Overloaded SISO & MISO Systems with MMSE-based Equalization Receivers

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ABSTRACT

In this paper the performance of the MMSE-based equalization receivers under overloading conditions is analyzed, for SISO (Single Input, Single Output) and MISO (Multiple Input, Single Output) antenna arrangements. Both random and orthogonal spreading sequences are analyzed, for the main UMTS (Universal Mobile Telecommunications System) TDL (Tapped Delay Line) channel models, namely Pedestrian A and Vehicular A. The downlink transmission and a SF (Spreading Factor) of 16 is chosen for the simulated cases, in order to mimic the HSDPA (High Speed Downlink Packet Access) mode of the UMTS.

Keywords: Equalization, MMSE, overloading, UMTS.

I. INTRODUCTION

In a Mobile Cellular UMTS Network, the quality of the communication link between the transmitter and the different receivers varies depending on several issues, such as the received power levels, and most importantly, the noise level of the received signal. This noise may come from different sources, such as MAI (Multiple Access Interference), ISI (Inter-Symbolic Interference) and thermal noise. The system must be projected taking these variables into account, and be able to provide a reasonable quality under full-loading conditions.

For an operator, it is crucial to "fit" the maximum amount of users per cell, with a good quality of service. For this to be accomplished, it is necessary to have a good receiver, able to compensate for the interference present in the channel. The performance of a simple RAKE/ MF (Matched Filter) receiver (or enhanced schemes based on the MF) has a severe interference canceling limitation that does not allow for the system to perform at full capacity, due to the inability to cancel the correlation between different paths and antennas. Therefore, an MMSE-based equalization receiver [1], (adapted for multipath) was developed for such cases acting as an equalizer, effectively canceling out the ISI (Inter-Symbolic Interference) and MAI (Multiple Access Interference), yielding very interesting results.

In this work, the MMSE receiver was taken to its limit, in order to see what its overloading capability is. This being, simulations were run for both under- and over-loading, in order to analyze the steady performance degradation as the system begins to accommodate more users/ physical channels.

The structure of the paper is as follows. In Section II, the MMSE receiver, considering MIMO (Multiple Input, Multiple Output) and multipath, is introduced. A brief introduction to overloading is given in Section III. The performance results are discussed in Section IV and the main conclusions are drawn in Section V.

II. MMSE RECEIVER

A standard model for a DS-CDMA system with K users (assuming 1 user per physical channel) and L propagation paths is considered. The modulated symbols are spread by a Walsh-Hadamard code with length equal to the Spreading Factor (SF). The signal on a MIMO system with N_{TX} transmit and N_{RX} receive antennas, at one of the receiver's antennas, can be expressed as:

$$r_v(t)_{RX=1} = \sum_{n=1}^{N} \sum_{tx=1}^{N_{TX}} \sum_{k=1}^{K} \sum_{l=1}^{L} A_{k,tx} b_{k,tx}^{(n)} c_{k,tx,rx}(t) s_k(t - nT - \tau_{k,l}) + n(t) \quad (1)$$

where N is the number of received symbols,

$$A_{k,tx} = \sqrt{E_k}, \quad (2)$$

E_k is the energy per symbol, K is the number of users, $b_{k,tx}^{(n)}$ is the n-th transmitted data symbol of user k and transmit antenna tx, $s_k(t)$ is the k-th user's signature signal (combined spreading and scrambling code - equal for all antennas), T denotes the symbol interval, $n(t)$ is a complex zero-mean AWGN (Additive White Gaussian Noise) with variance σ^2,

$$c_{k,tx,rx}(t) = \sum_{l=1}^{L} c_{k,tx,rx,l}^{(n)} \delta(t - \tau_{k,l}) \quad (3)$$

is the impulse response of the k-th user's radio channel, $c_{k,tx,rx,l}$ is the complex attenuation factor of the k-ths user's l-th path of the link between the tx-th and rx-th antenna and $\tau_{k,l}$ is the propagation delay (assumed equal for all antennas).

Using matrix algebra, the received signal can be represented as

$$r_v = S C A b + n, \quad (4)$$

where S, C and A are the spreading, channel and amplitude matrices respectively.

The spreading matrix S has dimensions $(SF \cdot N \cdot N_{RX} + \rho_{MAX} \cdot N_{RX}) \times (K \cdot L \cdot N \cdot N_{RX})$ (ρ_{max} is the maximum delay of the channel's impulse response, normalized to number of chips, and SF is the Spreading Factor), and is composed of sub-matrices S_{RX} in its diagonal for each receive antenna $S = \text{diag}(S_{RX,1}, \dots, S_{RX,N_{RX}})$. Each of these sub-matrices has dimensions $(SF \cdot N + \rho_{MAX}) \times (K \cdot L \cdot N)$, and are further composed by smaller matrices S_n^L, one for each bit position, with size $(SF + \rho_{MAX}) \times (K \cdot L)$. The S_{RX} matrix structure is made of

$$S_{SRX,n} = \left[0_{(SF \cdot (n-1)) \times (K \cdot L)} ; S_n^L ; 0_{(SF \cdot (N-n)) \times (K \cdot L)} \right]$$

$$S_{RX} = \left[S_{SRX,1}, \dots, S_{SRX,N} \right]$$

The S^L matrices are made of $K \cdot L$ columns;

$$S_n^L = \left[S_{\text{col}(k=1,l=1),n}, \dots, S_{\text{col}(k=1,l=L),n}, \dots, S_{\text{col}(k=K,l=L),n} \right]. \text{ Each of}$$

these columns is composed of

$$S_{\text{col}(kl),n}=\left[0_{(1\times\text{delay}(l))},sp_n(k)_{1\times SF},0_{\left(1\times(\rho_{MAX}-\text{delay}(l))\right)}\right]^T,$$

where $sp_n(k)$ is the combined spreading & scrambling for the bit n of user k.

These S^L matrices are either all alike if no long scrambling code is used, or different if the scrambling sequence is longer than the SF. The S^L matrices represent the combined spreading and scrambling sequences, conjugated with the channel delays. The shifted spreading vectors for the multipath components are all equal to the original sequence of the specific user.

$$S_n^L=\begin{bmatrix} S_{1,1,1,n} & \cdots & \cdots & S_{K,1,1,n} \\ \vdots & \ddots & S_{1,1,L,n} & \cdots & \vdots & \ddots & S_{K,1,L,n} \\ S_{1,SF,1,n} & & \vdots & \cdots & S_{K,SF,1,n} \\ & \ddots & S_{1,SF,L,n} & \cdots & \cdots & \ddots & S_{K,SF,L,n} \end{bmatrix}$$

Note that, in order to correctly model the multipath interference between symbols, there is an overlap between the S^L matrices, of ρ_{MAX}.

The channel matrix C is a $(K\cdot L\cdot N\cdot N_{RX})\times(K\cdot N_{TX}\cdot N)$ matrix, and is composed of N_{RX} sub-matrices, each one for a receive antenna $C=\left[C_{RX,1}^R;\dots;C_{RX,N_{RX}}^R\right]$. Each C^R matrix is composed of N C^{KT} matrices alongside its diagonals.

$$C=\begin{bmatrix} C_{RX,1}^R = \begin{bmatrix} C_{1,1}^{KT} & & \\ & \ddots & \\ & & C_{N,1}^{KT} \end{bmatrix} & & \\ & \vdots & \\ C_{RX,N_{RX}}^R = \begin{bmatrix} C_{1,N_{RX}}^{KT} & & \\ & \ddots & \\ & & C_{N,N_{RX}}^{KT} \end{bmatrix} \end{bmatrix}$$

Each C^{KT} matrix is $(K\cdot L)\times(K\cdot N_{TX})$, and represents the fading coefficients for the current symbol of each path, user, transmit antenna and receive antenna. The matrix structure is made up of further smaller matrices alongside the diagonal of C^{KT}, $C^{KT}=\text{diag}\left(C_{K,1}^T,\dots,C_{K,K}^T\right)$, with C^T of dimensions $L\times N_{TX}$, representing the fading coefficients for the user's multipath and tx-th antenna component.

$$C^{KT}=\begin{bmatrix} C_{1,1,1} & \cdots & C_{N_{TX},1,1} & & & \\ \vdots & & \vdots & & & \\ C_{1,L,1} & \cdots & C_{N_{TX},L,1} & & & \\ & & & \ddots & & \\ & & & & C_{1,1,K} & \cdots & C_{N_{TX},1,K} \\ & & & & \vdots & & \vdots \\ & & & & C_{1,L,K} & \cdots & C_{N_{TX},L,K} \end{bmatrix}$$

The A matrix is a diagonal matrix of dimension $(K\cdot N_{TX}\cdot N)$, and represents the amplitude of each user per transmission antenna and symbol, $A=\text{diag}\left(A_{1,1,1},\dots,A_{N_{TX},1,1},\dots,A_{N_{TX},K,1},\dots,A_{N_{TX},K,N}\right)$.

The matrix resultant from the SCA operation (henceforth known as SCA matrix) is depicted in Figure 1. It is a $N_{TX}\cdot K\cdot N\times N_{RX}\cdot(N\cdot SF+\rho_{MAX})$ matrix, and is the reference matrix for the decoding algorithms.

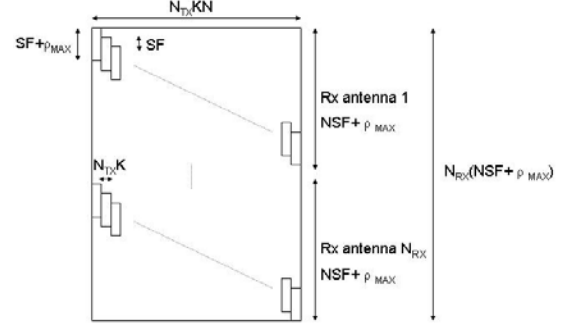Figure 1 - Layout of the SCA matrix

Vector b represents the information symbols. It has length $(K\cdot N_{TX}\cdot N)$, and has the following structure $b=\left[b_{1,1,1},\dots,b_{N_{TX},1,1},\dots,b_{1,K,1},\dots,b_{N_{TX},K,1},\dots,b_{N_{TX},K,N}\right]^T$.

Note that the bits of each transmit antenna are grouped together in the first level, and the bits of other interferers in the second level. This is to guarantee that the resulting matrix to be inverted has all its non-zeros values as close to the diagonal as possible. Also note that there is usually a higher correlation between bits from different antennas using the same spreading code, than between bits with different spreading codes.

Finally, the n vector is a $(N\cdot SF\cdot N_{RX}+N_{RX}\cdot\rho_{MAX})$ vector with noise components to be added to the received vector r_v, which is partitioned by N_{RX} antennas, $r_v=\left[r_{1,1,1},\dots,r_{1,SF,1},\dots,r_{N,1,1},\dots,r_{N,SF+\rho_{MAX},1},\dots,r_{N,1,N_{RX}},\dots,r_{N,SF+\rho_{MAX},N_{RX}}\right]^T$ (note that the effects of the delay ρ_{MAX} are present throughout r_v).

The MMSE algorithm yields the symbol estimates, y_{MMSE}, where σ^2 is the noise variance of n, y_{MF} is the matched filter output and E_M is the Equalization Matrix (cross-correlation matrix of the users' signature sequences after matched filtering, at the receiver).

$$y_{MF}=(SCA)^H r_v \tag{5}$$

$$R=A\times C^H\times S^H\times S\times C\times A \tag{6}$$

$$E_M=R+\sigma^2 I \tag{7}$$

$$y_{MMSE}=\left(E_M\right)^{-1}y_{MF} \tag{8}$$

The configuration is done in such a way that the E_M presents itself as if the Sparse Reverse Cuthill-McKee ordering algorithm [2] had been applied to it, and thus there is no fill-in when performing the E_M inverse using the Choleski algorithm. The expected main problem associated with such scheme is the size of the matrices, which assume huge proportions. This has been the main perceived drawback of such scheme, responsible for the reduced amount of work of MMSE-based schemes in MIMO and frequency selective channels. However, if the sparseness of the matrices is taken into account, only a fraction of the memory and computing power is required. Some algorithms for solving the E_M in a similar case (SISO TD-CDMA) taking advantage of the E_M structure are given in [3]. The MMSE algorithm is fully described in [4].

III. OVERLOADING

Overloading for a SISO DS-CDMA system occurs when the number of used codes exceeds the maximum value which is equal to the SF (assuming all codes use the same SF). Whenever an additional code is used, it can be composed by a combination of other codes, and thus it becomes very hard to decode it (impossible, unless some extra information regarding the transmitted symbols is known, such as their relative power levels).

For a MIMO DS-CDMA system, overloading may occur with an excess number of codes and/or an excess of transmit antennas (in a BLAST philosophy, transmitting different symbols, in order to increase capacity) to the number of receive antennas, if all codes are used. Overloading of the cell leads to severe performance degradation and a significant performance floor, by definition. However, when the overloading factor is low enough, the system might still perform under satisfactory conditions, if robust receivers are employed.

When the ZF receiver algorithm is analyzed closely, it can be seen that the resolution of the matrix equation becomes impossible for overloading conditions, since the E_M is singular for such conditions. A way to overcome this problem is to use a ZF approach that considers only part of the variables, considering the remaining variables as noise. The same reasoning applies for the MMSE algorithm, under very low noise conditions. However, under normal noise conditions, the E_M is no longer singular, due to the addition of the noise power to its diagonal. This makes its columns linearly independent, and therefore possible to find its invert (though the final estimates are biased by the added noise power). The performance floor is obviously still present, nonetheless.

Different simulations were run for overloading, using as basis the MMSE receiver algorithm; the simulation results should be compared against the fully-loaded condition (16 physical channels with a SF of 16) of the SISO system. Simulations were run for 1 receive antenna, under a downlink philosophy. Both a SISO and MISO (2 transmit antennas, each with a different scrambling code) setup were considered. Two different types of spreading were employed; random spreading (where each spreading codes is obtained randomly, with the usage of Gold codes), and orthogonal spreading (where each code is part of a Hadamard sequence). Note that, in the case of overloading with orthogonal spreading, the orthogonal codes are used until the maximum number of orthogonal codes is reached. After this number, all other spreading codes are random (via the usage of Gold codes).

IV. PERFORMANCE RESULTS

The main UMTS channels, namely Pedestrian A and Vehicular A (taken from [5]) were simulated. Since only 1 sample per chip was used in the simulations, the channels were adjusted to the chip delay time of 260ns, using the constant mean delay spread method [6]. For the particular case of Vehicular A, since the method yields 8 taps, with the last ones having low power levels, an adjustment was made so that only the main taps were considered. The resulting channels are depicted in Figure 2. The considered velocities

were 50km/h for Vehicular A and 3km/h for the remaining channels.

		0	1	3	4
PedA	delay (chips)	0	1		
	% received power	94,98%	5,02%		
VehA	delay (chips)	0	1	3	4
	% received power	49,50%	39,32%	6,23%	4,95%

Figure 2 - Resulting UMTS channels

From the results, it can be inferred that it is possible to operate an overloaded system, with the obvious drawback of reduced performance. Comparing Figure 3 and Figure 4 with Figure 5 and Figure 6, we can conclude that orthogonal spreading should be used while the maximum capacity isn't reached. Once full capacity is reached, the system's performance decreases substantially – this can be seen clearly for the orthogonal spreading case, whilst the case for random spreading exhibits smooth performance degradation with the increase of physical channels. Note that the performance is similar for both spreading types once the overloading region is reached.

For the case when there are more transmit than receive antennas operating under a BLAST philosophy (more specifically the MISO setting of 2 transmit and 1 receive antennas), it can be seen that the BER of the system is under 10%, when each transmit antenna employs 12 physical channels, corresponding to an overloading factor of $\frac{(PhysCh=12) \times (tx\_antennas=2)}{SF=16} - 1 = 50\%$. Note, however, that once coding is employed, this figure is suffice to yield satisfactory results.
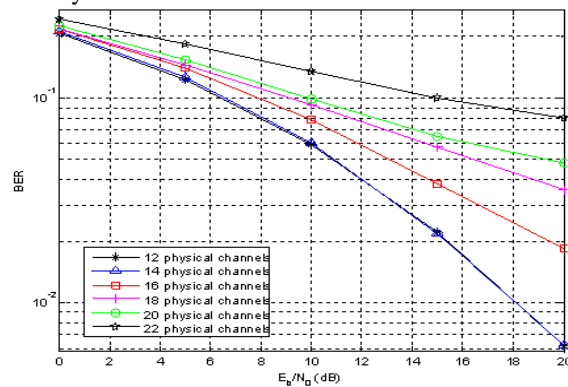

Figure 3 - MMSE overloading, QPSK, SISO – Random Spreading, Pedestrian A.
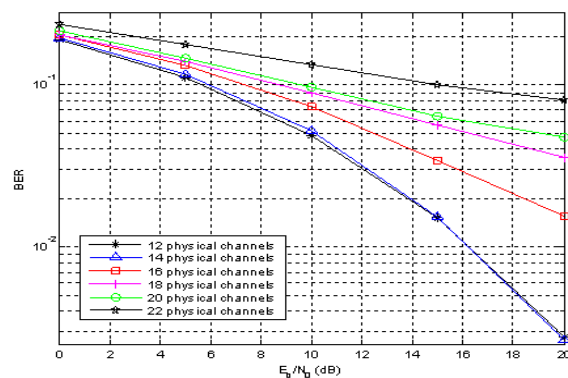

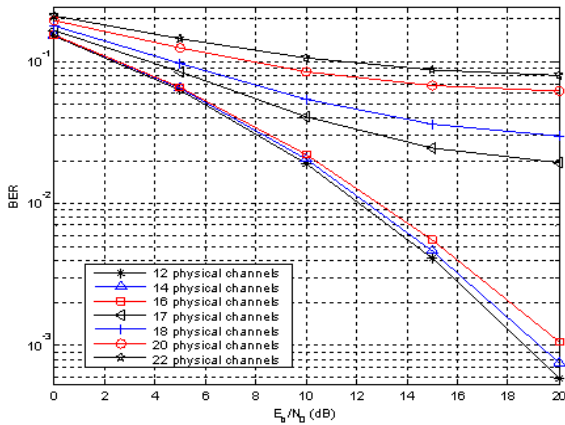Figure 4 - MMSE overloading, QPSK, SISO – Random Spreading, Vehicular A.

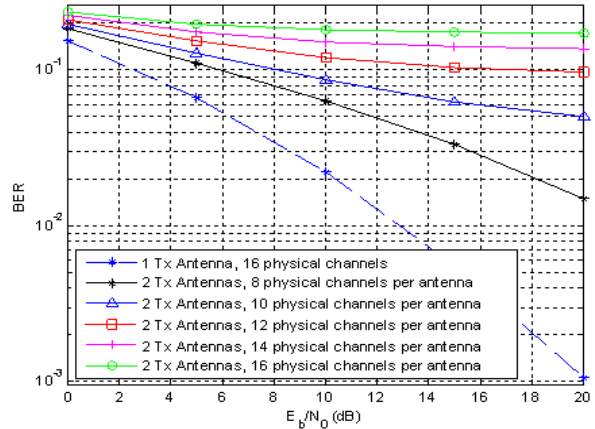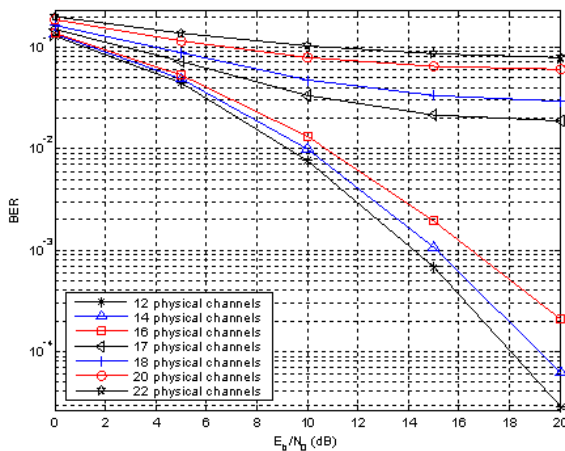Figure 5 - MMSE overloading, QPSK, SISO – Orthogonal Spreading, Pedestrian A.

Figure 6 - MMSE overloading, QPSK, SISO – Orthogonal Spreading, Vehicular A.

Figure 7 - MMSE overloading, QPSK, MISO – Orthogonal Spreading, Pedestrian A.
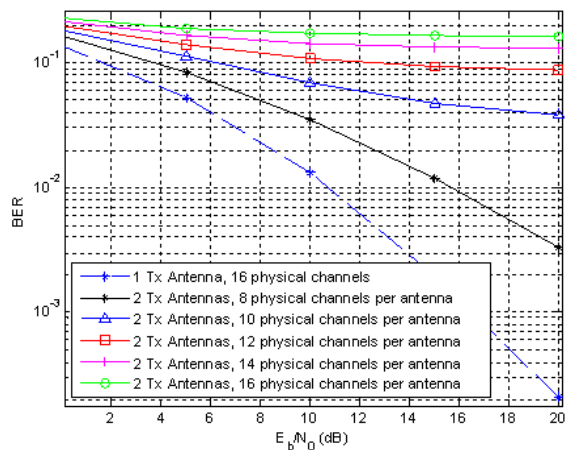

Figure 8 - MMSE overloading, QPSK, MISO – Orthogonal Spreading, Vehicular A.

V. CONCLUSIONS

In this paper we tested the use of overloading for the main UMTS channels, namely Pedestrian and Vehicular A, in the downlink transmission. As expected, there is severe performance degradation once the overload-threshold is crossed, noticeable when using orthogonal spreading codes (the best to use in the downlink). When the used codes are random (somewhat resembling the uplink case, aside the fact that the channel doesn't differ between users/physical channels), this transition is not as abrupt.

It was interesting to notice that an overloading factor up until 50% yields results that are reasonable for use with turbo coding, constituting a major source of capacity augmentation for services that don't require very high quality levels.

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