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MULTI-CARRIER CDMA USING INTERFERENCE CANCELLATION

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Abstract: *In this paper, various detection techniques in the synchronous case of a multi-user MC-CDMA system operating in frequency selective Rayleigh channel are compared with respect to the achievable spectral efficiency. It is shown that a parallel interference cancellation MMSE scheme with two stages could be a good compromise between performance and complexity.*

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 an ideal 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 desinterleaving, the received sequence must be "equalized" by employing a bank of adaptive one tap equalizers to combat 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 combat the MAI, one may use various Single-user Detection (SD) techniques which do not take into account any information about this MAI. When the receiver does not know either the number of users or 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 receivers 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 multi-user 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 promising potential of MC-CDMA receivers with SD based on minimum mean square error (MMSE) detection is confirmed for full load and non full load systems. Then a comparison of the performance of various interference cancellation receivers with two stages and even three stages 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 , $j = 1, \dots, N_u$ and transmitted during the symbol interval n is multiplied bit-synchronously with its user specific Walsh-Hadamard spreading code $\mathbf{C}_j = [c_j^1, c_j^2, \dots, c_j^{L_C}]^T$ 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 simultaneously active users. The vector of the data symbols transmitted during the n^{th} OFDM symbol by all the users can be written $\mathbf{X}^n = [x_1^n, x_2^n, \dots, x_j^n, \dots, x_{L_C}^n]^T$ with $x_j^n = 0$ when user j is inactive. The code matrix \mathbf{C} is defined to be:

$$\mathbf{C} = \begin{bmatrix} c_1^1 & c_2^1 & \dots & c_{L_C}^1 \\ c_1^2 & c_2^2 & \dots & c_{L_C}^2 \\ \dots & \dots & \dots & \dots \\ c_1^{L_C} & c_2^{L_C} & \dots & c_{L_C}^{L_C} \end{bmatrix} \quad (1)$$

where the j^{th} column vector of \mathbf{C} corresponds to the spreading code \mathbf{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 4PSK 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.

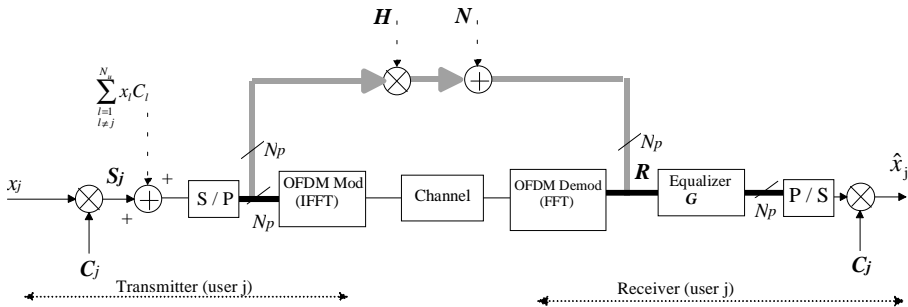


Figure 1. MC-CDMA transmitter and receiver.

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 modelised in the frequency domain as represented in grey lines in figure 1. The complex channel fading coefficients are considered as independent for each subcarrier and constant during each OFDM symbol. Using this assumption, the temporel index n can be suppressed 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:

$$\mathbf{H} = \begin{bmatrix} h_1 & \dots & 0 & 0 \\ \dots & h_2 & \dots & 0 \\ 0 & \dots & \dots & \dots \\ 0 & 0 & \dots & h_{N_p} \end{bmatrix} \quad (2)$$

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

$$\mathbf{R} = [r_1, r_2, \dots, r_{N_p}]^T = \mathbf{H} \cdot \mathbf{C} \cdot \mathbf{X} + \mathbf{N} \quad (3)$$

The $N_p \times N_p$ matrix \mathbf{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.

3. Single-user detection

3.1 Basic detection techniques

The complex channel coefficients h_k are supposed to be estimated by the receiver and are consequently treated as deterministic constants. Various detection techniques can be carried out [1], [5]. For those well known basic techniques, the assigned equalization coefficient is equal to:

$$g_k = h_k^* \quad \text{Maximum ratio combining (MRC)} \quad (4)$$

$$g_k = h_k^* / |h_k| \quad \text{Equal Gain Combining (EGC)} \quad (5)$$

$$g_k = 1 / h_k \quad \text{Orthogonality Restoring Combining (ORC)} \quad (6)$$

3.2 MMSE equalization

The MMSE equalization minimises the mean square error between the transmitted symbol and the estimated one. This equalization technique is the application of Wiener filtering. Let $\mathbf{W}_j = [w_j^0, w_j^1, \dots, w_j^{N_p}]$ be the weighting optimal vector. The estimated symbol of the j^{th} user can be written:

$$\hat{x}_j = \mathbf{W}_j^T \cdot \mathbf{R} = \mathbf{C}_j^T \cdot \mathbf{G} \cdot \mathbf{R} \quad (7)$$

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

$$\mathbf{W}_j = \mathbf{\Gamma}_{R,R}^{-1} \cdot \mathbf{\Gamma}_{R,x_j} \quad (8)$$

where $\mathbf{\Gamma}_{R,R}$ is the autocorrelation matrix of the received vector \mathbf{R} and $\mathbf{\Gamma}_{R,x_j}$ is the cross-correlation vector between the desired symbol, x_j and the received signal vector, \mathbf{R} . Those quantities are equal to:

$$\begin{aligned} \mathbf{\Gamma}_{R,R} &= E\{\mathbf{R}^* \cdot \mathbf{R}^T\} = \mathbf{H}^* \cdot \mathbf{C} \cdot E\{\mathbf{X}^* \cdot \mathbf{X}^T\} \cdot \mathbf{C}^T \cdot \mathbf{H} + E\{\mathbf{N}^* \cdot \mathbf{N}^T\} \\ \mathbf{\Gamma}_{R,x_j} &= E\{\mathbf{R}^* \cdot x_j\} = \mathbf{H}^* \cdot \mathbf{C} \cdot E\{\mathbf{X}^* \cdot x_j\} \end{aligned} \quad (9)$$

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

$$\mathbf{W}_j^T = E\{x_j \cdot \mathbf{X}^{*T}\} \cdot \mathbf{C}^T \mathbf{H}^* \cdot \left(\mathbf{H} \cdot \mathbf{C} \cdot E\{\mathbf{X} \cdot \mathbf{X}^{*T}\} \cdot \mathbf{C}^T \cdot \mathbf{H}^* + E\{\mathbf{N} \cdot \mathbf{N}^{*T}\} \right)^{-1} \quad (10)$$

The subcarrier noises have the same variance and are independent. Thus, $E\{\mathbf{N} \cdot \mathbf{N}^{*T}\} = \sigma_N^2 \mathbf{I}$ where \mathbf{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 $E\{\mathbf{X} \cdot \mathbf{X}^{*T}\} = E_s \mathbf{A}$, where $\mathbf{A} = \{a_{ij}\}$ is a diagonal matrix with the term $a_{ij} = 1$ if the user j is active and $a_{ij} = 0$ if the user j is inactive. Then, the equalization coefficient matrix can be expressed as:

$$\mathbf{G} = \mathbf{H}^* \cdot \left(\mathbf{H} \cdot \mathbf{C} \cdot \mathbf{A} \cdot \mathbf{C}^T \cdot \mathbf{H}^* + \frac{\sigma_N^2}{E_s} \cdot \mathbf{I} \right)^{-1} \quad (11)$$

In the full load case ($N_u = L_c$), the quantity $\mathbf{C} \cdot \mathbf{A} \cdot \mathbf{C}^T$ is equal to the identity matrix and the equalization coefficients matrix \mathbf{G} is a diagonal matrix with the k^{th} subcarrier equalization coefficient equal to [6]:

$$g_k = \frac{h_k^*}{|h_k|^2 + \frac{1}{\gamma_C}} \quad (12)$$

where γ_C is the subcarrier signal to noise ratio which is in this case equal to γ_X the signal to noise ratio of the received data symbol x .

In the non full load case, the equalization coefficient matrix is not diagonal. Then, to avoid matrix inversion, a suboptimal solution obtained when the wiener filter is optimised independently on each carrier, is to choose the k^{th} subcarrier equalization coefficient equal to [6]:

$$g_k = \frac{h_k^*}{|h_k|^2 + \frac{N_p}{N_u} \cdot \frac{1}{\gamma_X}} \quad (13)$$

4. 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.

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 [7], [8] and [9]. 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 2.

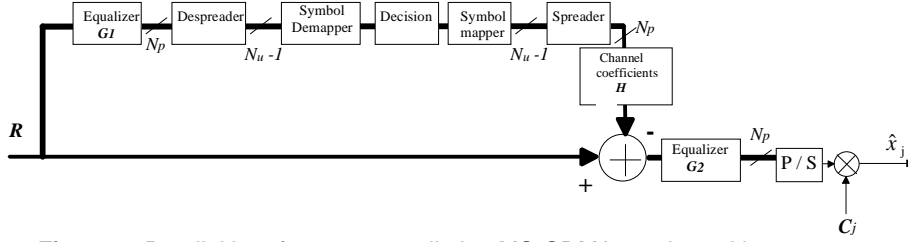


Figure 2. Parallel interference cancellation MC-CDMA receiver with two stages.

In the initial detection stage, the data symbols of all $N_u - 1$ active users are detected in parallel by the first SD equalizer with a gain $G1$. 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, the second and further detection stages work iteratively by using the decisions of the previous stage which yields the estimated data symbols at the m^{th} iteration:

$$\hat{x}_j^{(m)} = C_j^T \cdot G^{(m)} \cdot \left(R - H \sum_{\substack{l=1 \\ l \neq j}}^{N_u} \hat{x}_l^{(m-1)} \cdot C_l \right), m = 1, \dots, M_{it} \quad (14)$$

where M_{it} is the total number of iterations.

5. Simulation results.

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 a decorrelated 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 estimates of the frequency channel response for each subcarrier is available and that all the signals are received with equal power.

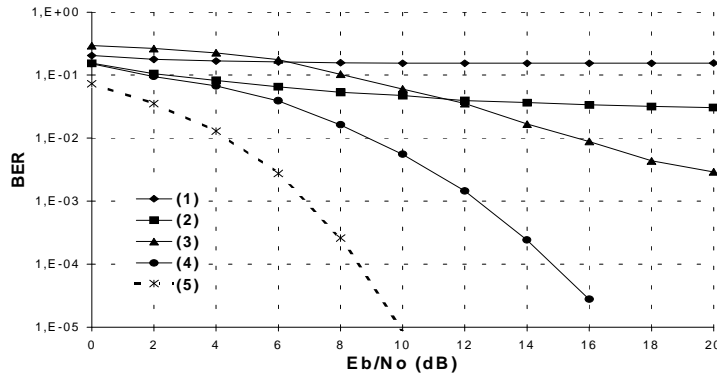


Figure 3. Single user detection performance for $N_u = L_c = N_p = 64$ with various receiver techniques: MRC (1), EGC (2), ORC (3), MMSE (4), MF bound (5).

The single detection based on minimum mean square error (MMSE) equalization offers the best results (figure 3) with full load systems as it has already been demonstrated in [5] and [6]. In figure 3, the number ($N_u = 64$) of

active users is equal to the length ($L_c = 64$) of the Walsh-Hadamard code. 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.

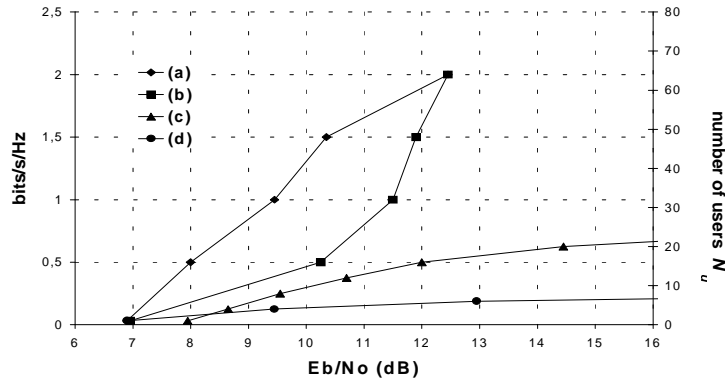


Figure 4. Spectral efficiency for various receiver techniques for $\text{BER}=10^{-3}$ and $N_p = 64$: matrix-MMSE (a), MMSE (b), EGC (c), MRC (d).

In figure 4, the performance of various single detection systems with $L_c = N_p = 64$ are compared, taking into account the resulting spectral efficiency in terms of the necessary E_b/N_0 to achieve a bit error probability of $P_b = 10^{-3}$. The maximum achievable spectral efficiency is 2 bit/s/Hz, corresponding to full load system ($N_u = L_c = N_p$), because the loss due to the guard interval, the synchronisation and the channel estimation is not taken into account. In any cases, MRC and EGC perform poorly. The curves (b) gives suboptimal MMSE system performance with the equalization coefficients optimised independently on each subcarrier and equal to the expression (13). The curve (a) corresponds to MMSE system performance according to matrix approach with the equalization coefficient matrix \mathbf{G} equal to the expression (11). For full load systems ($N_u = 64$), 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 matrix MMSE case with $N_u = 32$ or 16, which corresponds to a rough spectral efficiency respectively equal to 1 or 0.5 bit/s/Hz.

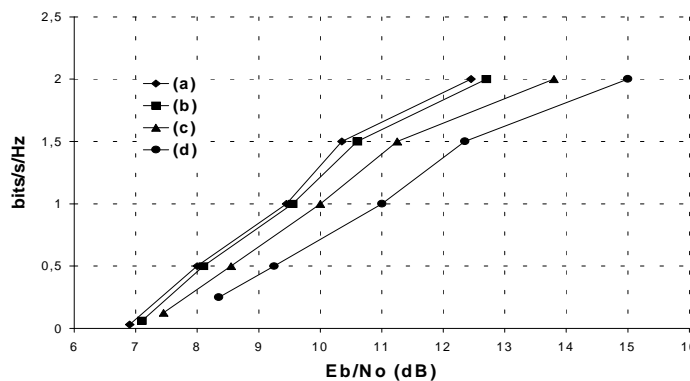


Figure 5. Spectral efficiency of QPSK matrix-MMSE SD MC-CDMA systems for various lengths of the spreading code for $\text{BER}=10^{-3}$: $N_p = 64$ (a), $N_p = 32$ (b), $N_p = 16$ (c), $N_p = 8$ (d).

In figure 5, the performance of matrix-MMSE MC-CDMA systems with various code lengths, are compared taking into account the resulting rough spectral efficiency in terms of the necessary E_b/N_0 to achieve a bit error probability of $P_b = 10^{-3}$. As expected, when the channel diversity (equal to the number N_p of independent subcarriers) increases, the results are better. For example, the matrix-MMSE 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.

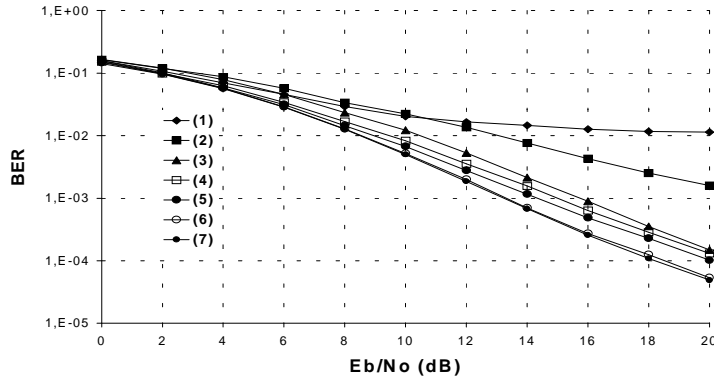


Figure 6. Multiuser detection performance for $N_l = N_p = 8$ with various receiver techniques: EGC1/EGC2 (1), ZF1/MRC2 (2), MMSE1/MRC2 (3), EGC1/MMSE2 (4), MMSE1/EGC2 (5), MMSE1/MMSE2 (6), MMSE1/MMSE2/MMSE3 (7)

A performance comparison of full load multi-stage parallel interference cancellation systems with various receiver techniques for the first and the second stage and, if necessary for the third stage, is presented in figure 6. Obviously, the systems with MMSE equalisation 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.

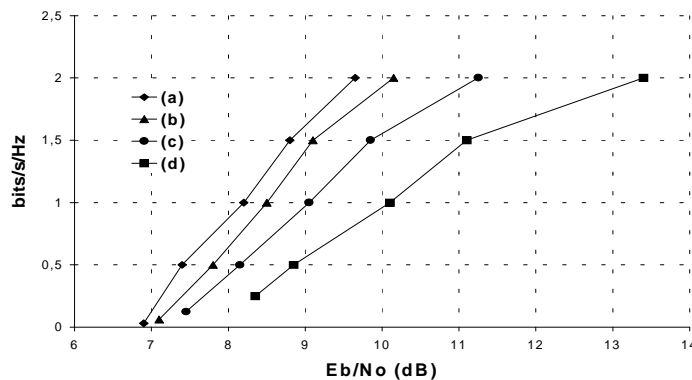


Figure 7. Spectral efficiency of 2 stage IC QPSK matrix-MMSE MC-CDMA systems for various lengths of the spreading code and for $BER = 10^{-3}$: $N_p = 64$ (a), $N_p = 32$ (b), $N_p = 16$ (c), $N_p = 8$ (d).

The resulting spectral efficiency in terms of the necessary E_b/N_0 to achieve a bit error probability of $P_b = 10^{-3}$ is given in figure 7 for 2 stage interference

cancellation matrix-MMSE systems with various code lengths $L_c = 8, 16, 32, 64$ equal to the number N_p of the subcarriers. The comparison of the curve (b) of the figure 5 with the curve (b) of the figure 7 shows that the full user capacity can be obtained with a 2.6 dB lower E_b/N_0 with the 2 stage interference cancellation 32 subcarrier scheme compared to the SD MMSE 32 subcarrier system. Furthermore, it appears that a system which will take advantage of a channel diversity equal to 32 will offer rather good performance.

6. Conclusion.

These simulation results have 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 matrix MMSE 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. Besides, it has been shown that a two stage interference cancellation matrix MMSE scheme could be a good compromise between performance and complexity.

Remark: Concerning the novel matrix approach, presented in this paper to implement the MMSE detection technique, a patent application has been filed.

References:

- [1] S. Hara, R. Prasad, "Overview of multicarrier CDMA", IEEE Communications Magazine, December 1997, pp 126-133.
- [2] K. Fazel and L. Papke, "On the performance of convolutionally-coded CDMA/OFDM for mobile communication system", Proceedings of IEEE PIMRC'93, Yokohama, Japan, September 1993, pp 468-472
- [3] N. Yee, J.P. Linnartz, "Wiener filtering of multi-carrier CDMA in a Rayleigh fading channel", Proceedings of IEEE PIMRC'94, September 1994, vol.4, pp 1344-1347.
- [4] K. Fazel, "Performance of CDMA/OFDM for mobile communication system", Proceedings of IEEE International Conference on Universal Personal Communications (ICUPC'93), Ottawa, Canada, October 1993, pp 975-979.
- [5] S. Kaiser, "On the performance of different detection techniques for OFDM - CDMA in fading channels", Proceedings of IEEE Global Telecommunications Conference (GLOBECOM'95), Singapore, November 1995, pp 2059-2063.
- [6] S. Kaiser, "Analytical performance evaluation of OFDM-CDMA mobile radio systems", Proceedings First European Personal and Mobile Communications Conference (EPMCC'95), Bologna, Italy, November 1995, pp 215-220.
- [7] S. Hara, T.H. Lee and R. Prasad, "BER comparison of DS-CDMA and MC-CDMA for frequency selective fading channels", Proceedings 7th Tyrrhenian International Workshop on Digital Communications, Tirrenia, Italy, September 1995, pp 3-14.
- [8] D.N. Kalofonos and J.G. Proakis, "Performance of the multi-stage detector for a MC-CDMA system in a Rayleigh fading channel", Proceedings of IEEE Global Telecommunications Conference (GLOBECOM'96), London, United Kingdom, November 1996, pp 1784-1788.
- [9] J.J. Maxey, R.F. Ormondroyd, "Multi-carrier CDMA using convolutional coding and interference cancellation over fading channels", First Workshop on Multi-Carrier Spread-Spectrum, Oberpfaffenhofen, Germany, April 1997, pp 89-96.