Abstract—In this paper, we explore Code Division Multiple Access (CDMA) systems with multiple transmit and receive antennas combined with Space-Time Trellis Codes over a frequency selective channel. The conventional multi-user Minimum Mean Square Error (MMSE) detector is generalized to deal with multiple antennas and multiple paths and, then, extended to include the turbo principle in an iterative fashion, allowing interference regeneration and cancellation at the receiver. Iterative multi-user MMSE receivers employing chip level and symbol level detectors are derived and their equivalence is demonstrated. Computer simulations show that the proposed iterative MMSE equalizer completely remove the interference of the other users and transmit antennas in the system, providing a significant improvement compared to the conventional non-iterative multi-user MMSE detector and effectively achieving the single-user performance, even in a fully loaded system.

I. INTRODUCTION

The recently developed Space-Time coding techniques have been shown to provide significant improvement in spectral efficiency over fading wireless channels, by exploiting transmit and receive diversity. Space-Time Trellis Codes (STTC), in particular, have been extensively studied in order to combat the effect of fading, and various code design criteria have been developed in order to achieve the highest possible antenna diversity and coding gain [1][2]. However, multiple antennas at the transmitter, multi-path in the channel and multiple users in the system inevitably introduce not only Inter Symbol Interference (ISI) and Multiple Access Interference (MAI), but also Intra Symbol Interference amongst the antennas. Thus, an enhanced multi-user detector is required to cope with this highly interfering scenario. The conventional multi-user MMSE detector has been introduced in [3] for a CDMA system and the iterative principle has been applied to MMSE equalization in [4] and [5]. The turbo principle has been integrated with MMSE detection and extended to multiple paths in [6]. In [7], this architecture has been further extended to multiple antennas, cancelling at each iteration only the interference from the other users. In this paper, we enhance this architecture by accounting in the cancellation process also the interference from the other antennas of the desired users and by considering asynchronous reception of the signal transmitted by different antennas. Furthermore, the iterative multi-user MMSE detector is derived by equalizing directly the received signal at the chip level or alternatively filtering the sufficient statistics at the output of a Space-Time matched filter at a symbol level. The equivalence of the two detectors is then demonstrated and necessary modifications in the decoders are illustrated. Finally, computer simulations of the described receiver structures are provided.

II. SYSTEM MODEL

In this paper, we focus on a K-user STTC coded CDMA system, signalling through a fading multi-path MIMO channel with Additive White Gaussian Noise (AWGN). The k-th user information block \( b_k \) is fed into an STTC encoder generating \( n_T \) sequences of coded data symbols. These are interleaved using \( n_T \) time-interleavers and then modulated by a set of \( n_T \) spreading sequences. The data vectors are finally transmitted by \( n_T \) antennas through the k-th user multi-path sub-channel. Each data block contains \( M \) symbols of duration \( T \), identified by the vector \( x_{i,k} = [x_{i,k}(0), ..., x_{i,k}(M-1)]^T \). We consider a spreading waveform \( s_{i,k}(t) = \sum_{n=0}^{N-1} c_{i,k}(n)w(t-nT_s) \), where \( c_{i,k}(n) \) is the spreading sequence of the k-th user for the m-th symbol at antenna \( i \), \( N_s \) is the spreading gain, \( w(t) \) is the chip waveform and \( T_s \) is the chip duration. The signal transmitted by antenna \( i \) (\( i \in [1, .., n_T] \)) and user \( k \) (\( k \in [1, .., K] \)) at time \( t \) is given by

\[
v_{i,k}(t) = \sum_{m=0}^{M-1} x_{i,k}(m)s_{i,k}(t-mT).
\]

Considering a system with \( n_R \) receive antennas, the signal transmitted by user \( k \) from antenna \( i \) to receive antenna \( j \), propagates through a multi-path channel with impulse response

\[
h_{i,j}^k(t) = \sum_{l=1}^{L_{i,j}^k} \alpha_{j}^{k,l} \delta(t-\tau_{j}^{k,l}), \quad \tau_{j}^{k,l} = \tau^{k} + \tau_{j,i}^{k,l},
\]

where \( L_{i,j}^k \) is the number of paths interfering between antennas \( i \) and \( j \) for the k-th user, and \( \alpha_{j}^{k,l} \) and \( \tau_{j,i}^{k,l} \) are, respectively, the l-th path gain and delay of user \( k \) in the sub-channel \( i-j \) (in a synchronous CDMA system \( \tau^{k}=0 \) for all the users). The signal received at the j-th antenna at time \( t \) is then given by

\[
r_j(t) = \sum_{k,i,j,m} \alpha_{j}^{k,l} x_{i,k}(m)s_{i,k}(t-mT-\tau_{j,i}^{k,l}) + n_j(t),
\]
where \( n_j(t) \) is an AWGN sample. Let us consider the \( m \)-th symbol \((m \in \{0, ..., M - 1\})\) of the \( k \)-th user’s information data block at antenna \( i \), whose spreading sequence is given by the vector \( \mathbf{f}_{i,k}^m = [e_{i,k}^m(0), ..., e_{i,k}^m(N_M - 1)]^T \), with spreading wave-form having energy normalized to the unity, i.e., \( \|\mathbf{s}_{i,k}(t)\|^2 = 1 \). Defined the block diagonal matrices

\[
\mathbf{F}_{i,k} = \text{diag}\{\mathbf{f}_{i,k}^1, ..., \mathbf{f}_{i,k}^{M-1}\} \quad (4a)
\]

\[
\mathbf{F}_i = \text{diag}\{\mathbf{F}_{i,1}, ..., \mathbf{F}_{i,K}\} \quad (4b)
\]

the complete augmented \( n_T KM N_s \times n_T KM \) diagonal block spreading matrix for the entire transmitted information by all the users from all the transmit antennas is given by

\[
\mathbf{F} = \text{diag}\{\mathbf{F}_1, ..., \mathbf{F}_i, ..., \mathbf{F}_{n_T}\}. \quad (5)
\]

Next, the sampled channel matrix between transmitter \( i \) and receiver \( j \) for user \( k \) is given by

\[
\mathbf{H}_{i,j}^k = \text{Toeplitz}(\mathbf{h}_{i,j}^k, \mathbf{h}), \quad (6)
\]

where \( \mathbf{h} = [h_{i,j}^k(0), 0, ..., 0] \) and \( \mathbf{h}_{i,j}^k = [h_{i,j}^k(0), ..., h_{i,j}^k(M N_s - 1)]^T \) are \( M N_s \times 1 \) vectors. The stacked \( M N_s \times K M N_s \) matrix

\[
\mathbf{H}_{i,j} = [\mathbf{H}_{i,j}^1, ..., \mathbf{H}_{i,j}^K, ..., \mathbf{H}_{i,j}^{n_T}] \quad (7)
\]

characterizes the sub-channel \( i-j \) for all the active users in the system. The complete \( n_R M N_s \times n_T KM N_s \) MIMO multi-path channel matrix can finally be written as

\[
\mathbf{H} = \begin{bmatrix}
\mathbf{H}_{1,1} & \cdots & \mathbf{H}_{1,n_T}
\vdots & \ddots & \vdots \\
\mathbf{H}_{n_R,1} & \cdots & \mathbf{H}_{n_R,n_T}
\end{bmatrix} \quad (8)
\]

for \( i \in [1, ..., n_R] \) and \( j \in [1, ..., n_T] \). Therefore, the total received \( n_R M N_s \)-vector can be expressed as

\[
\mathbf{r} = \mathbf{H} \mathbf{F} \mathbf{x} + \mathbf{n} = \mathbf{S} \mathbf{x} + \mathbf{n}, \quad (9)
\]

where the \( n_T KM \)-vector \( \mathbf{x} = [\mathbf{x}_1^T, ..., \mathbf{x}_{n_T}^T] \) is the total signal transmitted and the \( n_R M N_s \)-vector \( \mathbf{n} = [\mathbf{n}_1^T, ..., \mathbf{n}_{n_R}^T]^T \) is the total AWGN at the receiver. In the remainder of this paper, a user-synchronous CDMA transmission over a frequency selective channel with \( L \) resolvable multi-path components for each sub-channel is considered. However, no constraint is given for the time of arrivals of symbols transmitted by different antennas, meaning that the transmission is asynchronous among the transmit antennas.

### III. Conventional MMSE Detector

#### A. Multi-user Space-Time matched filter MMSE detector

In this paper, the signal transmitted by the \( k \)-th user is a set of \( n_T \) data blocks transmitted synchronously by \( n_T \) antennas. At the receiver, this is virtually equivalent to a system with \( n_T - K \) different interfering users. Thus, under this assumption, the sufficient statistics for this system are given by the complex \( MK n_T \)-vector [18]

\[
y \triangleq \mathbf{S}^H \mathbf{r} = \mathbf{S}^H \mathbf{S} \mathbf{x} + \mathbf{S}^H \mathbf{n} = \mathbf{G} \mathbf{x} + \mathbf{S}^H \mathbf{n}, \quad (10)
\]

where the \( ([(i - 1)K + (k - 1)]M + m) \)-th element of \( y \) represents the space-time matched filter output for user \( k \), transmit antenna \( i \) and symbol \( m \). Next, the multi-user MMSE detector applies a linear transformation to \( y \) in order to minimize the mean-squared error \( E[|e|^2] = E[||\mathbf{z} - \mathbf{x}||^2] = E[||\mathbf{W} \mathbf{y} - \mathbf{x}||^2] \) between the resulting vector \( \mathbf{z} \) and the data vector \( \mathbf{x} \) [3]. The \( MK n_T \times MK n_T \) matrix \( \mathbf{W} \) represents the Multi-User Space-Time Matched Filter MMSE (MU-STMF-MMSE) matrix. Using the principle of orthogonality for linear systems \( E[\mathbf{y} \mathbf{y}^H] = \mathbf{0} \), we arrive at

\[
\mathbf{W} = \mathbf{R}_e \mathbf{G}^H (\mathbf{G} \mathbf{R}_e \mathbf{G}^H + \mathbf{R}_n)^{-1}, \quad (11)
\]

where \( \mathbf{G} \) has been defined in (10) and \( \mathbf{R}_e \) and \( \mathbf{R}_n \) represent respectively the autocorrelations of the transmitted signal and the noise at the input of the MMSE filter. If we define the diagonal matrix \( \mathbf{A} \), whose diagonal entries are the real amplitudes of the transmitted symbols for all the users and all the antennas, the transmitted data vector can be expressed as \( \mathbf{x} = \mathbf{A} \mathbf{x} \), where \( \mathbf{x} \) is the transmitted data vector normalized to unity (\( ||\mathbf{x}||^2 = 1 \)). Considering additive AWGN with variance \( \sigma_n^2 \) \( \mathbf{y} \) at the receiver, we can write

\[
\mathbf{R}_e = E[\mathbf{x} \mathbf{x}^H] = \mathbf{A}^2 \quad (12a)
\]

\[
\mathbf{R}_n = E[\mathbf{S}^H \mathbf{n} (\mathbf{S}^H \mathbf{n})^H] = E[\mathbf{S}^H \mathbf{n} \mathbf{n}^H \mathbf{S}] = \sigma_n^2 \mathbf{G} \quad (12b)
\]

Next, it can be shown that a sufficient condition for the \( n_T KM \times n_T KM \) matrix \( \mathbf{G} = \mathbf{S}^H \mathbf{S} \) to be invertible is that the columns of \( \mathbf{S} \) are linearly independent. This is true with probability one if the spreading codes of all the users are linearly independent and the following relations hold:

\[
\begin{cases}
\frac{n_R}{n_T} N_s \geq n_T K & \text{if } n_R < n_T \\
N_s \geq K & \text{if } n_R \geq n_T
\end{cases} \quad (13)
\]

Hence, the spreading codes for the signals transmitted by the \( k \)-th user across the \( n_T \) transmit antennas are not required to be independent and considering that \( \mathbf{G} = \mathbf{G}_\bot \), (11) can be simplified to

\[
\mathbf{W} = (\mathbf{G} + \sigma_n^2 \mathbf{A}^{-2})^{-1}. \quad (14)
\]

Furthermore, since under the above conditions \( (\mathbf{G} + \sigma_n^2 \mathbf{A}^{-2}) \) is hermitian positive definite and hence invertible, the existence of the matrix \( \mathbf{W} \) is guaranteed. Note that for user-asynchronous transmission, through different uncorrelated sub-channels, the independence of the spreading sequences is not a requirement for the invertibility of \( \mathbf{G} \).
where, considering AWGN with variance $\sigma^2$.

The conventional multi-user MMSE detector is a linear transformation of the received signal. The signals of all the users and transmit antennas are jointly filtered at its output, by taking into account the effect of the interference due to ISI and MAI. The desired user’s information data are then estimated at the output of a ST-decoder. It is possible to enhance the detection of the received signal, by combining the MMSE criterion with the turbo processing principle, in order to suppress the interference [7]. In this section we derive the iterative multi-user MMSE in both version chip-synchronous and STMF-MMSE, where we include also the interference from the other antennas of the desired user in the regeneration and cancellation of the interfering data.

A. Iterative Multi-user MMSE detector

The received signal in (9) and the sufficient statistics in (10) can be then expressed as the sum of the $k$-th user contribution from antenna $i$, the interference from the other users and antennas and the AWGN at the receiver. They are given by

$$ \mathbf{r} = \mathbf{S}_i \mathbf{x}_i + \mathbf{S}_{-i} \mathbf{x}_{-i} + \mathbf{n} \quad (18a) $$
$$ \mathbf{y} = \mathbf{G}_i \mathbf{x}_i + \mathbf{G}_{-i} \mathbf{x}_{-i} + \mathbf{n}, \quad (18b) $$

where $\mathbf{S}_i$ is the $n_P N_i M \times M$ sub-matrix formed by the $M$ columns of $\mathbf{S}$ belonging to user $k$ and transmit antenna $i$ and $\mathbf{G}_i = \mathbf{S}_i^H \mathbf{S}_i$ is the $n_T K M \times M$ sub-matrix similarly obtained from $\mathbf{G}$. $\mathbf{S}_{-i} \mathbf{x}_{-i}$ denotes the $n_P N_i M \times (n_T K - 1) M$ sub-matrix obtained removing $\mathbf{S}_i$ from $\mathbf{S}$. $\mathbf{G}_{-i}$ is the $n_T K M \times (n_T K - 1) M$ sub-matrix obtained removing $\mathbf{G}_i$ from $\mathbf{G}$ and $\mathbf{x}_i$ and $\mathbf{x}_{-i}$ represent the data vectors transmitted respectively by user $k$ and antenna $i$ and by all the other users and antennas. Since (18a) and (18b) have a similar form, we can derive the Iterative Multi-User Chip-Synchronous MMSE (IMU-CS-MMSE) detector and then identify the Iterative Multi-User Space-Time Matched Filter MMSE (IMU-STMF-MMSE) detector by substitution. At a given iteration $n$, the a priori probabilities of the transmitted symbols of all the users and antennas are available at the receiver from the output of the decoders at iteration $n - 1$. Hence, it is possible to calculate an estimated mean of the transmitted symbols in order to enhance the symbol’s detection by regenerating the interference at the input of the MMSE filter $\mathbf{W}_k^{n,c}$.

## IV. ITERATIVE MMSE DETECTOR

The conventional multi-user MMSE detector is a linear transformation of the received signal. The signals of all the users and transmit antennas are jointly filtered at its output, by taking into account the effect of the interference due to ISI and MAI. The desired user’s information data are then estimated at the output of a ST-decoder. It is possible to enhance the detection of the received signal, by combining the MMSE criterion with the turbo processing principle, in order to suppress the interference [7]. In this section we derive the iterative multi-user MMSE in both version chip-synchronous and STMF-MMSE, where we include also the interference from the other antennas of the desired user in the regeneration and cancellation of the interfering data.

A. Iterative Multi-user MMSE detector

The received signal in (9) and the sufficient statistics in (10) can be then expressed as the sum of the $k$-th user contribution from antenna $i$, the interference from the other users and antennas and the AWGN at the receiver. They are given by

$$ \mathbf{r} = \mathbf{S}_i \mathbf{x}_i + \mathbf{S}_{-i} \mathbf{x}_{-i} + \mathbf{n} \quad (18a) $$
$$ \mathbf{y} = \mathbf{G}_i \mathbf{x}_i + \mathbf{G}_{-i} \mathbf{x}_{-i} + \mathbf{n}, \quad (18b) $$

where $\mathbf{S}_i$ is the $n_P N_i M \times M$ sub-matrix formed by the $M$ columns of $\mathbf{S}$ belonging to user $k$ and transmit antenna $i$ and $\mathbf{G}_i = \mathbf{S}_i^H \mathbf{S}_i$ is the $n_T K M \times M$ sub-matrix similarly obtained from $\mathbf{G}$. $\mathbf{S}_{-i} \mathbf{x}_{-i}$ denotes the $n_P N_i M \times (n_T K - 1) M$ sub-matrix obtained removing $\mathbf{S}_i$ from $\mathbf{S}$. $\mathbf{G}_{-i}$ is the $n_T K M \times (n_T K - 1) M$ sub-matrix obtained removing $\mathbf{G}_i$ from $\mathbf{G}$ and $\mathbf{x}_i$ and $\mathbf{x}_{-i}$ represent the data vectors transmitted respectively by user $k$ and antenna $i$ and by all the other users and antennas. Since (18a) and (18b) have a similar form, we can derive the Iterative Multi-User Chip-Synchronous MMSE (IMU-CS-MMSE) detector and then identify the Iterative Multi-User Space-Time Matched Filter MMSE (IMU-STMF-MMSE) detector by substitution. At a given iteration $n$, the a priori probabilities of the transmitted symbols of all the users and antennas are available at the receiver from the output of the decoders at iteration $n - 1$. Hence, it is possible to calculate an estimated mean of the transmitted symbols in order to enhance the symbol’s detection by regenerating the interference at the input of the MMSE filter $\mathbf{W}_k^{n,c}$, in a way similar to Parallel Interference Cancellation (PIC) [5][6][9]. Assuming that the $n_T K$-vector $\mathbf{z}_i^n = [\mathbf{x}_i^n, ... \mathbf{x}_i^{nT}]^T$ is the input of the $k$-th user decoder at the $n$-th iteration, we can write

$$ \mathbf{z}_i^n = \mathbf{W}_k^{n,c} \left( \mathbf{r} - \mathbf{S}_{-i} \mathbf{x}_{-i} \right) $$
$$ = \mathbf{W}_k^{n,c} \left[ \mathbf{S}_i \mathbf{x}_i + \mathbf{S}_{-i} \mathbf{x}_{-i} \right] + \mathbf{n}, \quad (19) $$

where $\mathbf{x}_{-i}^{-1}$ denotes the $(n_T K - 1) M$-vector of estimated mean values of the other users and antennas’ transmitted symbols from the previous iteration, as shown in figure 1. Standard minimization techniques allow us to derive the iterative MMSE filter for user $k$ and antenna $i$ at iteration $n$, given by

$$ \mathbf{W}_k^{n,c} = \mathbf{R}_i \mathbf{S}_i^H \left[ \mathbf{S}_i \mathbf{R}_i \mathbf{S}_i^H + \mathbf{S}_{-i} \mathbf{V}_{-i}^H \mathbf{S}_{-i} + \mathbf{R}_n \right]^{-1}, \quad (20) $$
where
\[
\mathbf{R}_{i,k} = E[\mathbf{x}_{i,k}\mathbf{x}_{i,k}^H] \quad \mathbf{R}_n = E[\mathbf{n}\mathbf{n}^H]
\]
\[
\mathbf{V}^{n-1}_{-i,k} = E[(\mathbf{x}_{-i,k} - \hat{x}_{-i,k}^{n-1})(\mathbf{x}_{-i,k} - \hat{x}_{-i,k}^{n-1})^H].
\] (21)

In the first stage of the detection process, we assume that the transmitted symbols are equally likely, and hence, \(\hat{x}_{-i,k}^{n-1} = 0\). Therefore, the feedback contribution is null and the stacked matrix \(\mathbf{R}^{n,c} = [\mathbf{R}^{n,c}_{1,1} \cdots \mathbf{R}^{n,c}_{n_T,K}]^T\) coincides with the MU-CS-MMSE detector in (15). Then, the IMU-STMF-MMSE detector can be directly derived from (20) by replacing \(\mathbf{r}, \mathbf{s}\) and \(\mathbf{n}\) respectively with \(\mathbf{y}, \mathbf{G}\) and \(\hat{\mathbf{n}}\). Next, it is necessary to analyze the structure of the iterative multi-user MMSE filter matrices, in order to investigate sufficient conditions for their existence. In the case of IMU-CS-MMSE in (20), assuming AWGN at the receiver, this is always guaranteed, since the matrix within the brackets is strictly positive definite, and hence invertible one. Instead, the IMU-STMF-MMSE matrix is guaranteed to exist only if the matrix \(\mathbf{G}\) is invertible. Sufficient conditions for \(\mathbf{G}\) to be invertible have been already derived in (13) and, still, apply for this more general case.

B. Equivalence of IMU-STMF-MMSE and IMU-CS-MMSE

The IMU-STMF-MMSE detector requires a bank of space-time matched filters and equalizes the sufficient statistics at the symbol level. The IMU-CS-MMSE detector operates at a chip level and reduces the whole receiver to a single bank of digital MMSE filters. However, given the same channel state information and the transmitted signals, we demonstrate that their performance is identical. In fact, given an invertible \(N \times N\) complex matrix \(\mathbf{B}\) and a full column rank \(N \times M\) complex matrix \(\mathbf{S}\), for any complex \(N\)-vector \(\mathbf{u}\) the following equality holds:
\[
\mathbf{B}^{-1}\mathbf{u} = \mathbf{S}(\mathbf{S}^H\mathbf{S})^{-1}\mathbf{S}^H\mathbf{u}. \quad (22)
\]

Then, the IMU-STMF-MMSE output can be written as
\[
\mathbf{z}_{i,k} = \mathbf{R}_{i,k}\mathbf{S}^H\mathbf{S}(\mathbf{S}^H\mathbf{S})^{-1}\mathbf{S}^H\mathbf{u} + \mathbf{R}_n(\mathbf{S}^{-1}\mathbf{S}^H(\mathbf{r} - \mathbf{S}_{-i,k})\hat{x}_{-i,k}^{n-1})), \quad (23)
\]
which is, employing (22), identical to \(\mathbf{z}_{i,k}^{n,c}\) derived in (20) and demonstrates the equivalence of the two detectors.

V. SPACE-TIME DECODER

The signal at the output of the MMSE detectors is deinterleaved and fed in a bank of single-user Space-Time (ST) decoders. From [1], assuming ideal channel information, the path gains \(\alpha_{k,l}^{n,T}\) introduced in (2) can be used in the decoders to calculate the branch metrics for each transition labelled \(q_k^1(t)q_k^2(t)q_k^3(t)\) in the trellis, in the following way:

\[
\sum_{j=1}^{n_R} |y_{k,j}(t) - q_k^j(t)|^2. \quad (24)
\]

where \(y_{k,j}(t)\) is the received signal at receive antenna \(j\) at time \(t\) after despreading and summing over all the paths. However, this metric cannot be used in this form at the output of the MMSE detector, where all the replicas across the received antennas and multiple paths have already been taken into account and an estimate of the \(n_T\) transmitted signals is available at the input of the decoders. Therefore, we suggest to remove the unnecessary channel information and rewrite the path metrics as

\[
\sum_{i=1}^{n_T} |z_{i,k}(t) - q_k^i(t)|^2. \quad (25)
\]

The Space-Time Soft-Output Viterbi Algorithm (ST-SOVA) described in [9] is then employed to generate the log-likelihood ratios (llrs), as in the standard SOVA. At iteration \(n\) and time \(t\) the soft-output is represented by the llrs of the detected codeword, used to calculate the \(a\ posteriori\) probabilities of the transmitted symbols, while at the last iteration the maximum-likelihood (ML) path is chosen as hard decision for the information block.

VI. SIMULATION RESULTS

In this section, we present the performance of STTC user-synchronous CDMA systems over frequency selective fading channels when employing multi-user MMSE detectors. QPSK symbols are transmitted, after spreading (OVSF codes) and scrambling (Gold sequences), through a slow fading Rayleigh multi-path MIMO channel with \(L\) resolvable paths for each sub-channel. The same spreading sequences are chosen for each user across the \(n_T\) transmit antennas. We consider a delay spread of maximum \(N_s\) chips, i.e., one symbol duration. The performance is measured in terms of bit error rate (BER) and frame error rate (FER) as a function of the signal to noise ratio.

Fig. 2. 2-antennas 4-states STTC BER performance (\(K=8, N_s=16, n_T=4\)) for different number of paths and iterations.
per bit per receive antenna \( (E_b/N_0) \) and the number of active users in the system. We assume that all the users transmit a frame of 260 information bits \((M=130)\) with equal power from all the antennas. We first show simulation results for a 4-state 2-antennas STTC \( ((0,2),(1,2),(2,3),(2,0) [2]) \), spreading gain \( N_s=16, K=8 \) active users and \( n_R=4 \) receive antennas. Figure 2 illustrates the BER for the IMU-MMSE detector, for different number of iterations and resolvable paths. With no iterations the multi-user detector suffers from the other users and antennas’ interference, but after only one iteration \((n=1)\) it reaches the single-user lower bound (depicted in the figure for \( K=1)\). Considerable gain is also achieved by increasing the number of resolvable paths. Next, we consider a system coded with a 16-state 2-antennas STTC \( ((1,2),(1,3),(3,2),(2,0),(2,2),(2,0) [2]) \), \( n_R=2 \) receive antennas and spreading factor \( N_s=32 \). BER and FER curves have been derived as a function of the number of active users in the system, for a fixed \( E_b/N_0=6\text{dB} \). From figures 3 and 4 is evident how the MU-MMSE receiver (non-iterative) suffers from highly interfering scenarios, particularly in a fully loaded system \((K=32)\), where its performance is limited by the MAI, regardless of the number of resolvable paths in the channel. However, after only two iterations the IMU-MMSE detector achieves the single-user lower bound, exploiting the multi-path diversity, and at a given BER the capacity of the system doubles from 16 users to 32 after only one iteration.

VII. CONCLUSIONS

In this paper, an iterative multi-user MMSE receiver for STTC CDMA systems over multi-path fading channels has been derived and the equivalence of chip-synchronous and matched filter solutions has been demonstrated. The turbo principle applied to MMSE equalization is shown to be able to cope with the interference from the other users and also from the other antennas of the desired user, by a process of regeneration and cancellation. Simulation results show the consistent gain in capacity achieved by this structure compared to the non-iterative multi-user MMSE detector. This is obtained by exploiting multi-path and antenna diversities and effectively approaching the single-user lower bound in even highly loaded scenarios.

ACKNOWLEDGEMENTS

The work reported in this paper has formed part of the Wireless Access area from the Core 2 Research Programme of the Virtual Centre of Excellence in Mobile & Personal Communications, Mobile VCE, http://www.mobilevce.com. Their funding is gratefully acknowledged. More detailed information on this research is available to Industrial Members of Mobile VCE.

REFERENCES