An improved linear MMSE detection technique for multi-carrier CDMA system: Comparison and combination with interference cancelation schemes

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An Improved Linear MMSE Detection Technique for Multi–Carrier CDMA Systems: Comparison and Combination with Interference Cancellation Schemes

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Abstract. In this paper, various detection techniques are studied in the synchronous case of a multiuser MC–CDMA system operating in frequency selective Rayleigh channel. First of all, an improved linear detection approach named MMSE per user detection technique, which takes into account the despreading process, is presented. Simulation results over a Rayleigh fading channel show that this novel technique offers for non full load systems a significant gain compared to the MMSE equalization per carrier method. Then, the performance of various parallel and successive interference cancellation techniques is compared to the performance of the linear MMSE per user scheme. When the power of the interferers is roughly equal to the power of the useful signal, the performance of the linear MMSE per user is really close to the performance of the non linear PIC and SIC schemes.

1 INTRODUCTION

Since 1993, many researchers have investigated the suitability of the Multi–Carrier Code Division Multiple Access (MC–CDMA) for cellular systems [1], [2]. This promising multiple access scheme with high bandwidth efficiency is based on a serial concatenation of Direct Sequence (DS) spreading with Multi–Carrier (MC) modulation. The MC–CDMA transmitter spreads the original data stream over different subcarriers using a given spreading code in the frequency domain. For a synchronous system as the downlink mobile radio communication channel, the application of orthogonal codes such as Walsh–Hadamard codes guarantees the absence of Multiple Access Interference (MAI) in a Gaussian channel. However, through a frequency selective fading channel, all the subcarriers have different amplitude levels and different phase shifts, which results in a loss of the orthogonality among users and then generates MAI. So, after direct FFT and frequency deinterleaving, the received sequence must be "equalized" by using a bank of adaptive one tap equalizers to make up for the phase and amplitude distortions caused by the mobile radio channel on the subcarriers. The channel estimation is usually derived from the FFT of the channel impulse response which can be estimated using pilot inserted between the data.

To fight the MAI, one may use various Single–user Detection (SD) techniques that do not take into account any information about this MAI. When the receiver knows neither the number of users nor the received SNR, conventional and simple detection methods are Maximum Ratio Combining (MRC), Equal Gain Combining (EGC) or Orthogonal Restoring Combining (ORC). For more sophisticated receiver structures, the Minimum Mean Square Error (MMSE) algorithm [3] can provide performance improvements. In order to improve the performance of the receiver still further, Multi–user Detection (MD) techniques can be processed. Multi–user detection is based on the important assumption that the codes of the different users are known to the receiver a priori. Most of the proposed multiuser detectors can be classified in one of the two categories: Maximum Likelihood (ML) detectors and Interference Cancellation (IC) detectors. In this paper, various equalization strategies are studied in the case of a downlink transmission, i.e., from the base station to the mobiles. First of all, the potential of MC–CDMA receivers based on minimum mean square error (MMSE) criterion applied per user is demonstrated for full load and specially for non full load systems. Then a comparison of the performance of various parallel and successive interference cancellation receivers is presented.

2 SYSTEM DESCRIPTION

The block diagram of the considered MC–CDMA transmitter and receiver is depicted in figure 1. Each data symbol x_j^n assigned to user j, $j = 1, \ldots, N_u$, and transmitted during the symbol interval n is multiplied bit–synchronously with its user specific Walsh–Hadamard spreading code $C_j = [c_j^1, c_j^2, \ldots, c_j^{L_c}]^T$ of length L_c, where $[\ .\ ]^T$ denotes matrix transposition. L_c corresponds to the bandwidth expansion factor and is equal to the maximum number of simultaneous active users. The vector of the data symbols transmitted during the nth OFDM symbol by all the users can be written $X^n = [x_1^n, x_2^n, \ldots, x_j^n, \ldots, x_{L_c}^n]^T$ with $x_j^n = 0$ when user j is inactive.
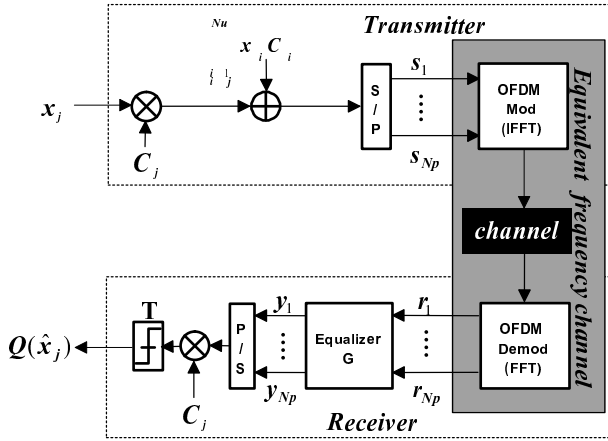

Figure 1: *MC-CDMA transmitter and receiver.*

The code matrix C is defined to be:

$$C = \begin{pmatrix} c_1^1 & c_2^1 & \ldots & c_{L_c}^1 \\ c_1^2 & c_2^2 & \ldots & c_{L_c}^2 \\ \vdots & \vdots & \ddots & \vdots \\ c_1^{L_c} & c_2^{L_c} & \ldots & c_{L_c}^{L_c} \end{pmatrix} \quad (1)$$

where the jth column vector of C corresponds to the spreading code C_j of the user j. Since we consider the synchronous downlink of an MC–CDMA system, the different data modulated spreading codes of the N_u users can be added before Serial–to–Parallel (S/P) conversion. Furthermore, the N_u user signals are supposed to be transmitted with the same power. The number N_p of subcarriers, which are QPSK modulated, is chosen equal to the spreading code length L_c. Thus, each of the N_p subcarrier In phase and Quadrature waveforms is modulated by a single chip belonging to a spreading Walsh–Hadamard code.

For this study, frequency non–selective fading per subcarrier and time invariance during one OFDM symbol are assumed. Furthermore, the absence of Intersymbol Interference and Intercarrier Interference is guaranteed by the use of a guard interval longer than the maximum excess delay of the impulse response of the channel. Under these assumptions and considering an ideal interleaving, the channel can be represented in the frequency domain as depicted in figure 1. The complex channel fading coefficients are considered independent for each subcarrier and constant during each OFDM symbol. In this case, the diversity is maximum. However in a practical situation, this hypothesis tends to be verified with appropriate frequency and time interleaving. Using this assumption, the temporal index n can be suppressed for all the quantities, and the channel response can be estimated for the subcarrier k by $h_k = \rho_k e^{i\theta_k}$. Due to the absence of ICI, the channel matrix is diagonal and equal to:

$$H = \begin{pmatrix} h_1 & 0 & \ldots & 0 \\ 0 & h_2 & 0 & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \ldots & 0 & h_{N_p} \end{pmatrix} \quad (2)$$

$N = [n_1, n_2, \ldots, n_{N_p}]^T$ is the vector containing the AWGN terms with n_k representing the noise term at the subcarrier k with variance given by $\sigma_N^2 = E\{|n_k|^2\}$, $k = 1, \ldots, N_p$. The received vector is:

$$R = [r_1, r_2, \ldots, r_{N_p}]^T = HCX + N \quad (3)$$

3 BASIC SINGLE USER DETECTION TECHNIQUES

After equalization the received signal can be written:

$$Y = [y_1, y_2, \ldots, y_{N_p}]^T = GR = GHCX + GN \quad (4)$$

and the estimated symbol of the jth user is equal to:

$$Q(\hat{x}_j) = Q(C_j^T GR) \quad (5)$$

where $Q(\ .\ )$ denotes quantization operation. The $N_p \times N_p$ matrix G represents the complex equalization coefficients obtained from the channel estimation which can be based on known transmitted pilot symbols inserted between the data carriers. Various detection techniques can be implemented [1], [5]: Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), Orthogonality Restoring Combining (ORC)... The assigned equalization coefficient is equal to:

$$g_k = h_k^* \qquad MRC \quad (6)$$
$$g_k = h_k^*/|h_k| \qquad EGC \quad (7)$$
$$g_k = 1/h_k^* \qquad ORC \quad (8)$$

Among all those well–known single–user detection techniques, MMSE equalization offers the best results. It minimizes the mean square value of the error ε_k between the signal s_k transmitted on subcarrier k and the assigned output y_k of the equalizer (see figure 1). The equalization coefficients based on this MMSE criterion applied independently per carrier are equal to:

$$g_k = \frac{h_k^*}{|h_k|^2 + \dfrac{1}{\gamma_c}} \qquad (9)$$

where γ_C is the subcarrier signal to noise ratio, and $(\,.\,)^*$ denotes complex conjugation. For all these basic detection techniques, the matrix G is diagonal, which means that the received sequence is equalized by using a bank of N_p adaptive one tap equalizers. It results from this that the complexity of the equalizer is low. However, this MMSE equalization per carrier method is not optimal, since it does not take into account the despreading process and thus does not minimize the mean square error at the input of the threshold detector T.

4 MMSE EQUALIZATION PER USER

The aim of the novel proposed method is to minimize the mean square error between the transmitted symbol x_j and the estimated one $\hat{x}_j$. Let $W_j = [w_j^0, w_j^1, \ldots, w_j^{N_p}]^T$ be the weighting optimal vector related to the user j. The estimated symbol of this j^{th} user can be written:

$$\hat{x}_j = W_j^T R \qquad (10)$$

According to the Wiener filtering, the optimal weighting vector is equal to:

$$W_j = \Gamma_{R,R}^{-1} \Gamma_{R,x_j} \qquad (11)$$

where $\Gamma_{R,R}$ is the autocorrelation matrix of the received vector R and Γ_{R,x_j} is the crosscorrelation vector between the desired symbol, x_j and the received signal vector, R. Those quantities are equal to:

$$\begin{aligned} \Gamma_{R,R} &= E\{R^* R^T\} \\ &= H^* C E\{X^* X^T\} C^T H + E\{N^* N^T\} \\ \Gamma_{R,x_j} &= E\{R^* x_j\} \\ &= H^* C E\{X^* x_j\} \end{aligned} \qquad (12)$$

where $(\,.\,)^*$ denotes complex conjugation. Then, the optimal weighting vector can be written:

$$\begin{aligned} W_j^T &= E\{x_j X^{*T}\} C^T H^* \Big(H C E\{X X^{*T}\} C^T H^* \\ &\quad + E\{N N^{*T}\} \Big)^{-1} \end{aligned} \qquad (13)$$

The subcarrier noises have the same variance and are independent. Thus, $E\{N N^{*T}\} = \sigma_N^2 I$ where I is the identity matrix. Since the user signals have the same power ($E\{|x_j|^2\} = E_s$) and are independent, we can write $E\{X X^{*T}\} = E_s A$, where $A = \{a_{ij}\}$ is a diagonal matrix with the term $a_{jj} = 1$ if the user j is active and $a_{jj} = 0$ if this user is inactive. Then, the optimal weighting vector can be expressed as:

$$W_j^T = C_j^T G \qquad (14)$$

with the equalization coefficient matrix equal to:

$$G = H^* M^{-1} = H^* \left(H C A C^T H^* + \frac{\sigma_N^2}{E_s} I \right)^{-1} \qquad (15)$$

In the full load case ($N_u = L_c$) and only in that case, the quantity $C A C^T$ is equal to the identity matrix and the equalization coefficient matrix G is a diagonal matrix with the kth subcarrier equalization coefficient equal to the former equation (9). On the other hand, in the non full load case ($N_u < L_c$), the equalization coefficient matrix G is no more diagonal. A known suboptimal solution obtained when the Wiener filter is optimized independently on each carrier, is to choose the kth subcarrier equalization coefficient equal to [6]:

$$g_k = \frac{h_k^*}{|h_k|^2 + \dfrac{1}{\gamma_c}} = \frac{h_k^*}{|h_k|^2 + \dfrac{L_c}{N_u \gamma_X}} \qquad (16)$$

where γ_X is the signal to noise ratio of the received data symbol x_j.

As we will see in the next section, the algorithm MMSE per user based on expression (15) outperforms the algorithm MMSE per carrier based on expression (16) in the non full load case, since it minimizes the decision error taking into account the despreading process instead of minimizing the error independently on each subcarrier.

In [7], it was suggested to use a MMSE detection technique that was also named MMSE per user method. However, with this approach the minimum mean square error was not calculated by using the weighting vector $W_j^T = C_j^T G$ as it is proposed in this paper, but with respect to the variable G. In that case, the matrix G is diagonal and the performance is not optimal.

To implement the MMSE per user solution, according to equation (15), complete knowledge of H and A is required. Furthermore, the inversion of M may be an expensive and time consuming operation, especially for large

lengths L_c of codes. To determine the equalization coefficient matrix G, an alternative solution is to use an iterative procedure based on popular algorithms such as Least-Mean-Square (LMS) or Recursive-Least-Square (RLS) algorithms. In this case, the choice of the algorithm will depend on the trade–off which is required between the computational complexity, the tracking capability and the steady–state error. In this study, we assume that the channel matrix H is perfectly known to the receiver, and therefore, it is possible to compute the optimum weights by direct matrix inversion.

5 PERFORMANCE COMPARISON

The simulation results are presented without channel coding for various detection techniques and for various numbers N_u of active users and number N_p of subcarriers. Each of the independent subcarriers is QPSK modulated at the transmitter side and then multiplied by an uncorrelated Rayleigh fading. The diversity N_D offered by the channel is then equal to the number N_p of subcarriers. Furthermore, it is assumed that accurate estimate of the frequency channel response for each subcarrier is available and that all the users' signals are received with the same mean power.
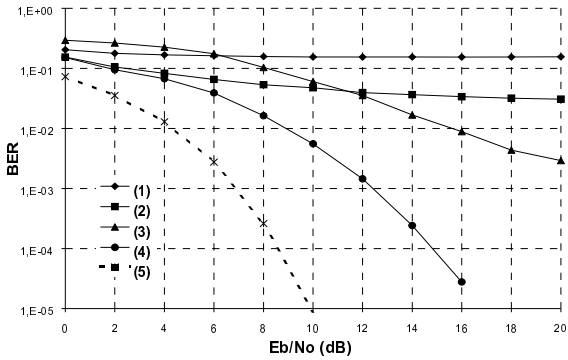

Figure 2: *Basic single user detection performance for $N_u = L_c = N_p = 64$ (full load system) with various receiver techniques: MRC (1), EGC (2), ORC (3), MMSE per carrier (4), MF bound (5).*

Figure 2 compares the performance of the well–known basic detection techniques presented in previous section 3 with full load systems: the number ($N_u = 64$) of active users is equal to the length ($L_c = 64$) of the Walsh–Hadamard code. The single detection based on minimum mean square error (MMSE) per carrier equalization offers the best results as it has already been demonstrated in [5] and [6]. The Matched Filter (MF) bound is given as reference (curve 5). The MF bound for an uncoded MC–CDMA system corresponds to the BER obtained in the case of data transmissions over N_p statistically independent Rayleigh fading channels with MRC detection and

without MAI. The MMSE (curve 4) outperforms the other techniques avoiding an excessive noise amplification for low signal to noise ratios while restoring the orthogonality among users for large signal to noise ratios.
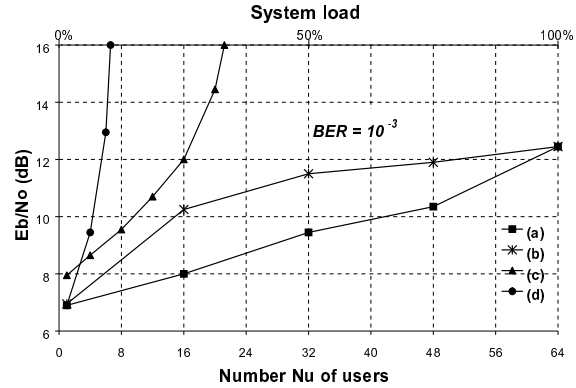

Figure 3: *Required E_b/N_0 for $BER = 10^{-3}$ versus number N_u of active users (system load) for various receiver techniques and $N_p = 64$: MMSE per user (a), MMSE per carrier (b), EGC (c), MRC (d).*

In figure 3, the performance of basic single user detections with $L_c = N_p = 64$ are compared with the performance of the novel MMSE per user technique, taking into account the required E_b/N_0 to achieve a $BER = 10^{-3}$ in terms of the number N_u of active users (system load). In any case, MRC and EGC perform poorly. The curve (b) gives suboptimal MMSE per carrier system performance with the equalization coefficients optimized independently on each subcarrier and equal to the expression (16). The curve (a) corresponds to MMSE per user system performance according to matrix approach with the equalization coefficient matrix G equal to expression (15). For full load systems ($N_u = L_c = 64$), the performance of the two MMSE approaches are the same. On the other hand, comparing them for non full load systems shows a gain of more than 2 dB in the MMSE per user case with $N_u = 32$ or 16, which corresponds to a system load respectively equal to 50% and 25%.

Figure 4 shows the performance of MMSE per user MC–CDMA systems with various code lengths, taking into account the required E_b/N_0 to achieve a $BER = 10^{-3}$ in terms of the system load. In full load case, N_u is equal to N_p and L_c. As expected, the higher the channel diversity (equal to the number N_p of independent subcarriers), the better the results. For example, the MMSE per user system with $N_p = L_c = 64$ can handle a full user capacity ($N_u = 64$ in this case) at $E_b/N_0 = 12.4$ dB. However, the performance improvement due to the increase of the number of subcarriers (and then the channel diversity) from 32 to 64, is inferior to 0.3 dB for full load systems.

In conclusion of this section, it can be noted that the novel MMSE per user approach offers for non full load sys-
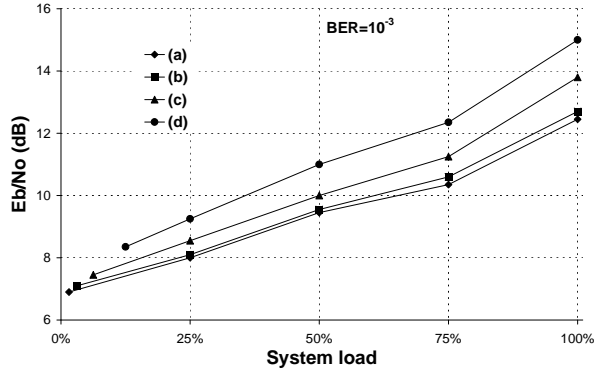
Figure 4: *Required E_b/N_0 for $BER = 10^{-3}$ versus system load for QPSK MMSE per user MC–CDMA systems for various lengths of the spreading code for $N_p = 64$ (a), $N_p = 32$ (b), $N_p = 16$ (c), $N_p = 8$ (d).*

tems a significant gain compared to the MMSE per carrier technique: typically, for a MC–CDMA system with a maximum number of users $N_u = L_c = 64$ (figure 3), the gain for a $BER = 10^{-3}$ is close to 2 dB for a number N_u of active users varying from $L_c/4$ to $3L_c/4$ which corresponds to the most likely cases. Indeed, in a dynamic multiuser scenario, where users continuously enter and leave the network, the number of active users is rarely equal to the maximum. Furthermore, a system using voice activity monitoring which prevents a mobile or the base station from radiating power during speech pauses reduces the number of active users at a given time [8]. Therefore, the probability that the maximum number L_c of active users are talking at once is very low.

6 MULTI-USER DETECTION

Based on the exploitation of the maximum likelihood criterion, the ML detector is the optimum detector. Theoretically, this method is applicable to both uplink and downlink channels. However, since its complexity grows exponentially with the number of users and with the code length, this method appears to be applicable only when the spreading sequences of all users are relatively short. Therefore, to handle a large number of users, receivers can implement sub–optimal non–linear interference cancellation techniques which can be divided into parallel and successive algorithms.

6.1 PARALLEL INTERFERENCE CANCELLATION

The Parallel Interference Cancellation (PIC) detector estimates the interference due to the simultaneous other users in order to remove this multiple user interference component from the received signal. Interference Cancellation can be carried out iteratively in multiple detection

stages. To cope with the MAI, various combinations of single detection techniques have been studied, as for example EGC in all stages [4] which appears to be less efficient than a solution with MMSE in all stages presented in [5] and [6]. An other combination with ORC (or Zero Forcing) or ORC with threshold at the first stage followed by MRC is presented in [9], [10] and [11]. In this case, the multiuser interference is eliminated using the orthogonality restoring detection and then the user detects its own information applying the maximum ratio combining method. The block diagram of the considered MC–CDMA receiver with parallel interference cancellation is illustrated in figure 5.
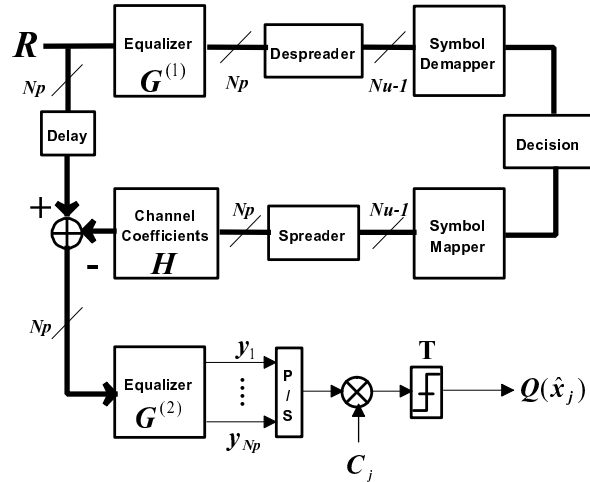

Figure 5: *Parallel interference cancellation MC–CDMA receiver with two detection stages.*

In the initial detection stage, the data symbols of all $N_u - 1$ active users are detected in parallel by the first equalizer with a gain $G^{(1)}$. After the despreading and the demapping, the decisions of this initial stage are used to reconstruct the interfering contribution in the received signal R. The resulting interference is then subtracted from the received signal and the data detection is performed again on the signal with reduced MAI. Thus, in the initial stage the data symbols of the N_u active users are detected in parallel applying:

$$Q\{\hat{x}_j^{(1)}\} = Q\{C_j^T G^{(1)} R\} \qquad (17)$$

The second and further detection stages work iteratively by using the decisions of the previous stage which yields the estimated data symbols at the mth iteration:

$$\hat{x}_j^{(m)} = C_j^T G^{(m)} \left(R - H \sum_{\substack{l=1 \\ l \neq j}}^{N_u} Q\{\hat{x}_l^{(m-1)}\} C_l \right)$$

$$\forall m \in [1, \dots, M_{it}] \qquad (18)$$

where $Q\{\ .\ \}$ denotes the quantization operation which assigns to each soft decided value an element of the finite alphabet, and M_{it} is the total number of iterations.

6.2 SUCCESSIVE INTERFERENCE CANCELLATION

In Successive Interference Cancellation (SIC), the detection is based on successive cancellations of the signal with the highest reliability from the received waveform. Thus, the operation carried out in the considered SIC receiver consists of:

- estimating the energy $E_j = E\{|x_j|^2\}$ of the various received signals and ranking them so that: $E_{r_1} > E_{r_2} > \cdots > E_{r_i} > \cdots > E_{r_{N_u}}$, where r_i denotes the rank of the user j,

- detection of the strongest user and regeneration of the strongest user spread spectrum using its Walsh–Hadamard code and the estimation of the channel frequency response,

- cancelling the strongest user interferer,

- repeating until all user signals are detected.

The complexity of the receiver is linear in the number of users and each stage leads to an additional time delay. Thus, the receiver can be simplified by cancelling only the strongest signals instead of cancelling all interferers. In the initial detection stage, only the strongest interferer x_{r_1} is detected and obtained by:

$$Q\{\hat{x}_{r_1}\} = Q\{C_{r_1}^T G^{(1)} R\} \qquad (19)$$

Then the expression of the next detected interferer at the ith interference cancellation stage, which is the $(i+1)^{th}$ detection stage, is given by:

$$\hat{x}_{r_{i+1}} = C_{r_{i+1}}^T G^{(i+1)} \left(R - H \sum_{l=1}^{i} H C_{r_l} Q\{\hat{x}_{r_l}\} \right)$$
$$\forall i \in [1, \ldots, N_u - 1] \qquad (20)$$

where N_u is the number of active users, $N_u - 1$ the number of interference cancellation stages and $j = r_{N_u}$ the last user detected.

7 INTERFERENCE CANCELLATION SIMULATION RESULTS

In the forward link of a single cell system, it is usually assumed that the N_u different users' signals are transmitted by the base station with the same power level, which is the hypothesis which has been retained for the previous

results presented in section 5. In this case, the carrier to interference ratio of the reference received signal desregarding its position in the cell is $1/(N_u - 1)$, where $N_u - 1$ is the number of interferers. No forward power control is needed. In a multiple cell system, a user located near the boundary of three cells receives considerable interference from other base stations. In this case, in order to minimize the total power transmitted by each base station, a possible solution is to use a forward power control by transmitting at a higher power level to users located at the cell boundary and at a lower power level to users close to the base station. That is why, in the following sub–sections the performance of the different detection techniques are given with equal mean power signals but also with unequal mean power signals.

7.1 PERFORMANCE WITH EQUAL MEAN POWER SIGNALS

A performance comparison of full load multistage Parallel Interference Cancellation (PIC) systems with various basic detection techniques (presented in section 3) for the first and the second stage and, if necessary for the third stage, is presented in figure 6. For those results, the MMSE equalization per carrier according to expression (16) has been implemented and the different users' signals are received with the same power.
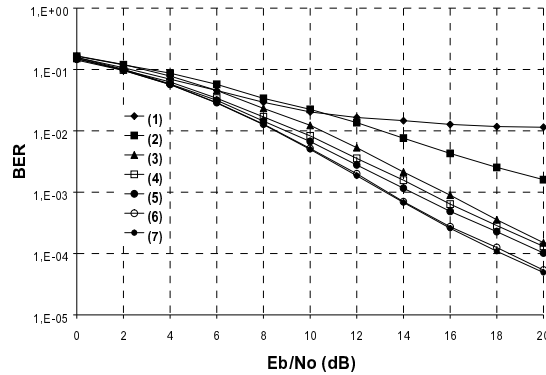

Figure 6: *PIC detection performance for $N_u = N_p = 8$ (full load system) with various receiver techniques: EGC1/EGC2 (1), ZF1/MRC2 (2), MMSE1/MRC2 (3), EGC1/MMSE2 (4), MMSE1/EGC2 (5), MMSE1/MMSE2 (6), MMSE1/MMSE2/MMSE3 (7).*

Obviously, the systems with MMSE equalization at the first stage (curves 3, 5, 6, 7) outperforms other schemes. The combination with Zero Forcing for the first stage followed by MRC (curve 2, ZF1/MRC2) requires a 8 dB higher E_b/N_0 to achieve a BER equal to 10^{-3} compared to a system with MMSE for the two stages (curve 6, MMSE1/MMSE2). Finally, the performance improvement obtained by a third MMSE stage is inferior to 0.1 dB

(comparison of the curves 6 and 7), which does not justify the additional complexity.
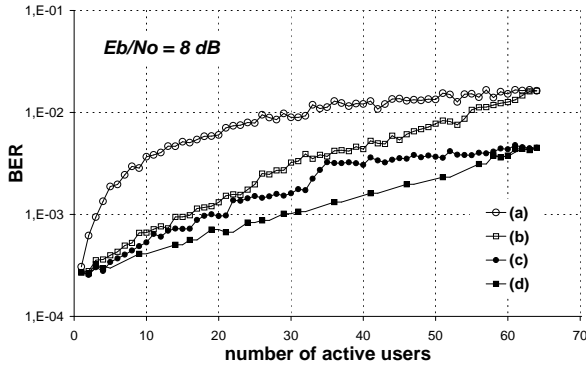

Figure 7: *BER versus the number N_u of active users for $E_b/N_0 = 8$ dB ; $N_p = L_c = 64$; MMSE per carrier (a), MMSE per user (b), PIC-MMSE per carrier (c), PIC-MMSE per user (d).*

In figure 7, the performance of two stage parallel interference cancellation MMSE per carrier and MMSE per user systems is compared to the performance of linear MMSE systems with $L_c = N_p = 64$, versus the number N_u of active users which are received with the same power. In any case, the new MMSE per user detection scheme outperforms the MMSE per carrier system. For example, with $E_b/N_0 = 8$ dB and for a $BER = 10^{-3}$, the base station can supply $N_u = 21$ users with PIC–MMSE per carrier and up to $N_u = 31$ users with PIC–MMSE per user detection. Furthermore, this figure shows that for N_u inferior to the maximum number $L_c = 64$ active users, especially when $N_u < 50$, the linear MMSE per user (curve (b)) and the non linear 2 stage PIC–MMSE per carrier (curve (c)) systems have almost equal performance. This clearly indicates a possible trade–off between performance and complexity in favor of the less complex linear MMSE per user technique. On the other hand and as expected, the best results are obtained with the 2 stage MMSE per user approach, mainly for non full load system.

7.2 PERFORMANCE WITH UNEQUAL MEAN POWER SIGNALS

In this case, as the different signals are not received with the same mean power level, the $E_b/N_0(1)$ ratio of the useful reference signal and the $E_b/N_0(i \neq 1)$ of the interfering signals may be different.

The simulation results for MMSE per carrier, MMSE per user, PIC–MMSE per carrier and SIC–MMSE carrier are given in figure 8 with a number N_u of active users equal to 32 and with $L_c = N_p = 64$. The number of stages of the SIC detector is equal to 31. The
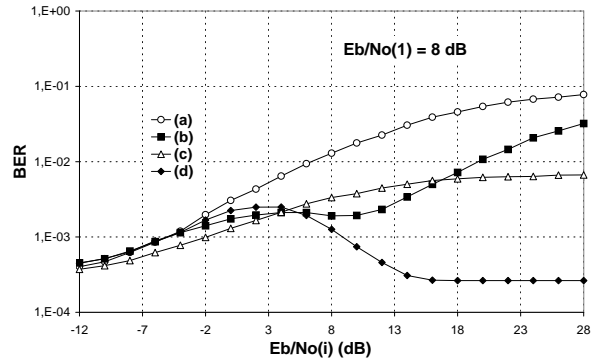

Figure 8: *BER versus the ratio $E_b/N_0(i)$ of all the interferers i with various detection techniques: MMSE per carrier (a), PIC–MMSE per carrier (b), MMSE per user (c), SIC–MMSE per carrier (d); $L_c = N_p = 64$, $N_u = 32$.*

$E_b/N_0(1)$ ratio of the useful signal is equal to 8 dB and all the interfering signals ($i \neq 1$) are received with the same power. For high Interference to Signal Ratio (ISR), which corresponds to $E_b/N_0(i) \gg Eb/N0(1) = 8$ dB, the SIC–MMSE outperforms the other schemes. On the other hand, for low ISR, which corresponds to $E_b/N_0(i) \ll E_b/N_0(1) = 8$ dB, the performance of all detection techniques are similar. Lastly, when the power of the interferers is roughly equal to the power of the useful signal ($Eb/N0(i) \approx E_b/N_0(1) = 8$ dB), the performance of linear MMSE per user is really close to the performance of non linear PIC–MMSE per carrier and SIC–MMSE per carrier.

8 CONCLUSION

The first set of results has confirmed the potential of MMSE detection techniques in the synchronous case of a multiuser MC–CDMA system operating in frequency selective Rayleigh channel. For non full load systems, the novel MMSE per user approach presented in this paper, offers a gain of more than 2 dB for a BER equal to 10^{-3} compared to a system applying the MMSE algorithm independently on each subcarrier.

Multiuser detection techniques can be implemented to improve the performance of MC–CDMA systems. However for downlink transmission, their application in a mobile terminal with limited available resources is highly dependent of the trade–off between performance and complexity. In the second part of this paper, it was shown that the SIC–MMSE is better than the PIC–MMSE when the power of the interferers is higher than the power of the useful reference signal. Furthermore, when the power of the interferers is roughly equal to the power of the useful signal, the performance of the linear MMSE per user is really close to the performance of the non–linear PIC and SIC schemes.

Finally, the MMSE per user approach offers good performance for non full load systems with both linear detection and interference cancellation schemes. To overcome the complexity of the matrix inversion, the alternative solution based on an iterative procedure can be implemented.

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