Turbo PIC and Antenna Diversity for DS-CDMA 3G Systems for Wireless Block Fading Communications

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***Abstract*: This paper presents a Turbo Multiuser detector for Turbo-Coded DS-CDMA systems, which is based on the utilization of Parallel Interference Cancellation scheme and antenna diversity in the receiver. Since a wireless rich-scattering block fading channel is considered, Multiple Access Interference effects are naturally reduced by antenna diversity, and, successively, completely eliminated by a single turbo cancellation iteration, for a half-loaded system. We will also show that the proposed Turbo-PIC detector is characterized by remarkable performance in term of BER even for overloaded systems: particularly, we will stress out the low complexity required to suppress MAI and achieve excellent results, also in the block fading environment where the high correlation strongly limits single user bound.**

1. Introduction

The main performance losses for a wireless coded CDMA system are caused by the Multiple Access Interference (MAI) and the poor capacity of error correction of turbo codes on slowly fading channels [1] [2].

For what concerns muliple access systems, firstly Multiuser Detection (MUD) researches have been focused on uncoded systems; however, practical CDMA communications rely on the utilization of error control coding and interleaving so that, recently, more and more attention has been addressed to the coded systems. Optimal joint decoding/detection is an excellent solution to this problem, as shown in [3]. However, this scheme results in a prohibitive computational complexity for actual implementation. In contrast, suboptimal solutions, which separate the operations of symbol detection and channel decoding, appears more attractive for practical applications.

Since the proposal of turbo codes [4], the ”Turbo-Principle”, i.e., the soft information iterative exchange between receiver constituent blocks, has been foreseen as a possible booster for the MUD schemes. Several iterative receivers have been proposed for coded CDMA communication systems. In particular, the attention has been devoted to Parallel Interference Cancellation (PIC) receivers because of their relatively reduced complexity compared to the linear detectors and small delay with respect to serial cancellation.

For what concerns wireless channel drawbacks, antenna diversity at the receiver has been proposed as a low-cost solution to the fading impairments. Furthermore spatial diversity at the Base-Station (BS) provides an increased signal-to-noise ratio, which helps to remove more accurately MAI thanks to a better initial estimate of the received signal [9]. Moreover, the recent studies on Multiple Input Multiple Output (MIMO) systems [5] [6] [7] showed that it is possible to exploit a rich scattering wireless channel to separate users and, as a consequence, reduce the MAI.

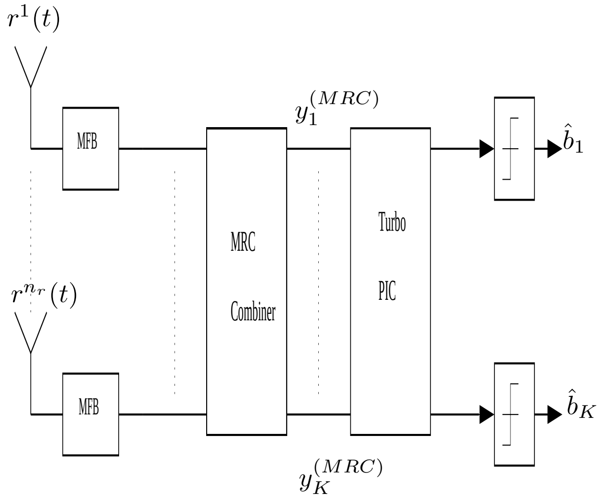

Figure 1: The Turbo-PIC sheme employed

According to [7] a multiuser CDMA scheme with one antenna per user and antenna array at the BS can be regarded as a MIMO single user system; therefore, we can state that near-capacity-limit performance are achievable using both MUD and spatial diversity [6] [7].

The aim of this paper is to show that the utilization of low complexity iterative receiver, such as the PIC, together with receive diversity permits to completely eliminate MAI even for heavily loaded systems in highly correlated fading channels: particularly, the MUD receiver which has been considered is based on the generalization of a Turbo-PIC detector to a multiple antenna diversity system. It is important to point out that, conversely from [17], different PIC strategies are proposed and compared herein.

It is worth stressing that the ultimate limit for the proposed scheme is the single user bound: since turbo codes fail to recover errors in presence of a strongly correlated fading channel, performance in block fading channel can be regarded as a sort of worst case bound for the wireless communications. Nonetheless a proper diversity schemes naturally leads to user separation, boosts the convergence of cancellation algorithm and affords remarkable performance to the turbo MUD receivers.

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2. System Model

We consider the up-link of a synchronous DS-CDMA communication system, where the BPSK baseband symbol spreading is performed by a PN code. Each user uses a single element antenna, i.e., no transmit diversity is introduced, and transmits a coded stream to a BS with n_r receiving antennas: the receiving antennas are properly spaced so each of them receives indipendent replicas of the trasmitted signals.

Without loss of generality, we can assume that one generic bit-interval is observed. The baseband signal received in antenna j-th can be written as:

$$r^j(t) = \sum_{k=1}^{K} h_{jk} c_k s_k(t) + n(t) \qquad t \in [0, T_b] \tag{1}$$

where:

- K is the number of active users;
- T_b is the bit interval;
- h_{jk} is the complex channel coefficient of the link between the antenna j-th and the k-th user;
- $c_k \in \{+1, -1\}$ is the coded bit transmitted by k user;
- $s_k(t)$ is the k-th user's spreading sequence;
- $n(t)$ is an Additive White Gaussian Noise (AWGN) process with double sided spectrum density $\sigma^2 = No/2$ [W/hz].

A Rayleigh block-fading channel model as in [5] is assumed: h_{jk} is a complex coefficient and its real and imaginary part are Gaussian distributed with zero mean and $\frac{1}{\sqrt{2}}$ variance; moreover each link is assumed to be uncorrelated and identically distributed (iid assumption). As is known, in the Block-Fading (BF) model, the fading factors for each link remain constant for the duration of the entire transmitted frame, then assuming a new, uncorrelated set of random values for the next block.

We also assumed single path propagation between each user and and each antenna at the BS and that all the transmit power for each user is received and equally divided between each BS antenna.

The detailed receiver structure, shown in Fig. 1 can be described as follows:

1 The baseband signal $r^j(t)$ which is received by each j-th antenna is filtered by a Matched Filter Bank (MFB) in order to separate users. The i-th user's signal at the output of the MFB on the j-th antenna can be written as follows:

$$y_i^j = h_{ji} c_i + \sum_{k=1 k \neq i}^{K} h_{jk} \rho_{ki} c_k + \nu_i^j, \tag{2}$$

where $\nu_i^j = \int_0^{T_b} n(t) s_i(t) dt$ is the filtered Gaussian noise sample and $\rho_{ki} = \frac{1}{T_b} \int_0^{T_b} s_i(t) s_k(t) dt$ is the normalized crosscorrelation coefficient between users k-th and i-th.

2 For each user the Maximal Ratio Combining (MRC) is performed collecting signal's replicas from each antenna. At the output of the combiner the desired i-th user's signal is:

$$\begin{aligned} y_i^{(MRC)} &= \sum_{j=1}^{n_r} h_{ji}^* y_i^j = \sum_{j=1}^{n_r} |h_{ji}|^2 c_i \\ &+ \sum_{j=1}^{n_r} \sum_{k=1 k \neq i}^{K} h_{ji}^* h_{jk} \rho_{ki} c_k \\ &+ \sum_{j=1}^{n_r} h_{ji}^* \nu_i^j . \end{aligned} \tag{3}$$

It is worth stressing that, due to the previous hypotheses, the statistical mean $E\left[h_{ji}^* h_{jk}\right]$ is equal to zero if a infinite number of antenna elements are considered: channel tends to naturally decorrelates users if a high degree of space diversity is introduced. Nonetheless, since a limited number of antenna elements is considered, the second term in (3) is only an approximation of the crosscorrelation and, therefore, MAI is not completely eliminated after MRC blocks. In order to highlight the gain achieved by means of the antenna diversity at the BS, we define the combined SNR per bit at the output of the MRC as follows [16]:

$$\overline{\gamma_b} = n_r \frac{E_b}{N_o}. \tag{4}$$

As it can be noted, the SNR will be increased n_r times after MRC, so providing two benefits [9] : firstly, a better initial signal estimate is obtained; besides, a more accurate MAI estimation can be achieved, due to the lower error rate.

3 The combined signal $y^{(MRC)}$ is fed into the Turbo-PIC detector which provides interference cancellation and turbo decoding. Based upon the estimated bits, MAI is generated for all users and subtracted from the received signal to get the desired signal (with a reduced MAI level) for each user. The K soft outputs of PIC are the inputs for the decoders of each user. In the following section the Turbo-PIC receiver will be analyzed in more detail.

3. The Iterative Turbo-PIC Receiver

An iterative cancellator consists of an Interference Cancellation (IC) based Multiuser Detector followed by K single-user turbo decoders. Each constituent block iteratively provides soft informations to the others, as shown in Fig 2.

The PIC stage delivers soft outputs $\tilde{y}_k$ to the input of turbo decoders. After one decoding iteration [2], the extrinsic information of coded bits are fed back to the cancellator and assumed equal to the a priori information for the next iteration.

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[2] The number of turbo decoder iteration could also be greater than one.

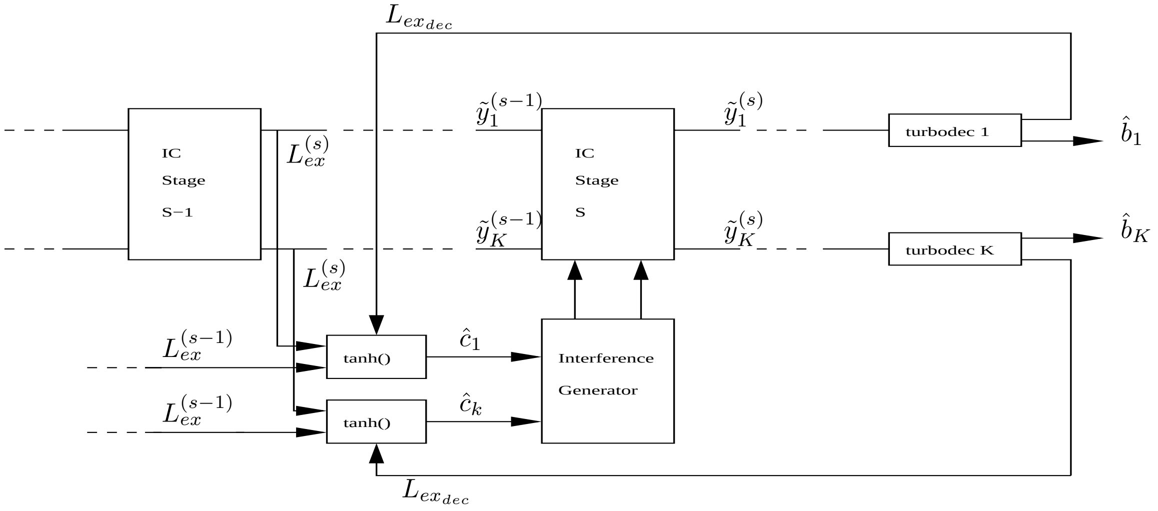

Figure 2: Block diagram of the Turbo-PIC.

This type of detector has been shown to achieve very good performance in AWGN and fast fading environments [14] [11]. Our effort is to investigate the possibility to use the same scheme even for BF channel by means of space processing.

The considered turbo codes are composed by two Recursive Systematic Convolutional (RSC) codes linked by an interleaver; a MAP based algorithm is used for iterative decoding [13]. Since the IC receiver requires soft information about the reliability of both the systematic and the parity bits, the decoding algorithm is properly modified to produce also extrinsic information about the latter [14]. At each new iteration, the iterative structure permits the multiuser receiver to have a more reliable a priori information and the decoders to operate on soft inputs, after the cancellation of a significtive amount of interference.

In this work we used a partial PIC mainly derived by the one proposed by Divsalar *et alii* [15], with a slight modification in the calculation of extrinsic information, together with some other PIC receivers derived from the literature. As it is well known, the receiver proposed by Divsalar significantly reduces the effects of interference by removing only a fraction of MAI at each stage according to data estimates' reliability. As stated above, the convergence of cancellation algorithm can be boosted using extrinsic information coming from the turbo decoders; hence, the combination antenna diversity, partial PIC and turbo decoding should provide high performance in terms of MAI suppression with few turbo-MUD iterations.

3.1. Theorical Outline

After MRC block , the i-th user's signal at the output of MRC is fed to the PIC device, which attempts to eliminate MAI using other users'signal estimates. The signal at the output of the s-th stage of the cancellator can be written as follows:

$$\tilde{y}_i^{(s)} = \overline{p}_i^{(s)}(y_i^{(MRC)} - \hat{I}_i^{(s)}) + (1 - \overline{p}_i^{(s)})\tilde{y}_i^{(s-1)}, \quad (5)$$

where $\hat{I}_i^{(s)}$ is the amount of reconstructed interference and $\overline{p}_i^{(s)}$ is the weight for the s-th stage. The a posteriori Log-Likelihood-Ratio (LLR) of the i-th user at the s-th stage is defined as follows:

$$L^{(s)}\left(c_i\right) \triangleq \log\frac{p\left(c_i = +1 |\, y_i^{(MRC)}, \tilde{y}_i^{(s-1)}, \hat{I}_i^{(s)}\right)}{p\left(c_i = -1 |\, y_i^{(MRC)}, \tilde{y}_i^{(s-1)}, \hat{I}_i^{(s)}\right)} . \quad (6)$$

By means of Bayes' rule, equation (6) can be rewritten as:

$$\begin{aligned} L^{(s)}\left(c_i\right) = {} & \log\frac{p\left(y_i^{(MRC)} |\, c_i = +1, \tilde{y}_i^{(s-1)}, \hat{I}_i^{(s)}\right)}{p\left(y_i^{(MRC)} |\, c_i = -1, \tilde{y}_i^{(s-1)}, \hat{I}_i^{(s)}\right)} + \\ & + \log\frac{p\left(\tilde{y}_i^{(s-1)} |\, c_i = +1, \hat{I}_i^{(s)}\right)}{p\left(\tilde{y}_i^{(s-1)} |\, c_i = -1, \hat{I}_i^{(s)}\right)} + \\ & + \log\frac{p\left(c_i = +1, \hat{I}_i^{(s)}\right)}{p\left(c_i = -1, \hat{I}_i^{(s)}\right)} , \quad (7) \end{aligned}$$

Under the assumptions that users are statistically indipendent and terms $\tilde{y}_i^{(s-1)}$ and $y_i^{(MRC)}$ are uncorrelated, eq. (7) can be approximated by:

$$\begin{aligned} L^{(s)}\left(c_i\right) \approx {} & \log\frac{p\left(y_i^{(MRC)} |\, c_i = +1, \hat{I}_i^{(s)}\right)}{p\left(y_i^{(MRC)} |\, c_i = -1, \hat{I}_i^{(s)}\right)} + \\ & + \log\frac{p\left(\tilde{y}_i^{(s-1)} |\, c_i = +1\right)}{p\left(\tilde{y}_i^{(s-1)} |\, c_i = -1\right)} + \log\frac{P\left(c_i = +1\right)}{P\left(c_i = -1\right)} . \quad (8) \end{aligned}$$

The first and the second terms represent the extrinsic information $L_{ex}^{(s)}$ at the output of s-th stage, while the third one is the a priori information $L_{ap}^{(s)}$ provided by previous stages and decoders.

The tentative decision function we use takes into account both extrinsic information from the decoders and channel outputs [17]: in particular, the extrinsic information term that takes into account the channel information is [15]:

$$L_{ex}^{(s)} = \frac{2}{\overline{p}_i^{(s)} \sigma_{i,s}^2} \tilde{y}_i^{(s)}, \tag{9}$$

where $\sigma_{i,s}^2$ is the noise-plus-residual interference variance and $\overline{p}_i^{(s)}$ is the weight coefficient at stage s. Soft estimates of coded bits, $L_{ex}^{(s)}$ are achieved by a suitable hyperbolic tangent tentative decision function with the a priori information coming from previous stages and decoders, as in the following :

$$\hat{c}_i^{(s)} = \tanh\left(L_{ex}^{(s)} + L_{ap}^{(s)}\right), \tag{10}$$

$$L_{ap}^{(s)} = L_{ex}^{(s-1)} + L_{ex_{dec}}. \tag{11}$$

In order to keep the required complexity low, the weights $\overline{p}_i^{(s)}$ are pre-assigned and noise-plus-residual interference variance $\sigma_{i,s}^2$ is approximated by thermal noise variance σ^2. At the first iteration, the parameters are set as follows:

$$\hat{c}_i^{(0)} = \operatorname{sgn}\left(y_i^{(MRC)}\right)$$

$$\tilde{y}_i^{(0)} = y_i^{(MRC)}.$$

After last cancellation, the soft outputs are sent to the inputs of turbo decoders, which use these values in the calculation of probability transition.

3.2. The considered PIC schemes

In this work we have considered two different PIC schemes, both derived by the general Turbo-PIC, that has been described previously. Aiming to keep the required complexity low with no performance loss, we compared the performance results, of a Total PIC (TPIC) and a Modified Weighted PIC (MWPIC).

The TPIC is a classical one-stage cancellator where all the cancellation weights have been set equal to 1 for all the users.

Conversely, the MWPIC device has been introduced to achieve the best performance from the use of space processing. As shown in section 2., antenna diversity helps to obtain a better initial estimate of the received signal; hence, the reconstructed signals can be considered more reliable and cancelled with a higher weigth. The weights assigned to the cancellation stages are pre-calculated.

Moreover, we also think to increase the slope of the tentative decision so that in a second cancellation stage, a larger amount of MAI can be subtracted. The slope of the tanh() function is controlled by the parameter α, which needs to be calculated [10].

4. Single-User Bound

In order to show the performance degradation due to the use of turbo codes in a correlated fading channel , in this section the single user (SU) case is considered.

The architecture of the receiver that has been used in this case is similar to the one descrbed in Fig. 1. The only difference is that the Turbo-PIC has been substituted by a turbo decoder.

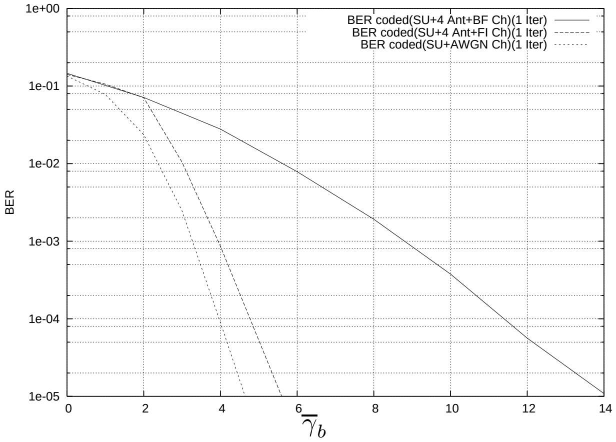

Figure 3: BER comparison for different types of channels. Turbo Codes with rate $R_c = 1/2$, number of receiving antennas $n_r = 4$, frame length equal to 800.

In Fig. 3 we compared the performance of the receiver in the cases of Block-Fading, Fully-Interleaved[3] (FI) and AWGN channels. It can be easily noted the considerable performance due to the increased correlation in fading: in the FI case the receiver achieves performance close to the AWGN bound, whereas in the BF case the receiver performance is quite poor.

We also noted that increasing the number of decoding iterations is ineffective in a correlated fading environment; in Fig. 4 it is shown that three iterations provide a slight gain (< 1 dB) over the single iteration case and no additional gain is reached with more than three iterations. The performance of the system could be improved only by means of an external interleaver; however, this solution can result in the introduction of an intolerable decoding delay [2]. Nevertheless antenna diversity is an essential feature to control the degradation in performance caused by fading; this effect is particularly detrimental in low-mobility scenarios (e.g. pedestrian and wireless LAN channels), which are well modelled by the BF channel used in this work.

5. Simulation Results

In this section we investigate the effectiveness of the proposed receiver through computer simulations. In order to mitigate the complexity burden due to the implementation of a non-linear decision device, the tanh() function has been approximated through an eight-values look-up table. For all simulations we use a rate R_c=1/2 turbo code, composed by two 8-state RSC codes with generator polynomials $G_0 = (13)_8$ $G_1 = (15)_8$, and the Block Interleaver recommended by the UMTS standard [18]. The BF Rayleigh channel model presented in section 2. represents the worst operative condition for the proposed scheme [8]. We also assume that all signal and channel parameters are known at the receiver.

Even if the system which has been considered is completely general and the remarks that can be drawn from

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[3] We assumed that fading coefficients vary from bit to bit and that they are statistically independent.

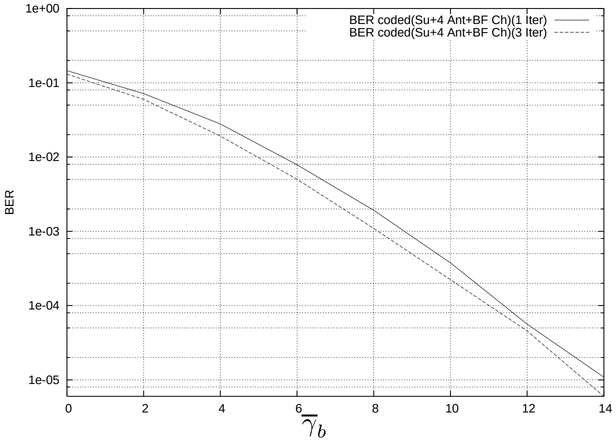

Figure 4: BER performance for the SU case with 1 and 3 decoding iterations. Turbo Codes with rate $R_c = 1/2$, number of receiving antennas $n_r = 4$, frame length equal to 800.

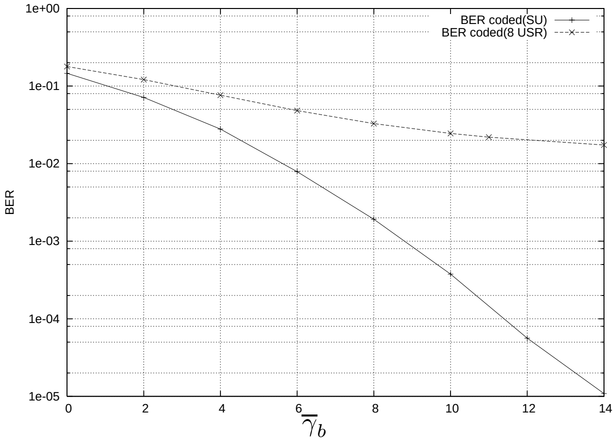

Figure 5: Performance comparison of the SU case and Multiuser with $K = 8$ users and $G = 16$. Users have equal-power.

the simulation results can be drawn for any wireless multi access system, the highly correlated block fading nature of the channel naturally leads to focus the conclusions of this work to a wireless indoor environment.

First, we analize the performance of the system with 8 active users, processing gain $G = 16$ and frame length equal to 800. The spreading sequences are PN codes with crosscorrelation factor $\rho \leq 0.75$ and the BS uses 4 separate antennas to receive users' signal. In Fig. 5 the performance of the conventional receiver, i.e., matched filter banks followed by turbo decoder, is reported in the case of a SU case and 8-users systems without interference cancellation: in the the multiuser case, the conventional system rapidly reaches a floor due to the MAI; the natural decorrelation effect provided by the channel is not sufficient to recover the performance loss. We could obtain better results only with a very large number of antennas; however, this solution is quite impractical. We also noted that the BER itself of the MAI-free case is limited; BER$= 10^{-3}$ is reached only at $\overline{\gamma}_b = 9$ dB: this result is due to the fact that the single user bound of turbo codes schemes is strongly limited by correlated fading.

Fig 6 and Fig 7 show the performance of the proposed scheme employing a TPIC device. Two Turbo-PIC iterations are needed to reduce MAI to negligible levels and get closer than 1 dB to the SU bound BER.

The results, obtained by using a MWPIC with weights $p_1 = 0.8, p_2 = 1.0, \alpha = 4.0$, are shown in Fig. 8 and Fig. 9. MWPIC outperforms TPIC both in BER and FER performances and it has a lower complexity because it needs just one iteration to reach the SU bound[4].

In this case the slope of the hyperbolic tangent tentative decision function has been increased: this strategy implies that the device acts more like a hard decision one, so confirming the assumption made on the improved reliability due to antenna diversity.

Finally, in order to highlight the remarkable MAI suppression of the proposed schemes, we have studied an overloaded system with load factor $\beta = K/G = 2.4$. We have assumed 12 active users, processing gain $G = 5$ and $\rho = 0.6$, the analisys has been carried out at a given $\overline{\gamma}_b = 8$ dB. As shown in Fig. 10, the TPIC needs 5 iterations to get very close to the MAI-free performance[5], whereas the MWPIC performance bounded is far from this limit. This behaviour can be explained by noting that the MWPIC set of parameters has not been optmized for this case: if a new set is consiedered ($p_1 = 0.6, p_2 = 0.8, \alpha = 2$) MWPIC achieves better performance than TPIC with the same number of iterations (Fig. 11).

6. Conclusion

In this paper a Turbo-PIC detector based on receive diversity has been presented. The utilization of antenna diversity provides better signal's estimate at the receiver and helps mitigate the loss in performance due to fading. The results obtained for the proposed scheme show that interference can be almost completely eliminated both for half-loaded and overloaded systems, even in the case of strongly correlated channel, such as the BF model used. Even if the number of required turbo-PIC iterations increases as the system's load gets higher, the Turbo-PIC detector is characterized an excellent behaviour and a sustainable complexity.

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[4] Since the main part of the complexity burden is due to the turbo decoding, to reduce the number of turbo iteration is quite beneficial.

[5] This bound represents the asymptotic value for the SU case (see Sec. 4.).

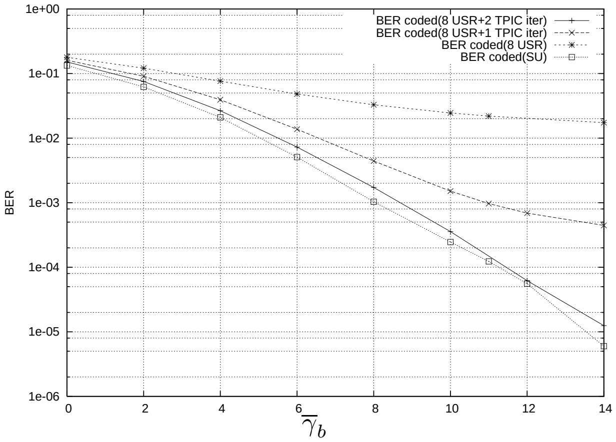

Figure 6: BER performance of the proposed system using a TPIC device ($K = 8, G = 16$). Users have equal power.

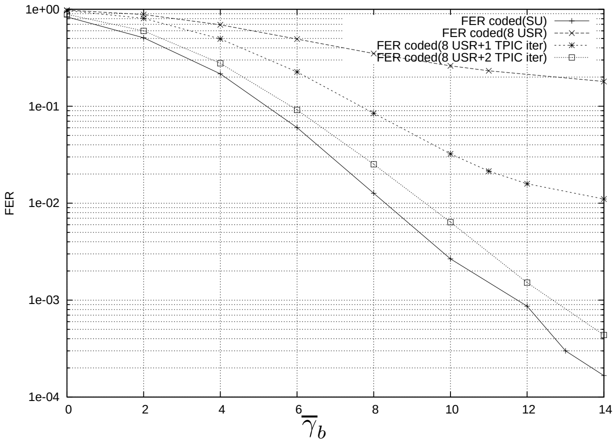

Figure 7: FER performance of the proposed system using a TPIC device ($K = 8, G = 16$). Users have equal power.

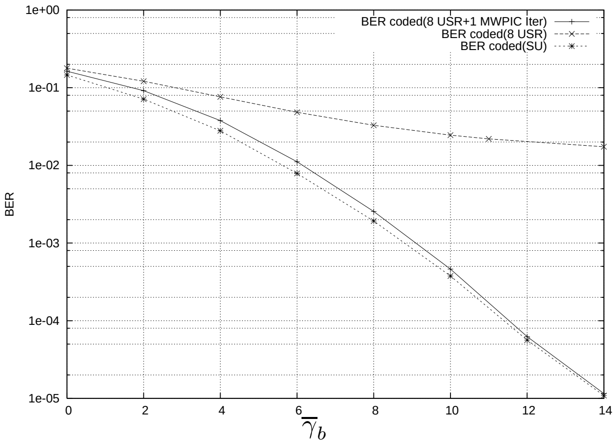

Figure 8: BER Performance of the MWPIC ($K = 8, G = 16$). Users have equal power.

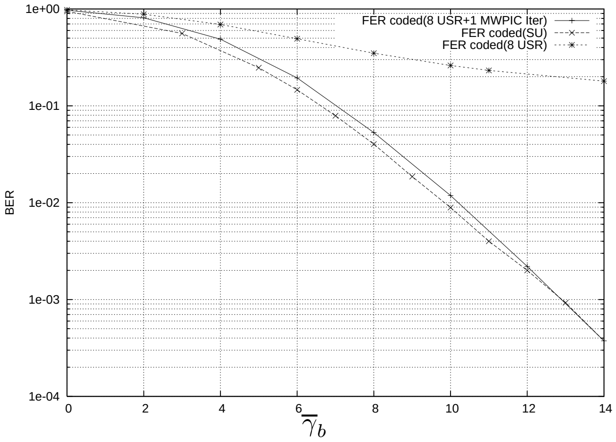

Figure 9: FER Performance of the MWPIC ($K = 8, G = 16$). Users have equal power.

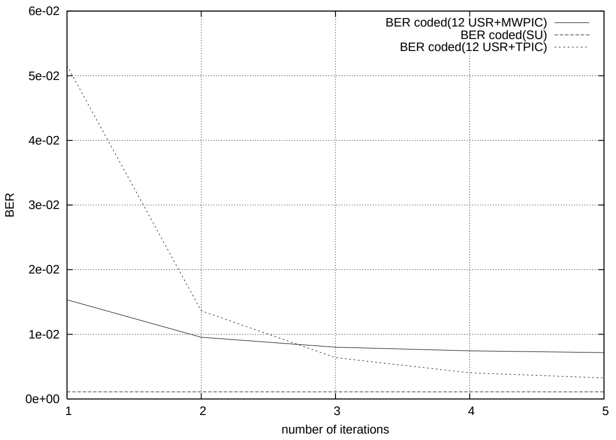

Figure 10: BER versus the number af iterations for the TPIC and MWPIC ($\overline{\gamma}_b = 8$ dB). Overloaded system with $\beta = 2.4$.

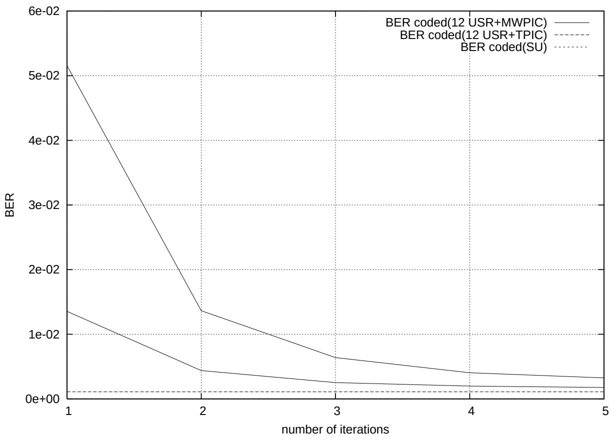

Figure 11: Performance of the TPIC and MWPIC (with a new set of parameters) against iterations at $\overline{\gamma}_b = 8$ dB. Overloaded system with $\beta = 2.4$.

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