Improved Iterative Parallel Interference Cancellation Receiver for DS-CDMA 3G Systems

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Abstract— **This paper presents a Turbo Multiuser Detector for Turbo-Coded DS-CDMA systems, based on the utilization of a PIC and a bank of turbo decoders, in which the PIC performs interference cancellation after each constituent decoder of the turbo decoding scheme. Moreover, we propose a new enhanced estimator of the signal-to-noise-plus-interference-ratio used in the decision device and in the MAP decoding algorithm. By means of computer simulations, we will show that the proposed receiver ouperforms other similar schemes for medium to very high system loads, in AWGN and multipath fading channel.**

I. INTRODUCTION

One of the main shortages of the Code Division Multiple Access (CDMA) communication systems can be identified in their vulnerability to Multiple Access Interference (MAI): hence, during the 90's, great attention has been devoted to Multiuser Detection strategies that constitute the natural answer to this problem; the receivers based on this technique aim to exploit the intereference as an additional information source but, generally, are characterized by a very high complexity. Firstly, multiuser detection 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 coded systems. Optimal joint decoding/detection is an excellent solution to this problem, as shown in [1]. However, this scheme results in a prohibitive computational complexity for actual implementation. In contrast, suboptimal solutions, wich separate the operations of symbol detection and channel decoding, appears more attractive for practical applications.

Particularly, the successful proposal of Turbo codes [2] naturally leads to investigate the feasibility of iterative (Turbo) processing techniques in the design of multiuser receivers. In the iterative multiuser detection, extrinsic information is determined in each detection and decoding stage and used as a priori information for the next iteration. This procedure is adopted at each iteration as in Turbo codes: this detection philosophy is defined as Turbo MUD and the advantages due to its introduction are remarkable, also for heavily loaded systems. In the last years many iterative receivers that can achieve near-optimal performance [3], [4] have been investigated, but with the drawback of the complexity, that is still exponential in the number of users. This is the reason of the attention addressed to Interference Cancellation schemes [5], [6], [7], [8].
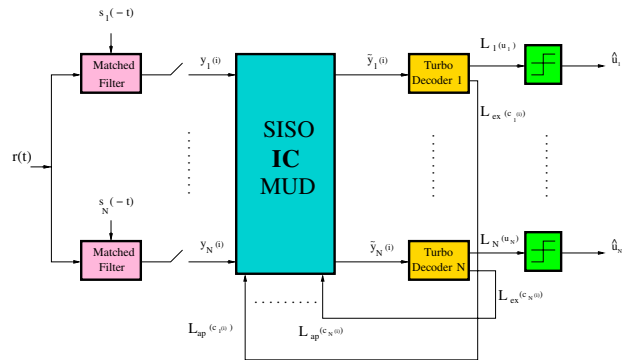

Fig. 1.   The general iterative IC receiver

In this paper, we propose a new iterative multiuser detector based on the utilization of a Parallel Interference Cancellation (PIC) and a bank of Turbo decoders. In the proposed structure the PIC detector is broken up so that it is possible to perform Interference Cancellation after each constituent convolutional decoder. Due to the tight relationship between the proposed receiver and the MAP decoders, we defined it as *MAP decoder aided PIC (MPIC)*: this solution aims to profit by IC introduction from the first iterations. Moreover, in the paper the variance of the noise-plus-(residual-)interference is determined by a new algorithm: particularly, only the most reliable symbols are used in variance determination, neglecting all the others. This solution affords performance improvement for all the considered systems.

II. SYSTEM MODEL

We consider an up-link DS-CDMA communication system with N synchronous turbo-coded users. Timing, amplitudes, carrier phases and spreading sequences of all the users are assumed to be perfectly known at the receiving end in the base station. Each user encodes blocks of information bits $u_k(i)$ with a Parallel Concatenated Convolutional Code (PCCC) and transmits the resulting codewords composed of M coded bits over a common AWGN channel with BPSK modulation. The equivalent baseband received signal can be written as

$$r(t) = \sum_{k=1}^{N} \sqrt{E_{b_k}} \sum_{i=0}^{M-1} c_k(i) p(t - iT_b) s_k(t - iT_b) + n(t) \quad (1)$$

where:

- T_b is the bit interval;
- E_{b_k} is the kth user received energy;
- $c_k(i) \in \{+1, -1\}$ is the bit transmitted by k user during the ith bit period;
- $p(t)$ is the unit-power rectangular pulse shape with duration T_b;
- $s_k(t)$ is the kth user unit-power spreading sequence;
- $n(t)$ is an Additive White Gaussian Noise (AWGN) process with double sided spectrum density $\sigma^2 = No/2$ [W/hz].

In the receiver a bank of matched filter is used for despreading. Without loss of generality, we can assume that the first bit-interval is observed. As a result, the output of the kth matched filter is given by

$$y_k = \frac{1}{T_b} \int_0^{T_b} r(t)s_k(t)dt = \sqrt{E_{b_k}}c_k + \sum_{\substack{j=1 \\ j \neq k}}^{N} \sqrt{E_{b_j}} c_j \rho_{jk} + n_k \tag{2}$$

where ρ_{jk} is the normalized crosscorrelation coefficient between users j and k and n_k is the noise Gaussian sample of user k with distribution $N(0,\sigma^2)$. The second term in eq.(2) represent the MAI, that has to be cancelled.

III. A NEW IC ITERATIVE RECEIVER

An iterative cancellator consists of an Interference Cancellation (IC) based Multi-User Detector (MUD) followed by N single-user turbo decoders. Each constituent block iteratively provides soft informations to the others, as shown in Fig 1.

In the first multiuser detection iteration, the a priori information of coded bits is not available, i.e. $L_{ap}(c_k(i)) = 0$, k=1,2,...,N, i=0,1,...M-1. The IC stage delivers interference-cancelled soft outputs $\tilde{y}_k(i)$ to the input of the turbo decoders. After a fixed number of turbo decoder iterations, the extrinsic information of coded bits at the output of turbo decoders are fed back to the input of the IC detector as the a priori information for the next receiver iteration.

The considered turbo codes are composed of two Recursive Systematic Convolutional (RSC) codes linked by an interleaver and a MAP based algorithm is used for iterative decoding [9]. Since the IC receiver requires soft information about reliability of both the systematic and the parity bits, the decoding algorithm is properly modified to produce also extrinsic information about the latter [10]. 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, in which a greater amount of interference has been cancelled.

A. The Conventional Iterative PIC Receiver

In the conventional iterative Parallel Interference Cancellation (PIC) receiver [11], at each IC stage, MAI is to be removed simultaneously from each user. Therefore, at the mth receiver iteration, the PIC soft output, i.e., the turbo decoders

input, can be expressed as

$$\tilde{y}_k^{(m)} = y_k - \sum_{\substack{j=1 \\ j \neq k}}^{N} \sqrt{E_{b_j}} \rho_{kj} \hat{c}_j^{(m)}$$

$$= \sqrt{E_{b_k}}c_k + \sum_{\substack{j=1 \\ j \neq k}}^{N} \sqrt{E_{b_j}} \rho_{kj} \left(c_j - \hat{c}_j^{(m)} \right) + n_k \tag{3}$$

where $\hat{c}_j^{(m)}$ is the estimate of bit c_j at iteration m. Note that the second summation represents the residual MAI after cancellation.

The data estimates $\hat{c}_k^{(m)}$ have been chosen in [11] as the expectation of coded bits, that is

$$\hat{c}_k^{(m)} = \mathrm{E}\left\{c_k^{(m)}\right\} = \tanh\left[\frac{1}{2}L_{ap}^{(m)}(c_k)\right], \tag{4}$$

in order to take advantage on the turbo decoders output. The term $L_{ap}^{(m)}(c_k)$ is the a priori *Log-Likelihood Ratio* of bit c_k at the mth iteration, defined as

$$L_{ap}^{(m)}(c_k) \triangleq \log \frac{P^{(m)}(c_k = +1)}{P^{(m)}(c_k = -1)} . \tag{5}$$

In the first receiver iteration no a priori information is available from the decoder output: hence, for the initializing condition, it is assumed $L_{ap}^{(0)}(c_k)=0$, k=1,2,...N. Instead, in the successive iterations the extrinsic information coming from the decoders can be used, leading to $L_{ap}^{(m)}(c_k)=L_{ex}^{(m-1)}(c_k)$.

B. The Proposed Iterative MPIC Receiver

As it is known, as the number of decoding iterations increases, the coding gain offered by a turbo decoder becomes larger. However, the performance improvement obtained by turbo codes is remarkable in the first iterations, and more and more negligible in the successive ones. This remark suggests to concentrate the significant part of interference-cancellation in the first iterations: for this reason many IC based iterative receiver with a first linear stage have been proposed [7], [8], [12]. Nevertheless, a linear MUD has the drawback of an extremely high computational complexity.

In this paper we present an iterative PIC receiver, wich exploits most interference-cancellation in the first receiver iterations: a conventional iterative receiver tries to cancel the MAI from all the parity and the systematic bits only once at the end of each decoding iteration. Note that in turbo decoding iteration, the first MAP decoder provides extrinsic informations about all the systematic and half of the parity bits while the second decoder gives the extrinsic information about the interleaved systematic bits and the second half of the parity bits; as a consequence, in the proposed receiver the interference-cancellation is performed after each decoding iteration and the systematic bits are cancelled twice. Because of the tight connection between the proposed receiver and the MAP decoders, we have named it as *MAP decoders aided PIC (MPIC)*. The structure of this receiver is shown in Fig. 2.

Assuming that R_c is the turbo encoder code rate and that only the parity bits are punctured at the transmitter end, the
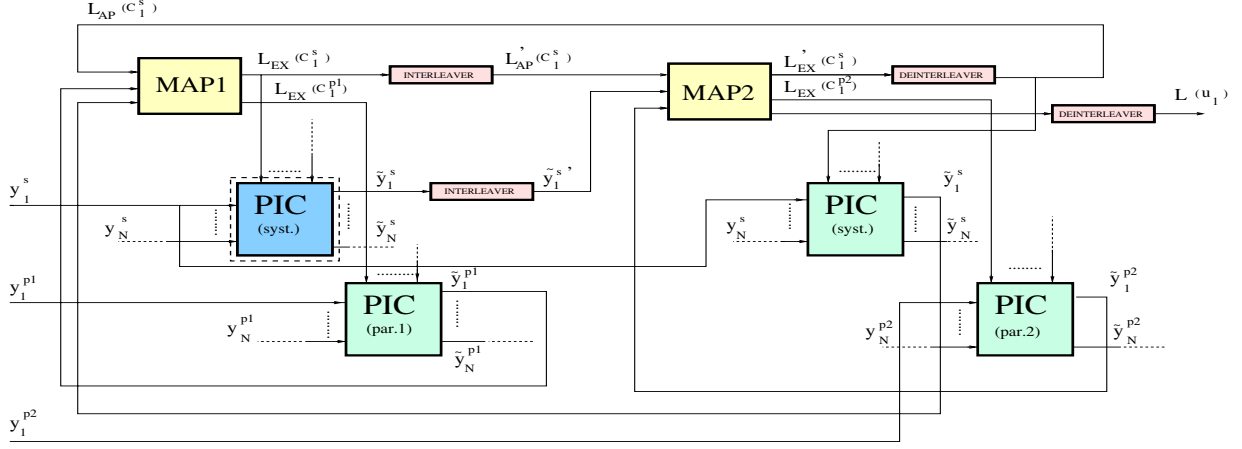
Fig. 2. Block diagram of the proposed iterative MUD.

computational complexity needed by the MPIC to perform interference cancellation at each iteration is $(1+R_c)$ greater than the conventional PIC. However it will be shown by simulation that the proposed iterative receiver performance is better than the conventional one even with equal complexity. This goal has been reached by removing in the last iterations so many cancellation stages as the ones added in the first iterations.

C. An Improved Non-Linear MMSE Estimator

The tentative decision device (4), used to estimate the data bits and reconstruct and cancel MAI, exploits only extrinsic informations from the decoders but not channel outputs; hence, only a fraction of available information sources is used in the decision. An improved data estimator can be obtained by exploiting jointly decoders and channel outputs, as in [6], where a ML estimator is used, producing tentative hard decisions [14]. Unlike [6], we derive a *non linear MMSE estimator*, that can also provide the reliability value of each estimated bit. The decision $\hat{c}_k^{(m)}$, for kth user at the mth receiver iteration, is taken as the expectation of c_k, given the channel output and the a priori probability, i.e.,

$$\hat{c}_k^{(m)} = \mathrm{E}\left\{c_k|\, y_k, \mathrm{P}(c_k)\right\} = \sum_{c_k \in \{+1, -1\}} c_k\, \mathrm{P}\left(c_k|\, \tilde{y}_k, \mathrm{P}(c_k)\right)$$

(6)

Making the assumption that the interference can be considered as a Gaussian process, we obtain

$$\hat{c}_k^{(m)} = \tanh\left[\frac{1}{2}\left(2\frac{\sqrt{E_{b_k}}\, y_k}{\sigma_k^2} + \mathrm{L}_{ap}^{(m)}(c_k)\right)\right]$$

(7)

where σ_k^2 is the termal noise-plus-interference variance, given by $\sigma_k^2 = \sigma^2 + \sigma_{k,MAI}^2$. As it is shown in [13], combination of channel output and extrinsic information in decision statistic yields a biased residual interference term wich tends to cancel the useful signal. However, computer simulations confirm that better performance is achieved by using all the information sources and that mitigation of the bias effect is obtained after few iterations.

D. Variance Estimation

The tentative decision device needs to know the noise-plus-(residual)interference variance, such as the channel reliability value used in the MAP decoding [2]; hence, an appropriate estimation method has to be used. In [15] and [5] a simple algorithm based on the data samples has been proposed: particularly, therein the variance is calculated as

$$\hat{\sigma}_{k,m}^2 = \frac{1}{M}\sum_{i=0}^{M-1}\left(\tilde{y}_k^{(m)}(i)\right)^2 - \overline{\tilde{y}_k^{(m)}}^2,$$

(8)

where the mean $\overline{\tilde{y}_k^{(m)}}$ has been either derived by the samples [15] or assumed equal to the square root of the received energy $\sqrt{E_{b_k}}$ [5]. As it will be confirmed by simulation results, this algorithm leads to underestimate the variance in the cases of low signal-to-interference-plus-noise-ratio (SINR). The motivaton of this behaviour is the following. Assuming that the (residual-)interference is Gaussian, the conditional probability density functions (pdf) of the variable $\tilde{y}_k^{(m)}(i)$, i.e., $p(\tilde{y}_k^{(m)}(i)\,|\,c_k = \pm 1)$, are also Gaussian. As a consequence, the unconditional pdf of $\tilde{y}_k^{(m)}(i)$ is given by

$$p(\tilde{y}_k^{(m)}) = P(c_k = +1)p(\tilde{y}_k^{(m)}\,|\,c_k = +1)$$
$$+ P(c_k = -1)p(\tilde{y}_k^{(m)}\,|\,c_k = -1)$$
$$= \frac{1}{2}\left[p(\tilde{y}_k^{(m)}\,|\,c_k = +1) + p(\tilde{y}_k^{(m)}\,|\,c_k = -1)\right],$$

(9)

where the last equality follows from the assumption that the transmitted bits are indipendent identically distributed (i.i.d.). As it can be seen from Fig.3, the values $\tilde{y}_k^{(m)}(i)$, satisfying the inequality $\left|\tilde{y}_k^{(m)}(i)\right| < \sqrt{E_{b_k}}$, are ambiguous, in the sense that they belong to the region of maximum superposition of the conditional pdfs. For this reason we have chosen to evaluate the variance only by the values satisfying $\left|\tilde{y}_k^{(m)}(i)\right| \geq \sqrt{E_{b_k}}$; these values has been defined as $\tilde{y}_{k,up}^{(m)}(i)$. This original variance definition can be used to improve the variance estimation
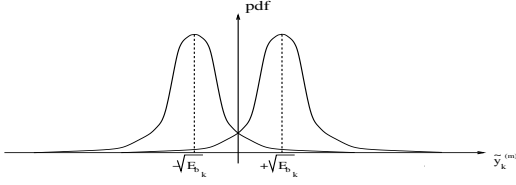
Fig. 3.   Decision variable probability density function.

Fig. 4.   Histograms and Gaussian approximations of Matched Filters and PIC output for different iterations: E_b/N_0=10 dB

through the formula:

$$\hat{\sigma}_{k,m}^2 = \frac{1}{M_1} \sum_{i=0}^{M_1-1} \left(\left| \tilde{y}_{k,up}^{(m)}(i) \right| - \sqrt{E_{b_k}} \right)^2 \qquad (10)$$

where $M_1 \leq M$ indicates the number of such values in a codeword.

IV. ITERATIVE MPIC FOR MULTIPATH SLOWLY FADING CHANNELS

Wireless CDMA systems usually have to cope multipath fading environments. The multipath fading channel is often assumed to be wide-sense stationary with uncorrelated scattering [16]. Based on this assumption, the received baseband DS-CDMA signal can be written as

$$r(t) = \sum_{k=1}^{N} \sum_{i=0}^{M-1} \sum_{l=1}^{L} \sqrt{E_{b_k}} c_k(i) \alpha_{k,l}(t) s_k(t - iT_b - \tau_{k,l}) + n(t) \qquad (11)$$

where L is the number of propagation paths and $\alpha_{k,l}(t)$ and $\tau_{k,l}$ are, respectively, the time-varying complex attenuation factor and the relative delay of the lth path of the kth user signal. Besides, we assume that $\mathrm{E}\{\sum_{l=1}^{L} \|\alpha_{k,l}\|^2\}=1/T_b$, so that E_{b_k} is the received averaged energy of kth user, and that channel fading is so slow that $\alpha_{k,l}(t)$ does not change in a chip interval and thus can be denoted as $\alpha_{k,l}(h)$, where h refers to chip position in the codeword. The chip matched filter output for the lth path of the kth user is then given by

$$y_{k,l}(h) = \frac{1}{T_c} \int_{(h-1)T_c+\tau_{k,l}}^{hT_c+\tau_{k,l}} r(t) s_k(t - \tau_{k,l} - \left\lfloor \frac{h}{G} \right\rfloor T_b) dt, \quad (12)$$

where T_c is the chip interval, that is tied to the bit interval through the processing gain $G = T_b/T_c$.

If a Maximal Ratio Combiner (MRC) RAKE receiver is used, the decision statistic can be expressed as

$$y_k(i) = \sum_{l=1}^{L} \sum_{h=iG}^{(i+1)G-1} \alpha_{k,l}^*(h) y_{k,l}(h) \qquad i=0,1,...,M-1. \quad (13)$$

In the mth iteration of the iterative PIC receiver, the kth received signal after MAI subtraction is given by

$$r_k^{(m)}(t) = r(t) - \sum_{\substack{j=1 \\ j \neq k}}^{N} \sum_{i=0}^{M-1} \sum_{l=1}^{L} \sqrt{E_{b_j}} \hat{c}_j^{(m)}(i) \alpha_{j,l}(t) s_j(t - iT_b - \tau_{j,l}) \qquad (14)$$

where the bit tentative decision $\hat{c}_j^{(m)}(i)$ is given by (7), while the variance estimation formula has to be modified
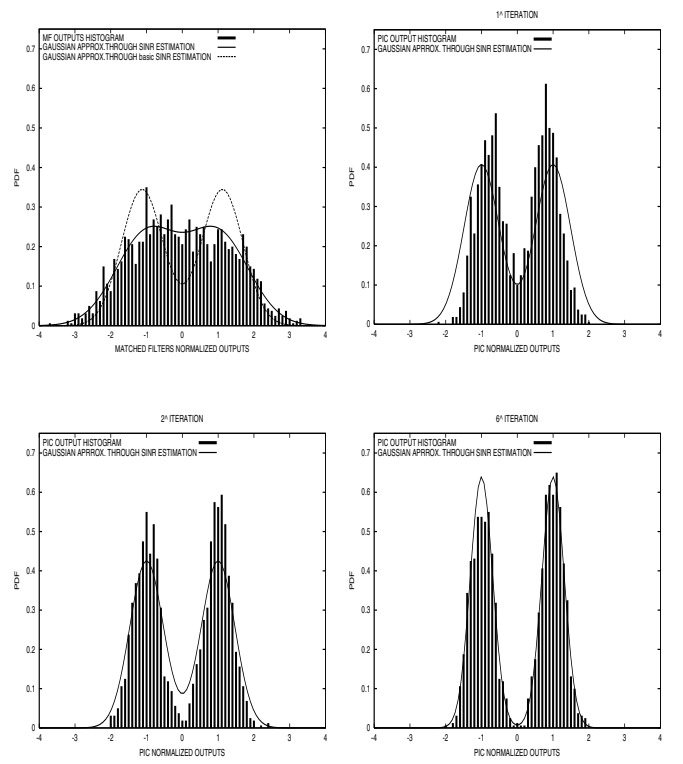
to take into account the fading attenuation. The conditional pdfs $p(\tilde{y}_k^{(m)}(i) \,|\, c_k = \pm 1, \, \alpha_{k,l})$ are Gaussian and (10) can be rewritten as

$$\hat{\sigma}_{k,m}^2 = \frac{1}{M_1} \sum_{i=0}^{M_1-1} \left(\left| \tilde{y}_{k,up}^{(m)}(i) \right| - \overline{\alpha_{k,up}(i)} \sqrt{E_{b_k}} \right)^2 \quad (15)$$

where $\overline{\alpha_k(i)}$ is the bit-averaged fading attenuation after recombination and it is computed as

$$\overline{\alpha_k(i)} = \frac{1}{G} \sum_{h=1}^{G} \sqrt{\sum_{l=1}^{L} \|\alpha_{k,l}(iG+h)\|^2} \, . \qquad (16)$$

V. 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 [17]. We compare the proposed iterative MPIC receiver with the conventional PIC and the iterative Partial PIC (PPIC) receiver proposed in [6] and derived from [14].

First, we analize the performance in a synchronous AWGN channel. The system has 10 equal-power users with Pseudo-Noise short codes, processing gain G=16 and frame lenght 800. The quantized Log-MAP algorithm is used for the decoding [9]. Fig.4 shows the decision variables histogram at the output of the MF bank and of the PIC receiver after 1, 2, 3 and 6 iterations for a signal-to-noise-ratio $E_b/N_0 = 10$ dB, compared with the Gaussian distribution with variance calculated through (10). We can remark the interference reduction through iterations and the accuracy of enhanced variance estimation, while a bias is evident just in the first iteration. In Fig.5 it is shown the performance improvement obtained using the enhanced variance estimator in comparison with the basic one, derived from (8). Fig.6 shows the performance gain achieved by the proposed receiver by increasing the number of iterations. At a BER of 10^{-4} and with 16 iterations the loss from single-user bound is about 0.8 dB. A comparison of performance vs iterations between the iterative PIC, MPIC and PPIC is made in Fig.7 at $E_b/N_0 = 3$ dB. The cancellation weights for PPIC have been found by a trial-and-error searching method, as p_0=0.55, p_1=0.65, p_2=0.75, p_3=0.85, p_4=0.92, p_5=0.97, $p_{i \geq 6}$=1.0.

Then, we illustrate the performance of the proposed receiver in a asynchronous 3-paths fading channel with perfect power control: the replica amplitudes are assumed to be Rayleigh distributed, with relative attenuations equal to 0, -1, -9 dB. Processing gain is G=15 and spreading is performed by a set of Pseudo-Noise short codes. The frame lenght is 500, a MRC-RAKE receiver is used as paths-combiner and the Max-Log-MAP algorithm is used for decoding. The channel has a normalized frequency Doppler $f_d T_b$=0.0002 and just 2 receiver iterations are performed. The other transmission parameters are the same of the AWGN case. In Fig.8 it can be seen that in a system with 20 active users, i.e.with a system load $\beta = N/G$ greater than one ($\beta = 1.33$), the MPIC outperforms the conventional PIC: a gain of 3.5 dB for the MPIC versus the PIC receiver at a BER of 10^{-3} is observed. In this figure it is also shown the great benefit obtained for both the receivers by using a correct estimate of the noise-plus-(residual)interference variance rather than approximating it by the ambient noise, assumed perfectly known, as in [6]. Fig.9 shows that the iterative MPIC receiver can supports heavily loaded DS-CDMA systems. This behaviour can be exalted with the assistance of low crosscorrelations spreading sequences, as shown in Fig.10 where the MPIC receiver reaches single-user performance in a fully loaded DS-CDMA system, with normalized Doppler frequency $f_d T_b$=0.0004, processing gain 31 and 31 equal-power users using Gold31 codes.

VI. Conclusion

In this paper a new Turbo Multiuser Detector for turbo-coded DS-CDMA systems has been presented. In the proposed detector a Parallel Interference Cancellation (PIC) has been divided in order to perform interference cancellation after each MAP constituent decoder. Moreover, an improved algorithm
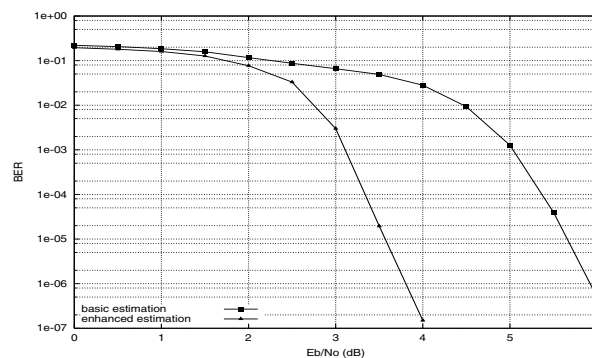

Fig. 5. Performance comparison of iterative PIC receiver with basic and enhanced variance estimator in a synchronous AWGN channel with 10 equal-power users and processing gain 16.
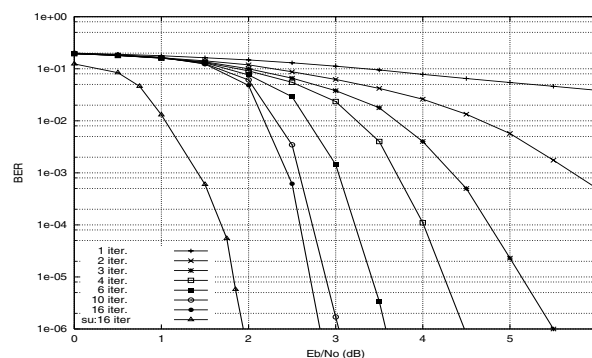

Fig. 6. BER versus E_b/N_0 of iterative MPIC through iterations in an AWGN channel.

to estimate the variance of the noise-plus-residual-interference has been derived. Performance results, evaluated by means of computer simulations for different system loads, in AWGN and multipath fading channel, confirms the excellent behaviour of the proposed receiver. It is shown that it outperforms recently proposed alternative IC based turbo MUD with the same complexity.

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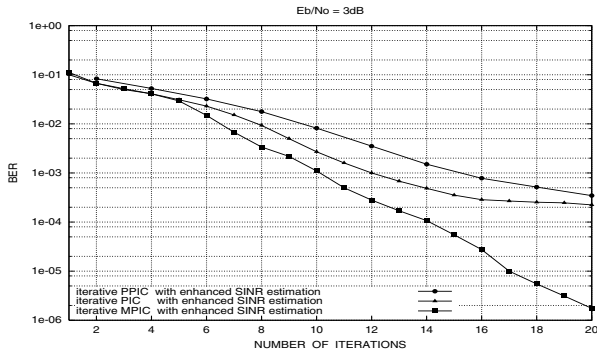
Fig. 7. Performance of different iterative IC receivers against iterations in an AWGN channel.
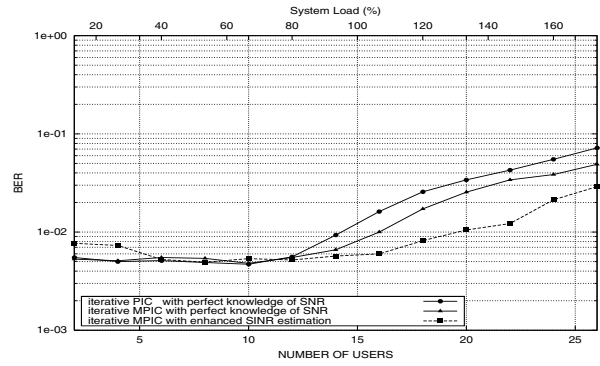

Fig. 9. BER versus System Load for iterative IC receivers in a multipath fading channel.
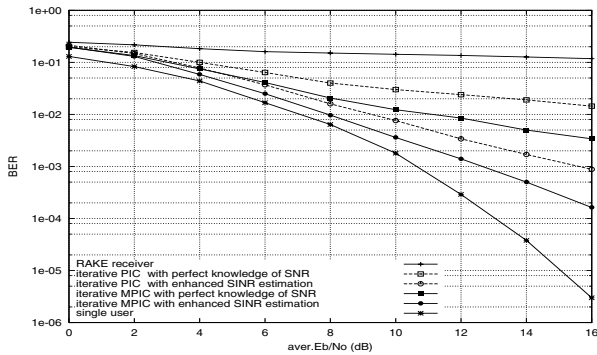

Fig. 8. Performance of iterative IC receivers in a multipath fading channel with 20 equal-power users.
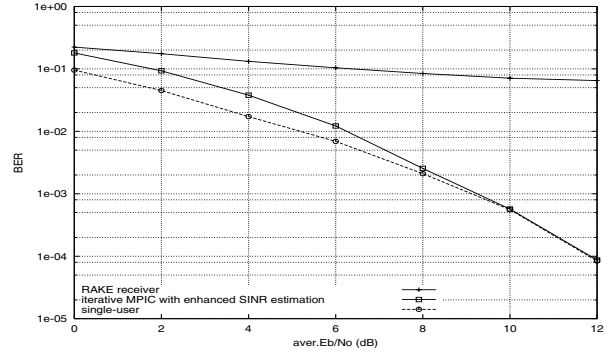

Fig. 10. Performance of iterative MPIC receiver in a multipath fading channel with 31 equal-power users using Gold31 spreading sequences.

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