Turbo Space-Time Multiuser Detection for DS-CDMA Systems in Rayleigh Fading Channels

Derrick B. Mashwama and Emmanuel O. Bejide, *Member, IEEE*

Abstract— In this paper, we investigate the performance of the partitioned and the iterative approach to concatenation of the Parallel Interference Cancellation (PIC) technique with turbo detection in the Space-Time Block Coded (STBC) system. The paper studies the comparative performance of both concatenation approaches. It was observed that at low Signal to Noise Ratio (SNR) the Iterative Approach (IA) performs better than the Partitioned Approach (PA). However, as the fidelity of the received signal increases the PA starts to have a better performance than the IA. Both PA and IA system performances are shown to be dependent on the diversity level, system loading, channel conditions and detector parameters. A case is made for the design of a switching algorithm that monitors the 'crossover' point and switches to the better performing concatenation approach for a given system setup.

Index Terms— Multiple access interference, multiuser detection, Parallel interference cancellation, space-time block codes.

I. INTRODUCTION

The presence of Multiple Access Interference (MAI) in Code-Division Multiple Access (CDMA) systems has led many researchers to investigate ways of exploiting the MAI to improve the system performance. The optimum Multiuser Detector (MUD) proposed in [1] that consists of the Maximum Likelihood Sequence Estimator (MLSE) based on the Viterbi decoding algorithm has shown huge improvements (i.e. a substantial increase in system capacity) over the conventional correlation receiver. Unfortunately as the number of users increases so does its computational complexity. This complexity grows exponentially with the number of active users and constraint length of the code making any practical implementation very prohibitive. Various suboptimum detectors have been proposed, which include, but not limited to, decorrelator, Minimum Mean Squared Error (MMSE), Successive Interference Cancellation (SIC) and Parallel Interference Cancellation (PIC) receivers [2],[3].

The demand on higher system capacity and higher data rates has led researchers to the investigation of Multiple-Input/Multiple-Output (MIMO) wireless systems [4]. The implementation of MIMO is particularly appealing because of its relative simplicity of implementation and the feasibility of multiple antennas at the base station where the MIMO costs can be evenly shared by the system users [5]. Moreover MIMO systems have been shown to offer much capacity gain over single antenna systems [4], [7]. Work done by [4] and [8] predicts a remarkable capacity increases for MIMO systems in the presence of multipath fading.

Space-Time Codes (STCs) have recently gained much attention as an effective MIMO algorithm [9] and [5]. There are two main types of STCs, being space-time block codes (STBCs) [10] and Space-Time Trellis Codes (STTCs) [5]. When many users are in the system, strong MAI will occur. In this case, diversity processing alone cannot improve the system performance.

Neither MUD alone nor channel coding techniques can completely eliminate the effects of MAI. Joint detection and decoding in multiuser systems has been an active research area for the last decade. Researchers like [10] have investigated the combined optimum detector [1] and convolutional decoding system performance. Due to the exponential complexity of the receiver in [1], the authors of [10] propose suboptimal MUD with convolution coding in [11]. By integrating a combination of various suboptimal MUDs with iterative channel decoding, the authors of [12] introduce a convolutionaly coded iterative interference canceller.

The powerful error correction ability of the turbo codes [13] has been combined with interference cancellation in [14] to produce the turbo interference cancellation detection approach. The work of [14] has further been studied in [15], [16] with further work being done by [17] and [18].

Though the above work investigates the combined MUD and error control coding performance it still does not investigate these in conjunction with diversity techniques. Recently, much work has been done on combining diversity techniques with MUD algorithms [19], [20], [21]. Some authors like [22] have proposed iterative MUD techniques using error control coding and antenna arrays while [23] proposes a soft iterative multisensor array receiver for coded MUD CDMA wireless uplink. Most recently work in [24] investigates the joint DS-CDMA space-time MUD system with error control coding over a multi-path fading channel. The authors of [24] use convolutional coding for error control coding and a space-time MMSE detector at the receiver end.

The objective of this paper is to investigate the performance (through simulation) of a turbo coded DS-CDMA system that employs space-time multiuser detection at reception. We use a PIC MUD coupled with STBC to achieve space-time multiuser detection. Depending on the concatenation scheme used, we divide these into partitioned approach (PA) and iterative approach (IA) MUDs.

The remainder of this paper is organized as follows. In section II we present the system model. Section III presents the partitioned approach multiuser detector. Section IV introduces the iterative approach multiuser detector. In section V we present comparative results between PA and IA turbo multiuser detectors. Finally in section VI we draw relevant conclusions and make recommendations.

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D. Mashwama is with the Department of Electrical Engineering, University of Cape Town, Private Bag, Rondebosch 7701, South Africa. (E-mail: deemash@crg.ee.uct.ac.za).
E.O. Bejide is with the Department of Electrical Engineering, University of Cape Town, Private Bag, Rondebosch 7701, South Africa. (E-mail: ebejide@ebe.uct.ac.za).

II. SYSTEM MODEL

A DS-CDMA system for Ks asynchronous number of subscribers (where subscribers are the users authorized to use the CDMA system) is considered. We further denote the number of subscribers currently actively engaged in transmission by K. all subscribers in the system are assigned spreading codes or signatures. Each user's spreading code will have a length of N chips, where N is termed the processing gain. The system in consideration is shown in figure 1 below.

Each user's signal of *m* information bits is first encoded using a rate $r = m/n$ turbo encoder to produce *n* coded symbols. We employ a rate $r = 1/3$ turbo encoder with the generator polynomial of the constituent codes being $(1\ 5/7)_{octal}$ and utilizes the MAP algorithm at the decoder. The *n* coded symbols are then passed through a random interleaver and then spread using a unique code sequence which is assumed to be known only to the mobile station and the base station. Once modulated, the signals are then transmitted over the Rayleigh fading channel.

The *k*th user's baseband signal can be modelled as:

$$s_k(t) = B_k d_k(t) c_k(t) \cos(\omega_c t \theta_k(t)) \quad (1.1)$$

or

$$s_k(t) = \sqrt{E_k}\, d_k(t) c_k(t) \cos(\omega_c t + \theta_k(t)) \quad (1.2)$$

$$E_k = B_k^2 = 2P_k \quad (1.3)$$

where B_k is the received amplitude of the *k*th user's signal, and E_k is referred to as the energy of the *k*th user's signal $d_k(t) \in \{+1,-1\}$ is the modulated symbol of the *k*th user consisting of rectangular pulses of duration T_b (bit interval) that correspond to the transmitted symbol. Each user's data is multiplied by the spreading code $c_k(t)$, and then the composite $d_k(t)$ modulates the carrier, we assume BPSK modulation. Here $k \in \{1,\cdots,k\}$ is the user number and E_k is the energy of the transmitted coded bit, and is related to the uncoded information bit through $E_k = R_c E_b$ and $R_c = m/n$ is the code rate and E_b is the energy per information bit, $d_k(t) \in \{+1,-1\}$ is the bit transmitted by user *k* at time *t*, ω_c is the carrier frequency and θ_k is the carrier phase of the *k*th user. $c_k(t) \in \{1,-1\}^N$ is the spreading code employed by user *k* at time *t*, consisting of *N* chips given by:

$$c_k(t) = \sum_{j=0}^{N-1} a_k[j] \psi(t - jT_c) \quad (1.4)$$

Where $a_k[j] \in \{-1,1\}$ is the jth element/chip of the spreading code for user *k* and $\psi(t)$ is the chip waveform with a chip duration of T_c. We assume that $c_k(t)$ has unit energy. We assume that all signature waveforms fall within the bit interval, T_b, and are zero outside this range, thus there is no inter-symbol interference (ISI) in the system under consideration.

By substituting (1.4) into (1.2) we can express the continuous time waveform transmitted by user *k* in symbol interval *i* as:

$$s_k(t) = \sqrt{E_k} \sum_{j=0}^{N-1} d_{k,j} [a_{k,j}]_j \psi(t - jT_c - iT_b) \quad (1.5)$$

where $[a]_j$ is the jth element of a.

We assume a flat fading channel such that the channel response does not vary with time. The continuous time signal at a receiver from a flat fading channel can be expressed as

$$r(t) = \sum_{n=0}^{+\infty} \sum_{k=1}^{K} d_k(t) c_k(t - nT) * h(t) + n(t) \quad (1.6)$$

Where $\tau_k \in [0,T]$ is the delay with which user *k*'s signal is received and $h(t)$ represents the channel coefficient subject to fading. We consider a Rayleigh fading channel, where $h(t)$ is a complex Gaussian random process, given as

$$h(t) = \beta(t) e^{j\theta} \quad (1.7)$$

Where $\beta(t)$ is Rayleigh distributed and θ is the phase value. Here * represents the convolution operation, and $n(t)$ is a zero mean additive Gaussian noise with a two-sided power spectral density of $N_0/2$.

For simplicity, and without loss of generality, we assume here that the system has $n_T = 2$ transmit antennas and $n_R = 1$ receive antenna. This can be easily extended to any arbitrary number of antennas [5], [30]. Following the approach in [12], during the first STBC symbol period, two signals x_1^k and x_2^k are simultaneously

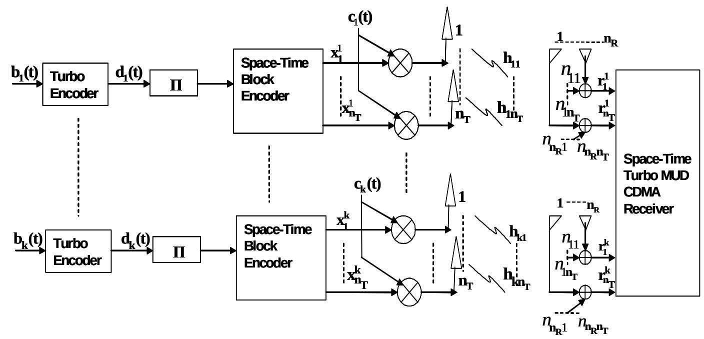

FIGURE 1: Turbo DS-CDMA system model with space-time PIC multiuser detector

transmitted from the two antennas ($n_{T=1}$ and $n_{T=2}$, respectively). On the second symbol period, $-x_2^{k*}$ is transmitted from antenna $n_{T=1}$ and x_1^{k*} is transmitted from antenna $n_{T=2}$. We assume that the channel is constant across all consecutive symbols.

Considering a multiuser DS-CDMA system with STBC, the received signals for user *k*, $r^k(t)$ and $r^k(t+T_b)$ during time *t* and $t+T_b$, respectively, for the uplink scenario can be expressed as

$$r_1^k(t) = \sum_{1}^{K} (h_{k1} x_1^k + h_{k2} x_2^k) + n_1 \quad (1.8)$$

$$r_2^k(t) = \sum_{1}^{K} (-h_{k1} x_2^k + h_{k2} x_1^k) + n_1 \quad (1.9)$$

Where from (1.2) x_1^k and x_2^k are written as

$$x_1^k = s_{k1} = \sqrt{E_k}\, d_{k1}(t) c_k(t) \cos(\omega_c t + \theta_k(t)) \quad (1.10)$$

$$x_2^k = s_{k2} = \sqrt{E_k}\, d_{k2}(t) c_k(t) \cos(\omega_c t + \theta_k(t)) \quad (1.11)$$

and d_{k1} and d_{k2} are the bits transmitted by user k during the first and second STBC symbol period, respectively.

Considering user *k* to be our user of interest, we can expressed the despread signal at the MF output as

$$\begin{aligned} \mathbf{y}^{\mathbf{MF}} &= \left[\mathbf{y}_{\mathbf{1}}^{\mathbf{MF}}, \cdots, \mathbf{y}_{\mathbf{K}}^{\mathbf{MF}} \right] \\ \mathbf{y}_k^{\mathbf{MF}} &= \left[y_{k1}^{MF}, \cdots, y_{kn_T}^{MF} \right] \end{aligned} \quad (1.12)$$

$$\begin{aligned} y_{k1}^{MF} &= \frac{1}{T_b} \int^{T_b} c_k(t) r_1^k \\ &= \sqrt{E_k}\, d_{k1} h_{k1} + \sqrt{E_k}\, d_{k2} h_{k2} + \\ &\quad \sum_{j \neq k}^{K} \left[\sqrt{E_j}\, \rho_{jk1} \begin{pmatrix} (d_{k1}^{-1} + d_{k1}) h_{j1} \cos(\theta_{k1} - \theta_{j1}) + \\ (d_{k2}^{-1} + d_{k2}) h_{j2} \cos(\theta_{k2} - \theta_{j2}) \end{pmatrix} \right] + n_k' \end{aligned} \quad (1.13)$$

$$
\begin{aligned}
y_{k2}^{MF} &= \frac{1}{T_b}\int^{T_b} c_k(t) r_2^k \\
&= -\sqrt{E_k}\, d_{k2} h_{k1} + \sqrt{E_k}\, d_{k1} h_{k2} + \\
&\sum_{j\neq k}^{K}\left[\sqrt{E_j}\,\rho_{jk2}\begin{pmatrix} -(d_{k2}^{-1}+d_{k2})h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)+ \\ (d_{k1}^{-1}+d_{k1})h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right) \end{pmatrix}\right] + n_k'
\end{aligned} \tag{1.14}
$$

where

$$n_1' = \frac{1}{T_b}\int^{T_b} n_1 c_k(t)\cos(\omega_c t)dt \tag{1.15}$$

$$n_2' = \frac{1}{T_b}\int^{T_b} n_2 c_k(t)\cos(\omega_c t)dt \tag{1.16}$$

and

$$\rho_{jki} =\leq \frac{1}{T_b}\int^{T_b} c_k(t-\tau_{ki}) c_j(t)dt \tag{1.17}$$

is the crosscorrelation between the *j*th and *k*th user during the *i*th STBC symbol period.

The *k*th user's previous bit during the *i*th STBC symbol period is given by d_{ki}^{-1}.

At the combiner the signals y_{k1}^{MF} and y_{k2}^{MF} are combined to extract x_1^k

$$
\begin{aligned}
\tilde{x}_1^k &= h_{k1} y_{k1}^{MF} + h_{k2} y_{k2}^{MF} \\
&= \left(\beta_{k1}^2+\beta_{k2}^2\right)\sqrt{E_k}\, d_{k1} \\
&+ \sum_{j\neq k}^{K} h_{k1}\left[\sqrt{E_j}\begin{pmatrix} \rho_{jk1} h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(d_{k1}^{-1}+d_{k1}\right)+ \\ \rho_{jk2} h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(d_{k2}^{-1}+d_{k2}\right) \end{pmatrix}\right] \\
&+ \sum_{j\neq k}^{K} h_{k2}\left[\sqrt{E_j}\begin{pmatrix} -\rho_{jk2} h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(d_{k2}^{-1}+d_{k2}\right)+ \\ \rho_{jk1} h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(d_{k1}^{-1}+d_{k1}\right) \end{pmatrix}\right] \\
&\quad + h_{k1} n_1' + h_{k2} n_2'
\end{aligned} \tag{1.18}
$$

and to extract x_2^k

$$
\begin{aligned}
\tilde{x}_2^k &= -h_{k1} y_{k2}^{MF} + h_{k2} y_{k1}^{MF} \\
&= \left(\beta_{k1}^2+\beta_{k2}^2\right)\sqrt{E_k}\, d_{k2} \\
&+ \sum_{j\neq k}^{K} -h_{k1}\left[\sqrt{E_j}\begin{pmatrix} -\rho_{jk2} h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(d_{k2}^{-1}+d_{k2}\right)+ \\ \rho_{jk1} h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(d_{k1}^{-1}+d_{k1}\right) \end{pmatrix}\right] \\
&+ \sum_{j\neq k}^{K} h_{k2}\left[\sqrt{E_j}\begin{pmatrix} \rho_{jk1} h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(d_{k1}^{-1}+d_{k1}\right)+ \\ \rho_{jk2} h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(d_{k2}^{-1}+d_{k2}\right) \end{pmatrix}\right] \\
&- h_{k1} n_2' + h_{k2} n_1'
\end{aligned} \tag{1.19}
$$

For notational convenience, the combined estimates of (1.18) and (1.19) can be expressed as

$$\tilde{x}_1^1 = X_1^1 + MAI_1^1 + N_1'^1 \tag{1.20}$$

and

$$\tilde{x}_2^1 = X_2^1 + MAI_2^1 + N_2'^1 \tag{1.21}$$

Where X_1^1 and X_2^1 denote the first user's desired signal during the first and second STBC symbol periods, respectively, given by

$$X_1^1 = (\beta_{k1}^2+\beta_{k2}^2)\sqrt{E_k}\, d_{k1} \tag{1.22}$$

$$X_2^1 = (\beta_{k1}^2+\beta_{k2}^2)\sqrt{E_k}\, d_{k2} \tag{1.23}$$

MAI_1^1 and MAI_2^1 denote the multiple access interference on user 1's signal during the first and second STBC symbol periods, respectively, given as

$$
\begin{aligned}
MAI_1^1 &= \sum_{j\neq k}^{K} h_{k1}\left[\sqrt{E_j}\begin{pmatrix} \rho_{jk1} h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(d_{k1}^{-1}+d_{k1}\right)+ \\ \rho_{jk2} h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(d_{k2}^{-1}+d_{k2}\right) \end{pmatrix}\right] \\
&+ \sum_{j\neq k}^{K} h_{k2}\left[\sqrt{E_j}\begin{pmatrix} -\rho_{jk2} h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(d_{k2}^{-1}+d_{k2}\right)+ \\ \rho_{jk1} h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(d_{k1}^{-1}+d_{k1}\right) \end{pmatrix}\right]
\end{aligned} \tag{1.24}
$$

$$
\begin{aligned}
MAI_2^1 &= \sum_{j\neq k}^{K} -h_{k1}\left[\sqrt{E_j}\begin{pmatrix} -\rho_{jk2} h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(d_{k2}^{-1}+d_{k2}\right)+ \\ \rho_{jk1} h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(d_{k1}^{-1}+d_{k1}\right) \end{pmatrix}\right] \\
&+ \sum_{j\neq k}^{K} h_{k2}\left[\sqrt{E_j}\begin{pmatrix} \rho_{jk1} h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(d_{k1}^{-1}+d_{k1}\right)+ \\ \rho_{jk2} h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(d_{k2}^{-1}+d_{k2}\right) \end{pmatrix}\right]
\end{aligned} \tag{1.25}
$$

and $N_1'^1$ and $N_2'^1$ denotes the AWGN introduced at the receiver and is expressed as

$$
\begin{aligned}
N_1'^1 &= \int^{T_b} h_{11} n_1 \sqrt{2/T_b}\, c_1(t)\cos(\omega_c t)dt \\
&+ \int^{T_b} h_{12} n_2 \sqrt{2/T_b}\, c_1(t)\cos(\omega_c t)dt
\end{aligned} \tag{1.26}
$$

$$
\begin{aligned}
N_2'^1 &= \int^{T_b} -h_{11} n_2 \sqrt{2/T_b}\, c_1(t)\cos(\omega_c t)dt \\
&+ \int^{T_b} h_{12} n_1 \sqrt{2/T_b}\, c_1(t)\cos(\omega_c t)dt
\end{aligned} \tag{1.27}
$$

III. PARTITIONED APPROACH MULTIUSER DETECTION

In PA the MUD precedes the decoder and does not utilize the decoder output. Decoding is only performed after the last PIC stage, thus the tentative decisions produced by the PIC of each stage treats each user data as if it were not coded. Figure 2 shows the partitioned approach turbo space-time PIC MUD. The signals are received by the multiple antennas, which consists of a bank of *K* MFs that are matched to the corresponding fading factor and signature waveforms of each user.

The MIMO MF receiver acts as the first stage of the detector, it combines and despreads the signals, giving, at each MF output $\mathbf{y}_k^{MF}$ as given by equations (1.13) and (1.14). This is then fed to the PIC, where *p* iterative stages are carried out. The output of the *p*th PIC stage, for the first and second STBC symbol period is

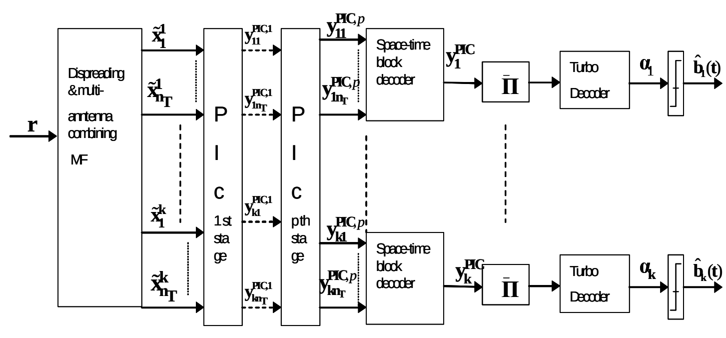

FIGURE 2: Partitioned approach turbo space-time PIC MUD

$$y_{k1}^{PIC,p}(t)=\tilde{x}_1^k(t)-\sum_{j\neq k}^{K}h_{k1}\left[\sqrt{E_j}\begin{pmatrix}\rho_{jk1}h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(\hat{d}_{k1}^{-1}+\hat{d}_{k1}\right)+\\ \rho_{jk2}h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(\hat{d}_{k2}^{-1}+\hat{d}_{k2}\right)\end{pmatrix}\right]$$
$$+\sum_{j\neq k}^{K}h_{k2}\left[\sqrt{E_j}\begin{pmatrix}-\rho_{jk2}h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(\hat{d}_{k2}^{-1}+\hat{d}_{k2}\right)+\\ \rho_{jk1}h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(\hat{d}_{k1}^{-1}+\hat{d}_{k1}\right)\end{pmatrix}\right]+n_1' \tag{1.28}$$

$$y_{k2}^{PIC,p}(t)=\tilde{x}_2^k(t)-\sum_{j\neq k}^{K}-h_{k1}\left[\sqrt{E_j}\begin{pmatrix}-\rho_{jk2}h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(\hat{d}_{k2}^{-1}+\hat{d}_{k2}\right)+\\ \rho_{jk1}h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(\hat{d}_{k1}^{-1}+\hat{d}_{k1}\right)\end{pmatrix}\right]$$
$$+\sum_{j\neq k}^{K}h_{k2}\left[\sqrt{E_j}\begin{pmatrix}\rho_{jk1}h_{j1}\cos\left(\theta_{k1}-\theta_{j1}\right)\left(\hat{d}_{k1}^{-1}+\hat{d}_{k1}\right)+\\ \rho_{jk2}h_{j2}\cos\left(\theta_{k2}-\theta_{j2}\right)\left(\hat{d}_{k2}^{-1}+\hat{d}_{k2}\right)\end{pmatrix}\right]+n_2' \tag{1.29}$$

and $\hat{d}_k^p$ is the tentative hard decision taken during the *p*th PIC stage (where $p>0$).

The output of the last PIC stage, $y_{kn_T}^{PIC,p}$ is then passed to the space-time block decoder where all the outputs from all antennas of the same user are summed up according to the MRC technique in [9], giving

$$y_k^{PIC}(t)=\tilde{d}_k(t) \tag{1.30}$$

The combined soft signal y_k^{PIC} is then decoded by the relevant turbo decoder to produce the soft decoded output μ_k. A hard decision is made on μ_k giving an estimate $\hat{b}_k$ of the transmitted symbol.

IV. ITERATIVE APPROACH MULTIUSER DETECTION

In IA the decoder outputs of interfering signals are used in the MUD to cancel MAI from the desired user's signal. Since in IA each user's signal is considered to be a coded bit sequence, then the tentative decisions must be made using a decoder with the bit sequence being re-encoded before the next stage of cancellation. Since we can not afford to have an encoder/decoder pair at each PIC stage, we thus estimate (using a decoder) the coded bit instead of the information bit [10]. Figure 3 shows a single stage IA turbo space-time PIC MUD.

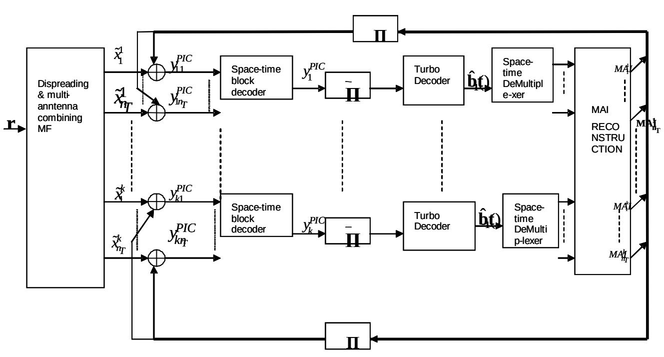

FIGURE 3: Iterative approach turbo space-time PIC MUD (single stage shown)

In the system shown in figure 3, both the PIC and turbo decoding stages perform only a single iterative step. The signals at the output of both the PIC and space-time multiplexer are given by equations (1.28) and (1.30) respectively. In contrast to PA, the output, at all but the last iteration, of the turbo decoder μ_k^p is demultiplexed by the space-time demultiplexer (this is to allow us to perform the iterative feedback procedure). The soft estimates produced $\tilde{x}_{n_T}^k$, are then used in the reconstruction of the MAI.

The MAI reconstruction procedure can be defined by (1.24) and (1.25) for the 2 x 1 diversity scenario. The MAI on each user for all antennas, $MAI_{n_T}^k$, is subtracted from the MIMO MF received signal, $\tilde{x}_{n_T}^k$, to produce a new (more clean) signal $y_{kn_T}^{PIC,p}$.

This joint PIC and turbo decoding process is repeated *p* times (as described above). On all iterations we take a hard decision on the soft decoder output $\hat{b}_k(t)=\mathrm{sgn}(\alpha_k)$ (this is the input data estimate).

V. COMPARISON BETWEEN PA AND IA SYSTEM PERFORMANCE

Because of complexity of analysis of multistage interference cancellation systems, most of this work relies heavily on Monte-Carlo simulation techniques to help supplement analysis. For all numerical results discussed in this section we consider the following: a flat-Rayleigh fading channel, a processing gain of 16 with random spreading codes. Each user encodes their data using a rate $r=1/3$ turbo code with the generator polynomial $\left(1\ 5/7\right)_{Octal}$ and transmits a frame of 1024 bits. We assume equal power users and perfect channel state information (CSI) at the receiver. For each approach we perform four iterative cancellation stages (or joint cancellation stages in the case of IA) thus giving a fair comparison, in terms of complexity, between the two systems as both are viewed to perform the same number of floating point operations *per user per symbol*, however in-depth complexity issues are not discussed in this paper.

Worthwhile to note is that figures 5, 6, 7 and 11 share the same legend as figure 4, while figures 8 and 9 use the same legend.

In figures 4, 5 and figures 6, 7 we investigate the performance gained with increasing the number of iterations for both PA and IA MUDs in the respective cases of four and eight users. Worth noting is that at low SNR IA performs better than PA. As the signal improves PA 'crosses' over the IA performance, giving a better performance. This phenomenon is easily observed in a 8-user system as depicted in figures 6 and 7. In both the 4-user and 8-user systems in figures 4 to 7, it can be observed that the 'crossover' performance point occurs at a lower SNR as we change from a lower diversity (2x1) to a higher diversity (2x2) system. Figures 8 and 9 show the 'crossover' point shift towards the left (i.e. lower SNR value) with an increase in diversity for both 4-user and 6-user systems. Furthermore from these two graphs it is observed that PA takes more advantage of diversity as there is a notable performance improvement over the IA system for a system with a higher load.

It can be noted from figures 10 and 11 that as the number of system users increases in both PA and IA MUDs, the IA scheme achieves more capacity gains than the PA scheme.

In figure 12 we investigate the performance of the two system as a function of the number of iterations. It is noted that the 'crossover' occurs at lower iterations for a lightly loaded system but shifts to the right in both heavy and overloaded systems.

From all the above observations, we can conclude that the point of 'crossover' in PA and IA system performance is very dependent on the receiver parameters (i.e. number of iterative stages), diversity level and also the channel loading.

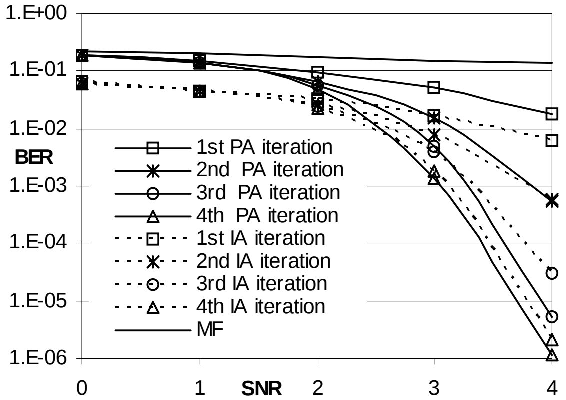

FIGURE 4: BER Performance vs. SNR for both PA and IA as a functions of increasing iterations. Here, users=4, 2x1 antennas

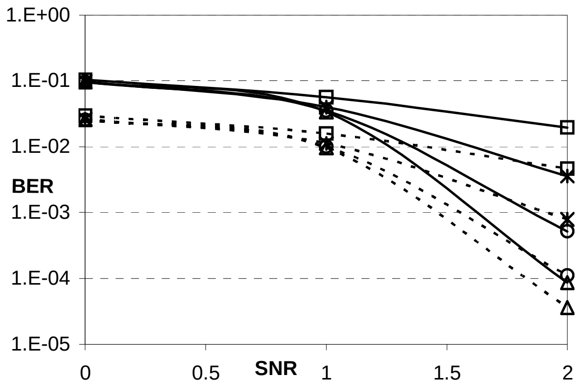

FIGURE 5: BER Performance vs. SNR for both PA and IA as a functions of increasing iterations. Here, users=4, 2x2 antennas

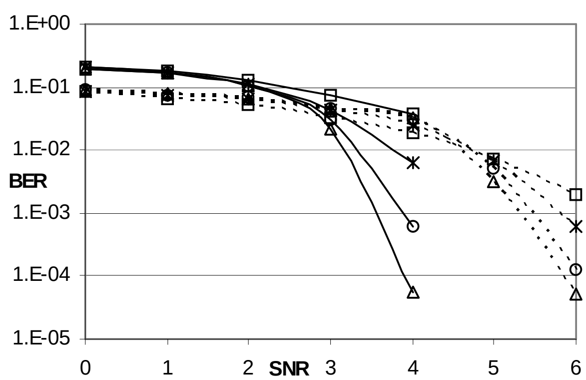

FIGURE 6: BER performance vs. SNR for both PA and IA as a function of increasing iterations. Here, users =8, 2x1 antennas

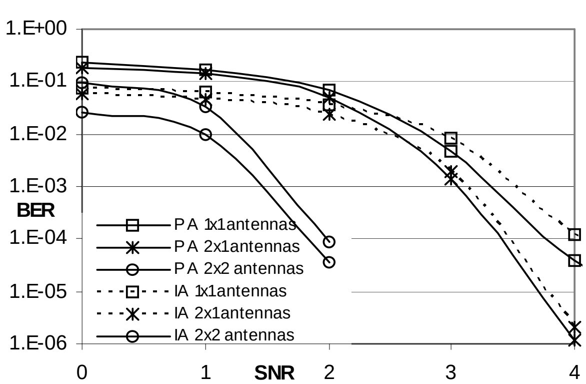

FIGURE 7: BER performance vs. SNR for both PA and IA as a function of increasing iterations. Here, users =8, 2x2 antennas

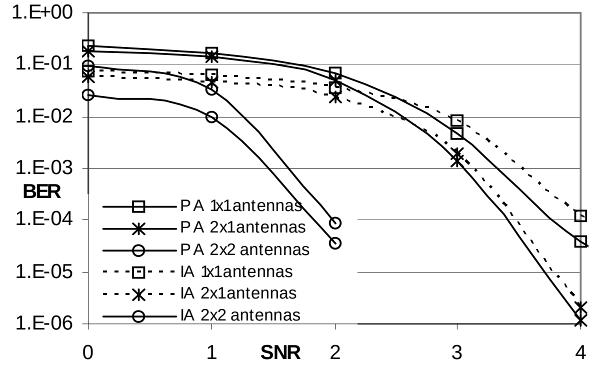

FIGURE 8: BER performance vs. SNR for both PA and IA as a function of diversity. Here, users=4, Iterations=4.

VI. CONCLUSION AND RECOMMENDATIONS

We observe that by employing either PA or IA MUDs we achieve considerable capacity gains. However, at low SNR IA outperforms PA, but as the fidelity of the signal improves PA gradually gains more performance improvements over IA. This behaviour of PA and IA follows that of, respectively, parallel and serial turbo concatenation. A further area of study is in the design of a hybrid system that switches to either IA or PA mode, based on the system and channel conditions. Possible ways of determining the crossover point such as statistical variables from both IA and PA system can be used to determine this switching point, in such work, a method like density evolution could be used.

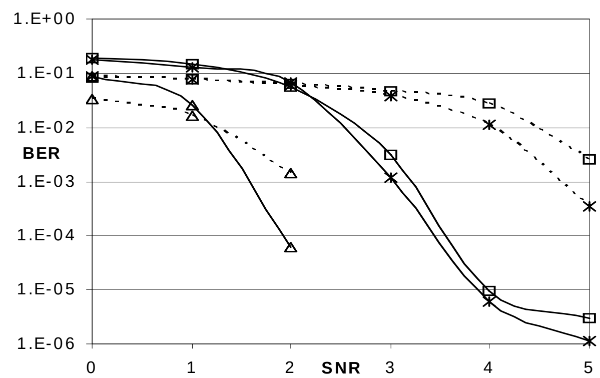

FIGURE 9: BER performance vs. SNR for both PA and IA as a function of diversity. Here, users=6, Iterations=4.

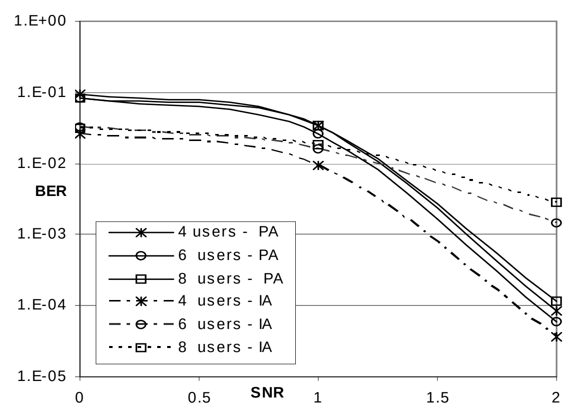

FIGURE 10: Performance comparison between PA and IA for different BER vs. SNR system loads. Here Iterations=4,2x2 antennas

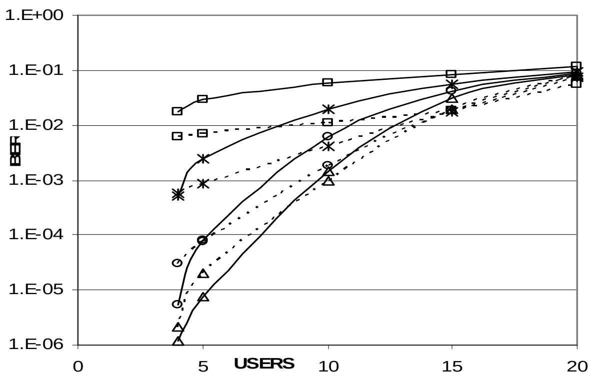

FIGURE 11: BER performance as a function of system load. Here, SNR =4 and 2x1 antennas

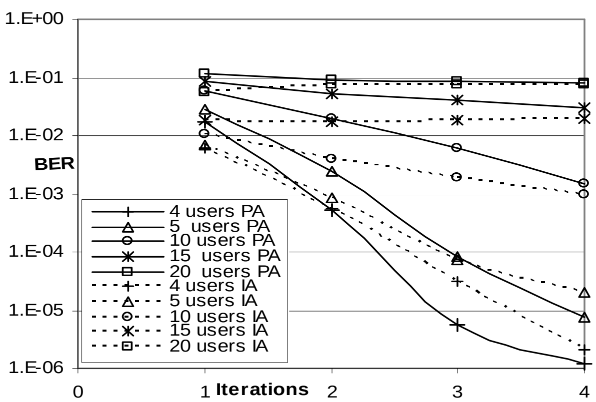

FIGURE 12: BER performance as a function of the number of PA and IA iteration. Here, SNR =4, 2x1 antennas

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Derrick B. Mashwama received his B.Eng. degree in electronic engineering from the University of Swaziland in 2005 and is currently working towards his MSc degree at the Department of Electrical Engineering, University of Cape Town, R.S.A. His research interests focus on advanced wireless communication systems. He is especially interested in turbo coded systems, Multiuser detection (MUD) techniques and Multiple-Input Multiple-Output (MIMO) systems.

Emmanuel O. Bejide is a senior lecturer in the Department of Electrical Engineering at the University of Cape Town – South Africa. He received his B.Sc. (Hons) and M.Sc. degrees in Electrical and Electronic Engineering from the Obafemi Awolowo University, Ile-Ife, Nigeria in 1995 and 1999 respectively. He received a PhD degree in Electronic Engineering from the University of KwaZulu-Natal, South Africa in 2004.