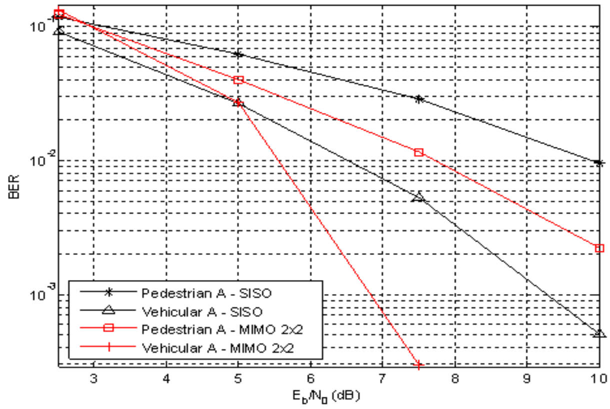

Figure 4 – Coded BER performance of the MMSE scheme, for a fully loaded scenario.

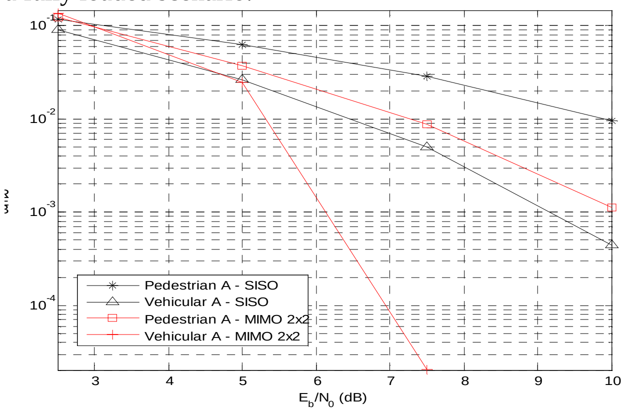

Figure 5– Coded BER performance of the IPC-MMSE scheme, for a fully loaded scenario.

Clearly, when turbo feedback is employed, the performances 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 remain identical. 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.

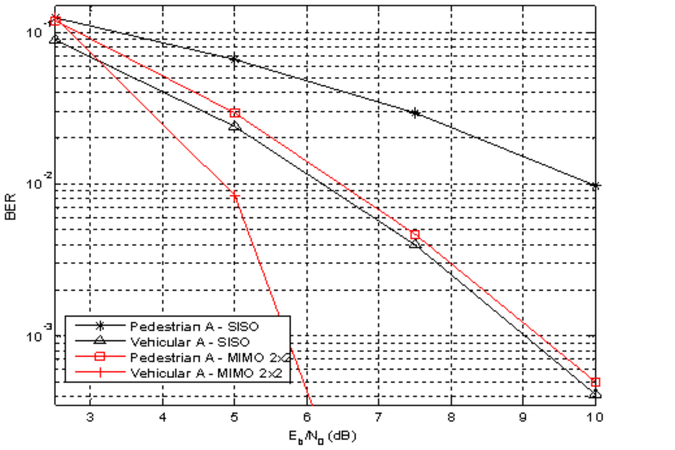

Figure 6– Coded BER performance of the IPC-MMSE scheme with feedback, for a fully loaded scenario.

SEMI-ANALYTICAL BER PERFORMANCE

The results for both the uncoded MMSE and IPC-MMSE performance can be approximate via semi-analytical analysis, in order to obtain initial estimates for system performance.

The MMSE estimated symbol is given by

$$y_{k,n} = \left(s_{k,n} + n_{k,n}\right)\alpha_{k,n}, \tag{17}$$

where $s_{k,n}$ is the symbol to be estimated, $\alpha_{k,n}$ is the associated bias of the MMSE algorithm, and $n_{k,n}$ is the remaining noise factor. The bias is thus given by

$$\alpha_{k,n} = \frac{y_{k,n}}{s_{k,n} + n_{k,n}}, \tag{18}$$

The variance of the remaining noise parameter is

$$Var\left(n_{k,n}\right) = E\left(\frac{y_{k,n}}{\alpha_{k,n}} - s_{k,n}\right)^2. \tag{19}$$

Using the MMSE system matrices [3], the bias is given by the diagonal of the matrix comprising all of the operations from the transmission to the reception and MMSE decoding of the symbols (in a noiseless setting, this resulting matrix is an identity matrix),i.e.,

$$\alpha = diag\left(\left(\mathbf{H}^H \mathbf{H} \mathbf{C}_b + \sigma_n^2 \mathbf{I}\right)^{-1} \cdot \left(\mathbf{C}_b \mathbf{H}^H \mathbf{H}\right)\right). \tag{20}$$

The variance of the noise is obtained from the variance of the MMSE estimate,

$$Var\left(n_{k,n}\right) = E\left[\left(\frac{y_{k,n}}{\alpha_{k,n}} - s_{k,n}\right)^2\right] = \frac{1}{\alpha_{k,n}^2} E\left[\left(y_{k,n} - \alpha_{k,n} s_{k,n}\right)^2\right] = \frac{1}{\alpha_{k,n}^2}\left[E\left(y_{k,n} - s_{k,n}\right)^2 - \left(\alpha_{k,n} - 1\right)^2\right], \tag{21}$$

subject to

$$E\left(y - s\right)^2 = \mathbf{C}_\varepsilon, \tag{22}$$

where $\mathbf{C}_\varepsilon$ is obtained from [4] in the MMSE derivation, and

$$E\left(s_{k,n}^2\right) = s_{k,n}^2 = s_{k,n} \cdot s_{k,n}^H = 1 \tag{23}$$
$$E\left(y_{k,n}\right) = \alpha_{k,n} E\left(s_{k,n}\right) = \alpha_{k,n} s_{k,n}.$$

Assuming that the overall noise is Gaussian, the BER performance can easily be obtained from the noise variance.

For instance, for the QPSK modulation, the BER performance is

$$BER = Q\left(\sqrt{SNR}\right). \tag{24}$$

To verify that the estimation is consistent with the results, some simulations were run to compare BER results. From the results in Figure 7, for the flat fading (1-tap) and the 6-tap (of equal power and equally spaced) channels, it can be seen that the predicted BER performance is identical to the simulated results.

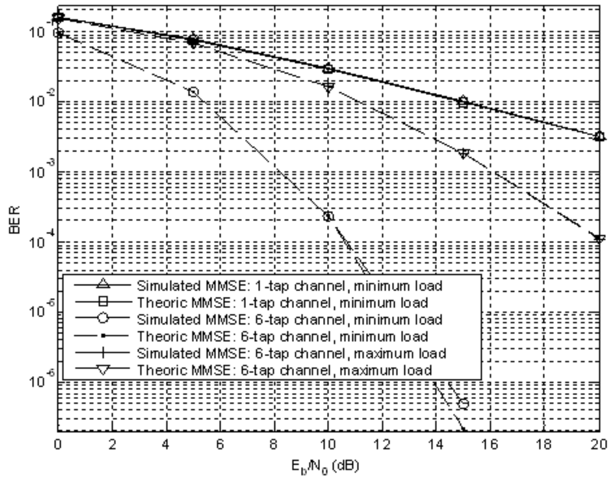

Figure 7 – BER performance when a MMSE receiver is employed, for MIMO 2x2.

The IPC-MMSE performance can also be estimated, although it is slightly more difficult due the complexity of the algorithm (see Figure 8).

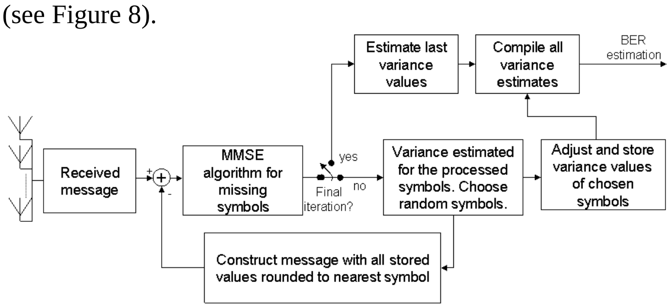

Figure 8 – Semi-analytical processing of IPC-MMSE scheme.

Initially, the normal MMSE estimation procedure is carried out and the initial variances are obtained. From these variances, the initial thought would be to sort the variances and choose the values with highest variance for the IPC iteration, and continue to process the values using this philosophy. This would provide pessimistic results since the IPC-MMSE algorithm chooses the received values that are most likely to be right; i.e., the values that are closer to the transmitted symbols after being subject to a soft-decision function (hyperbolic tangent, in this case), albeit the values with "high probability" in Figure 9 for the QPSK modulation (the further away, the higher the probability, in such a zone).

Therefore, the values with expected high variance might be well into the high probability zone (around 50% of the values). The best values chosen in the first iteration will most likely yield no errors, since they are the ones most likely to be correct. This means that a small variance value should be awarded. The same reasoning applies for all other iterations other than the last, whose final estimated variance values would be assumed to be correct.

The estimation algorithm run for the IPC-MMSE routine considered the top 10% best symbols to be absolutely correct (variance=0). All other values were considered to have a variance of 70% (obtained by trial-and-error, alongside an analysis on the IPC-MMSE algorithm for different cases) of their estimated variance, except for the remaining symbols of the last iteration, whose variance remained unchanged. Since three iterations were used, with processing percentages of 50%, the remaining symbols of the last iteration represented $50\% \times 50\% \times 50\% = 12,5\%$ of the total number of symbols.

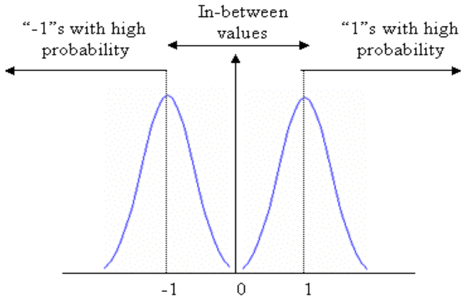

Figure 9 – Distribution of the noisy estimated symbols.

From the results in Figure 10, it is clear that the MF-PIC estimation is very close to the simulated results, proving that the Gaussian approximation of the overall noise was correct.

The IPC-MMSE estimates are slightly more different than those obtained experimentally (providing optimistic results), since the estimation parameters were obtained by trial and error, as explained earlier. However, the approximation is reasonable, with differences under 0.5dBs. Notice also that the estimated results are optimistic, since no canceling errors are considered between iterations.

CONCLUSIONS

In this paper, the IPC-MMSE scheme was implemented and compared against the normal MMSE receiver. Significant performance gains relatively to the MMSE receiver were obtained with the use of the IPC scheme, for both the coded and uncoded situations. It should be pointed out that the complexity associated to the IPC scheme is only about twice the complexity of the basic MMSE receiver, since the IPC scheme basically consists of running the MMSE algorithm repeatedly for the partial message for all iterations.

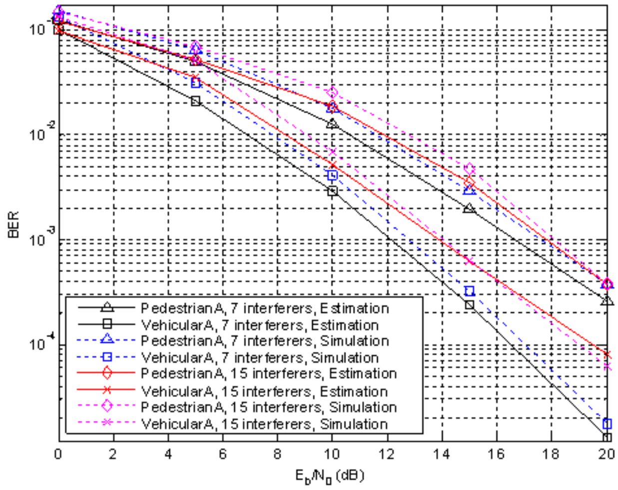

Figure 10 – Uncoded semi-analytical and simulated BER performance for a SISO setting, using the IPC-MMSE.

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REFERENCES

[1] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," Wireless Pers. Commun., vol. 6, pp. 311–335, Mar. 1998.

[2] M. Latva-aho, M. Juntti, "LMMSE Detection for DS-CDMA Systems in Fading Channels", IEEE Transactions on Communications, vol.48, no2, February 2000.

[3] J. Silva, N. Souto, A. Rodrigues, A. Correia, F. Cercas, R. Dinis, "A L-MMSE DS-CDMA Detector for MIMO/BLAST Systems with Frequency Selective Fading", IST Mobile&Wireless Communications Summit 2005, Dresden, Germany, 19.23 June 2005.

[4] S. Kay, "Fundamentals of Statistical Signal Processing: Estimation Theory", Englewood Cliffs, NJ: Prentice-Hall, 1993, pg391.

[5] S. S. Pietrobon, "*Implementation and performance of a serial MAP decoder for use in an iterative turbo decoder*", IEEE Int. Symp. Inform. Theory, Whistler, British Columbia, Canada, p. 471, Sep. 1995.

[6] H. Sugimoto, L. K. Rasmussen, T.J. Lim and T. Oyama, "*Mapping functions for successive interference cancellation in CDMA*", IEEE VTC, pp. 2301-2305, Ottawa, Canada, May 1998.

[7] 3GPP Technical Report 25.996 v6.1.0 (2003-09).

FP6-IST-507607 Project B-BONE, "Broadcasting and multicasting over enhanced UMTS mobile broadband networks", URL:http://b-bone.ptinovacao.pt/