Performance of the Multi-Stage Detector for a MC-CDMA System in a Rayleigh Fading Channel*

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Abstract

Multi-Carrier (MC) CDMA is a multiple access scheme that combines Multi-Carrier Modulation (or OFDM) with Direct Sequence Spread Spectrum (DS-SS), and allows for efficient utilization of the bandwidth, resistance against frequency selectivity inherent in broadband mobile radio channels, and efficient implementation using the FFT. Since the complexity of the optimum Maximum Likelihood Detector (MLD) grows exponentially with the number of users, simpler suboptimum detectors are considered in practical applications. In this paper we analyze the performance of a new form of the Multi-Stage Detector using the Threshold Orthogonality Restoring Correlation (TORC) detector at the initial stage, in a frequency selective, slowly fading Rayleigh channel. Analytical and simulation results are presented for the initial stage (TORC detector) and the first stage of the Multi-Stage detector, which show that with only one stage significant performance enhancement can be achieved.

15 Introduction

Recently the idea of combining Orthogonal Frequency Division Multiplexing (OFDM) with Direct Sequence Spread Spectrum (DS-SS) has attracted significant research interest. This approach is an alternative to the classical DS-CDMA systems in multiple access, broadband radio channels.

Four different schemes combining OFDM with DS-SS have been proposed in the literature. In all approaches the available bandwidth is divided into a large number of subchannels (typically a power of two for efficient implementation using FFT). In the first scheme [1], each symbol of each user is first spread as in DS-SS using a spreading code, and then multiple copies of the spread signal are transmitted on orthogonal carriers. This scheme uses multicarrier transmission as a way to achieve frequency diversity. The second scheme, proposed in [2], suggests that first a multicarrier block be formed using N symbols by each of the users, and then this signal be spread in the time domain by multiplying it with the spreading sequence. In the third scheme, proposed in [3], each user creates a block of N symbols (N is the number of subchannels) and each of these symbols is spread. A multicarrier block is formed by using one chip from each spread symbol, so that the transmission of each spread symbol is completed after N_s subsequent multicarrier blocks (N_s the number of chips per symbol). In the last scheme, proposed in [4], [5], [6], the basic idea is to spread each symbol in the frequency domain by transmitting all the chips of a spread symbol at the same time, but in different orthogonal subchannels. This MC-CDMA system seems to be the most promising and has attracted the largest research interest. This paper will refer to this scheme as MC-CDMA.

Various detectors have been proposed and analyzed for this MC-CDMA scheme. The Maximum Likelihood Detector (MLD) was considered in [4]. It was shown that its complexity grows exponentially with the number of users, so it can be used only for a small number of interfering users. This difficulty leads to the consideration of suboptimum but simpler detectors. Such detectors are the MMSE detector [5], the conventional correlation (EGC) detector, the Orthogonality Restoring Detector (ORC) [4], and the ORC detector with Threshold (TORC) [7], [8].

In this paper a new form of Multi-Stage detector will be examined. The idea of the Multi-Stage detector is initialy found in DS-SS multiuser systems. In MC-CDMA systems, it was first proposed in [4] where it is referred to as an Iterative Detector. In that work a conventional (EGC) detector was used to obtain subsequent estimates of the interfering symbols, the estimated interference was subtracted from the observation signal, and this procedure was repeated iteratively. Because of the use of EGC this detector reaches an error floor. Another form of the Iterative Detector was proposed in [9], where the MMSE Detector was used to obtain the initial estimate. In the proposed structure the initial estimate of the interference is obtained using the TORC detector, because this is a simple detector, with relatively good performance which does not reach an error floor. The multiuser interference is then subtracted, and each subsequent stage estimates the data using Maximum Ratio Combining (MRC). The use of MRC was motivated by the fact that in an interference "free" multipath environment MRC gives the best results.

This paper is organized as follows: In section 2 a description of the MC-CDMA system will be given; in section 3 the Multi-Stage detector will be described; in section 4 the analytical performance of this receiver will be examined; in section 5 numerical and simulation results will be presented; and in section 6 we give our conclusions of this investigation.

25 System Description

We consider a multiple access system where N_u users are transmitting simultaneously in a synchronous manner. This

*This work was supported in part by ARPA Grant MDA 972-93-1-6023.

assumption is valid for the forward link (downlink) from the base station to the users. The users use Walsh-Hadamard orthogonal codes of length N_s. Therefore up to N_s users can transmit at the same time. The multicarrier block for user k is formed by taking μ symbols (each of duration T_b) in parallel, spreading them with the user's spreading sequence $\mathbf{c}_k = [c_{1,k} ... c_{Ns,k}]^T, c_{i,j} = \pm 1$, performing frequency interleaving, and placing the resulting μNs chips into the $N = \mu Ns$ available subcarriers. After performing a parallel to serial conversion, a guard interval is added, in the form of a cyclic prefix, and the signals of all the users are added and transmitted through the channel. The block diagram of the transmitter is depicted in Fig. 1.

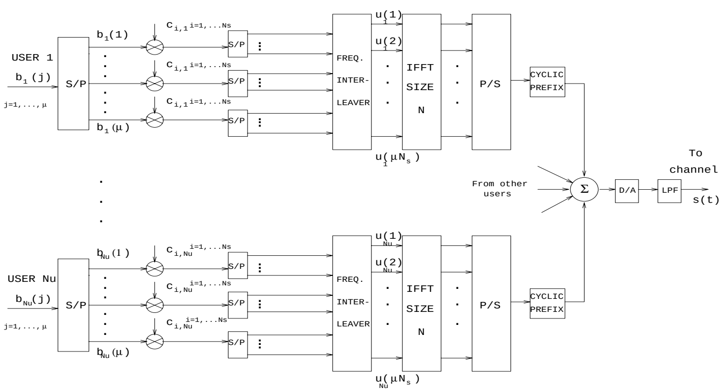

Figure 1: Transmitter block diagram

In the rest of this paper for simplicity of notation we will concentrate only on one of the μ symbols each user transmits, by setting $\mu = 1$, although the frequency interleaving function will still be assumed to exist. Also, we will consider binary symbols $b_k = \pm 1, k = 1, ..., N_u$ forming the data vector $\mathbf{b} = [b_1, ..., b_{Nu}]^T$, where the time index is dropped.

The transmitted signal during one MC block symbol period $T_b + T_G$ can be written as follows:

$$s(t) = \sum_{k=1}^{N_u} \sum_{m=1}^{N_s} \sqrt{E_c} u_k(m) e^{j \frac{2\pi m (t - T_G)}{T_b}} \quad (1)$$

where $t \in [0, T_b + T_G]$, T_G is the guard interval chosen to be at least equal to the delay time spread T_m of the channel, E_c is the energy per chip, and $u_k(m) = b_k c_{m,k}$.

The channel is assumed to be a slowly varying Rayleigh frequency selective fading channel. This assumption is valid only if the symbol duration is much smaller than the coherence time of the channel, i.e. $T_b \ll (\Delta t)_c$. Because of the large symbol duration $T_b \gg T_m$ the fading in each subchannel is approximately flat, and is described by a multiplicative complex channel coefficient $h_i, i = 1, ..., N_s$, which is a Gaussian distributed complex random variable with zero mean and variance σ_h^2. Because of the frequency interleaving function, the channel complex coefficients will be considered independent. This is valid in the case when $\mu/T_b > 1/T_m$. There is also additive white Gaussian noise. Because of the existence of a guard interval with duration at least equal to the channel's delay spread, there is no intersymbol interference.

The signal received by user i can be described by the following equation:

$$r(t) = \sum_{k=1}^{N_u} \sum_{m=1}^{N_s} \sqrt{E_c} h_m^{(i)} u_k(m) e^{j \frac{2\pi m (t - T_G)}{T_b}} + n(t) \quad (2)$$

where $t \in [0, T_b + T_G]$, $h_m^{(i)}$ are the complex channel coefficients which describe the channel between the transmitter and the user i, and $n(t)$ is the AWGN. For simplicity of notation in the rest of the paper, the superscript (i) will be dropped.

This signal is sampled at a rate N/T_b, the samples which correspond to the cyclic prefix are thrown away, an FFT of size N is performed, and frequency deinterleaving takes place. The output vector $\mathbf{r}$ is then fed to the detector which processes it. The vector $\mathbf{r} = [r_1, ..., r_{Ns}]^T$ at the output of the deinterleaver is given in matrix notation by the following equation:

$$\mathbf{r} = \sqrt{E_c} \mathbf{HCb} + \mathbf{n} \quad (3)$$

where $\mathbf{H} = diag\{h_1, ..., h_{Ns}\}$, matrix $\mathbf{C} = [\mathbf{c}_1 \mid ... \mid \mathbf{c}_{Nu}]$ is the N_sxN_u matrix whose columns are the spreading sequences of the users, $\mathbf{b}$ is the data vector of the users, and $\mathbf{n}$ is a vector containing uncorrelated complex Gaussian noise samples with zero mean.

3 The Multi-Stage Detector

The multi stage detector uses, in the zero stage, the TORC detector to obtain an initial estimate of vector $\mathbf{b}$. The TORC detector first inverts the effect of the channel by inverting matrix $\mathbf{H}$. In order to avoid excessive noise enhancement by inverting channel coefficients with very small amplitude, the detector dumps the chips which correspond to subchannels with attenuation below a chosen threshold. Then, it correlates the resulting signal with the users' spreading sequences, and performs a threshold decision. In each subsequent stage, the detector first subtracts the interference estimated in the previous stage, and then performs MRC in the resulting interference "free" observation vector.

The algorithm used in the Multi-Stage detector can be mathematically described as follows:

Stage-0 : $\mathbf{z}^{(0)} = \mathbf{C}^T \mathbf{U} \mathbf{H}^{-1} \mathbf{r}$

$$\hat{\mathbf{b}}_{MSD}^{(0)} = sgn[\mathcal{R}e\{\mathbf{z}^{(0)}\}]$$

Stage-m+1 : For each user $i, i = 1, ..., N_u$

$$\mathbf{z}_i^{(m+1)} = \mathbf{r} - \sqrt{E_c} \mathbf{H} \Big(\sum_{\substack{j=1 \\ j \neq i}}^{N_u} \mathbf{c}_j \hat{b}_{j,MSD}^{(m)} \Big)$$

$$\hat{b}_{i,MSD}^{(m+1)} = sgn[\mathcal{R}e\{\mathbf{c}_i^T \mathbf{H}^* \mathbf{z}_i^{(m+1)}\}]$$

where $\mathbf{U} = diag\{u(\mid h_k \mid - h_{THR})\}, k = 1, ..., N_s$, h_{THR} is the selected threshold for the TORC detector, and $u(x)$ is the unit step function.

4 Performance analysis

In this section the probability of error for bit b_i of user i, $i = 1, ..., N_u$ will be calculated for the initial and the first stage. For higher stages the decisions taken are highly correlated in a non-linear way, and analysis is very difficult.

4.1 Performance of TORC detector

The decision variable for bit b_i of user i at the initial stage has the following form:

$$v_i^{(0)} = \mathcal{R}e\{\mathbf{c}_i^T \mathbf{U} \mathbf{H}^{-1} \mathbf{r}\}$$

$$
\begin{aligned}
&= \sqrt{E_c}\mathbf{c}_i^T\mathbf{U}\mathbf{c}_i b_i + \sqrt{E_c}\sum_{\substack{j=1\\ j\neq i}}^{N_u}\mathbf{c}_i^T\mathbf{U}\mathbf{c}_j b_j + \mathcal{R}e\{\mathbf{c}_i^T\mathbf{U}\mathbf{H}^{-1}\mathbf{n}\}\\
&= S_i^{(0)} + I_i^{(0)} + \xi_i^{(0)} \qquad (4)
\end{aligned}
$$

where the first term $S_i^{(0)}$ is the desired signal, the second term $I_i^{(0)}$ is the multiuser interference and the third $\xi_i^{(0)}$ is the noise term.

Let the random variable N_0 denote the number of subchannels whose complex coefficients h_i have amplitude larger than h_{THR}. If $h_i = \rho_i e^{j\phi_i}, i = 1, ..., N_s$, we will say that a subchannel i is ON if $\rho_i > h_{THR}$.

Since we have assumed that the channel coefficients h_i are independent, the random variable N_0 is binomially distributed and its PMF is

$$
P(N_0 = n_0) = \binom{N_s}{n_0} e^{-\frac{n_0 h_{THR}^2}{2\sigma_h^2}} (1 - e^{-\frac{h_{THR}^2}{2\sigma_h^2}})^{(N_s - n_0)} \qquad (5)
$$

Below we examine the distribution of the three terms $S_i^{(0)}$, $I_i^{(0)}$, $\xi_i^{(0)}$ in (4), conditioned on the number of channels that are ON, i.e. conditioned on $N_0 = n_0$.

The signal term $S_i^{(0)}$ conditioned on n_0 takes the value

$$
S_i | n_0 = \sqrt{E_c} n_0 b_i \qquad (6)
$$

To find the distribution of the interference term, first we define the random variables P_{ij}, $(i, j = 1, ..., N_u, i \neq j)$, as follows:

$$
P_{ij} = \mathbf{c}_i^T\mathbf{U}\mathbf{c}_j \qquad (7)
$$

If X is a hypergeometric random variable with conditional PMF given n_0

$$
\mathcal{P}(X = k) = \begin{cases} \frac{\binom{N_s/2}{k}\binom{N_s/2}{n_0-k}}{\binom{N_s}{n_0}} & if\ k\ integer, \\ & max\{0, n_0 - N_s/2\} \leq k, \\ & k \leq min\{n_0, N_s/2\}, \\ & 0 \leq n_0 \leq N_s \\ 0 & otherwise \end{cases} \qquad (8)
$$

then it can be shown that for Walsh Hadamard codes

$$
P_{ij} = 2X - n_0 \qquad (9)
$$

Therefore the expected value and variance of P_{ij} are given by

$$
E\{P_{ij}\} = 0, \qquad Var\{P_{ij}\} = n_0(\frac{N_s - n_0}{N_s - 1}) \qquad (10)
$$

The random variables P_{ij}, $(i, j = 1, ..., N_u, i \neq j)$ are assumed to be independent. If the number of users is large enough ($N_u > 30$) the Central Limit Theorem can be invoked and the pdf of the interference term I_i can be considered approximately Gaussian:

$$
I_i^{(0)} | n_0 \sim \mathcal{N}(0, n_0(N_u - 1)(\frac{N_s - n_0}{N_s - 1})E_c) \qquad (11)
$$

The noise term $\xi_i^{(0)}$ can be written in the following form:

$$
\xi_i^{(0)} = \sum_{l=1}^{N_s} c_{li} u(\rho_l - h_{THR}) \frac{\mathcal{R}e\{e^{j\phi_l} n_l\}}{\rho_l} \qquad (12)
$$

If $n_{lr} = \mathcal{R}e\{e^{j\phi_l} n_l\}$, then $n_{lr} \sim \mathcal{N}(0, \sigma^2)$, and we define the random variable X_l as follows:

$$
X_l = \frac{n_{lr}}{\rho_l} \qquad (13)
$$

The conditional pdf of X_l given that subchannel l is ON is the following:

$$
\begin{aligned}
f_{X_l|l=ON}(x_l | l = ON) \quad = \quad & \frac{\sigma h_{THR} e^{-\frac{h_{THR}^2}{2\sigma^2} x_l^2}}{\sqrt{2\pi}(\sigma_h^2 x_l^2 + \sigma^2)} + \\
& + \frac{\sigma^2 \sigma_h e^{\frac{h_{THR}^2}{2\sigma_h^2}} Q(\frac{h_{THR}}{\sigma\sigma_h}\sqrt{\sigma_h^2 x_l^2 + \sigma^2})}{(\sigma_h^2 x_l^2 + \sigma^2)^{3/2}}
\end{aligned} \qquad (14)
$$

where $Q(x) = (1/2)erfc(x/\sqrt{2})$.

The conditional expected value and variance of X_l can be calculated using the distribution (14). Thus we obtain the following:

$$
\begin{aligned}
E\{X_l | l = ON\} &= 0 \\
Var\{X_l | l = ON\} &= 2\frac{\sigma^2}{\sigma_h^2} e^{\frac{h_{THR}^2}{2\sigma_h^2}} Gi(\frac{h_{THR}}{\sigma_h})
\end{aligned} \qquad (15)
$$

where

$$
Gi(x) = \int_0^\infty \frac{Q(x\sqrt{t^2 + 1})}{\sqrt{t^2 + 1}} dt \qquad x > 0 \qquad (16)
$$

Conditioned on the number n_0 of the subchannels which are ON, the noise term in (12) can be written as follows:

$$
\xi_i^{(0)} = \sum_{l}^{n_0} c_{li} X_i \qquad (17)
$$

Given the form of the distribution in (14), it is clear that the distribution of $\xi_i^{(0)}$ is practically impossible to be exactly defined. The only way is to consider the distribution of $\xi_i^{(0)}$ approximately Gaussian so that

$$
\xi_i^{(0)} | n_0 \sim \mathcal{N}(0, 2n_0 \frac{\sigma^2}{\sigma_h^2} e^{\frac{h_{THR}^2}{2\sigma_h^2}} Gi(\frac{h_{THR}}{\sigma_h})) \qquad (18)
$$

This approximation can be considered relatively accurate, because the number n_0 of the subchannels which are ON is larger than $N_s/2$ with high probability even for large values of h_{THR} ($h_{THR} \approx \sigma_h$).

Given the distributions of the signal (6), interference (11), and noise (18) terms, we average over the distribution (5) of the number N_0 of the subchannels which are ON, and we obtain the following expression for the average probability of bit error for the zero stage:

$$
\begin{aligned}
\mathcal{P}^{(0)}[error] = &\sum_{n_0=0}^{N_s} \binom{N_s}{n_0} e^{-\frac{n_0 h_{THR}^2}{2\sigma_h^2}} (1 - e^{-\frac{h_{THR}^2}{2\sigma_h^2}})^{(N_s - n_0)} \\
& Q\left(\sqrt{\frac{n_0\gamma_c}{4e^{\frac{h_{THR}^2}{2\sigma_h^2}} Gi(\frac{h_{THR}}{\sigma_h}) + (N_u - 1)(\frac{N_s - n_0}{N_s - 1})\gamma_c}}\right)
\end{aligned} \qquad (19)
$$

where the average SNR per chip γ_c and the average SNR per bit γ_b are defined as follows:

$$\gamma_c = \frac{E_c}{\sigma^2} E\{\rho_l^2\} = 2\frac{E_c}{\sigma^2}\sigma_h^2, \qquad \gamma_b = N_s \gamma_c \tag{20}$$

4.2 Performance of the first stage

The decision variable $v_i^{(1)}$ for bit b_i at the first stage has the following form:

$$\begin{aligned} v_i^{(1)} &= \mathcal{R}e\{\mathbf{c}_i^T \mathbf{H}^* \mathbf{z}_i^{(1)}\} \\ &= \sqrt{E_c}\mathbf{c}_i^T \widetilde{\mathbf{H}}\mathbf{c}_i b_i + \sqrt{E_c} \sum_{\substack{j=1 \\ j \neq i}}^{N_u} \mathbf{c}_i^T \widetilde{\mathbf{H}}\mathbf{c}_j \hat{\delta}_j^{(1)} + \mathcal{R}e\{\mathbf{c}_i^T \mathbf{H}^* \mathbf{n}\} \\ &= S_i^{(1)} + I_i^{(1)} + \xi_i^{(1)} \end{aligned} \tag{21}$$

where $\widetilde{\mathbf{H}} = \mathbf{H}\mathbf{H}^* = diag\{\rho_1^2, ..., \rho_{N_s}^2\}$, and

$$\hat{\delta}_j^{(1)} = b_j - \hat{b}_j^{(0)} = \begin{cases} 0 & , if \quad \hat{b_j}^{(0)} = b_j \\ 2b_j & , if \quad \hat{b_j}^{(0)} \neq b_j \end{cases} \tag{22}$$

The desired signal can be rewritten as follows:

$$S_i^{(1)} = \sqrt{E_c} b_i \sum_{k=1}^{N_s} \rho_k^2 \tag{23}$$

In the same way, the other user interference term can be written as:

$$I_i^{(1)} = \sqrt{E_c} \sum_{\substack{j=1 \\ j \neq i}}^{N_u} (\sum_{k=1}^{N_s} c_{ki} c_{kj} \rho_k^2) \hat{\delta}_j^{(1)} \tag{24}$$

Since $E\{\rho_k^2\} = 2\sigma_h^2$, and because of the use of Walsh-Hadamard spreading sequences, the term inside the parenthesis in the above equation can be written as follows:

$$\sum_{l=1}^{N_s/2} (\rho_{l,i,j}^2 - 2\sigma_h^2) - \sum_{l=N_s/2+1}^{N_s} (\rho_{l,i,j}^2 - 2\sigma_h^2) = A_{ij} - B_{ij} \tag{25}$$

where for given i, j, $\rho_{l,i,j} = \rho_k$, and index l is the index k renumbered in such a way that $l = 1, ..., N_s/2$ when $c_{ki}c_{kj} = 1$, and $l = N_s/2 + 1, ..., N_s$ when $c_{ki}c_{kj} = -1$.

If $N_{er} = n_{er}$ is the number of errors in the initial estimate of the other users' data ($b_j, j = 1, ..., N_u, j \neq i$), then the interference term can be written in the following form:

$$I_i^{(1)} = 2\sqrt{E_c} \sum_{j, j\neq i}^{n_{er}} (A_{ij} - B_{ij}) b_j \tag{26}$$

To calculate the average probability of error it is assumed that the errors in the initial estimate occur independently, an assumption which is valid if the random variables P_{ij} are independent. Then the random variable N_{er} is binomially distributed. Conditioned on the sum

$$Y = \sum_{k=1}^{N_s} \rho_k^2 \tag{27}$$

where Y is Chi-Squared distributed with $2N_s$ degrees of freedom and parameter σ_h^2, the desired signal term is not a random variable anymore and takes the value given in (23).

Using the Central Limit Theorem on each of the independent variables A_{ij}, B_{ij} ($N_s/2$ is considered large enough, say > 30), they can be considered approximately Gaussian, and the distribution of $A_{ij} - B_{ij}$ may be expressed as:

$$A_{ij} - B_{ij} \sim \mathcal{N}(0, 4N_s\sigma_h^4) \tag{28}$$

Conditioned on the number of errors n_{er}, the interference term given in (26) can be considered Gaussian, with distribution:

$$I_i^{(1)} | n_{er} \sim \mathcal{N}(0, 16 n_{er} E_c N_s \sigma_h^4) \tag{29}$$

Conditioned on Y given in (27), the noise term is Gaussian with

$$\xi_i^{(1)} \sim \mathcal{N}(0, \sigma^2 Y) \tag{30}$$

The average unconditional probability of error is obtained by averaging over the Chi-squared distribution of Y, and the binomial distribution of N_{er}. Thus we obtain:

$$\begin{aligned} &\mathcal{P}^{(1)}[error] = \\ &\sum_{n_{er}=0}^{N_u-1} \binom{N_u - 1}{n_{er}} (\mathcal{P}^{(0)}[error])^{n_{er}} (1 - \mathcal{P}^{(0)}[error])^{(N_u - n_{er} - 1)} \\ &\int_0^\infty \frac{y^{N_s - 1}}{(2\sigma_h^2)^{N_s}(N_s - 1)!} e^{-\frac{y}{2\sigma_h^2}} Q\left(\frac{\sqrt{E_c} y}{\sqrt{16 n_{er} E_c N_s \sigma_h^4 + \sigma^2 y}} \right) dy \end{aligned} \tag{31}$$

5 Numerical and Simulation Results

In the following numerical and simulation results the variance of the channel coefficients is normalized such that

$$E\{\rho_l^2\} = 1 \tag{32}$$

In all the cases perfect knowledge of the channel complex coefficients is assumed, and wherever SNR is mentioned it refers to γ_b given in (20).

By inverting the channel coefficients the TORC detector enhances the noise as can be seen in (15). This noise enhancement is controlled by the selection of the threshold. The lower the threshold, the more the noise is amplified. On the other hand if the threshold is too high, then a small number of subchannels will on average be ON, thus destroying the orthogonality between users, and leading to performance degradation due to multiuser interference. It is expected therefore that there is an optimum value of threshold. This is shown in Fig. 2, where the BER is plotted as a function of threshold for various SNRs. As it can be seen, the optimum threshold is a function of SNR. The larger the SNR, the weaker the effect of noise amplification as the threshold is decreased. The optimum threshold as a function of SNR is depicted in Fig. 3.

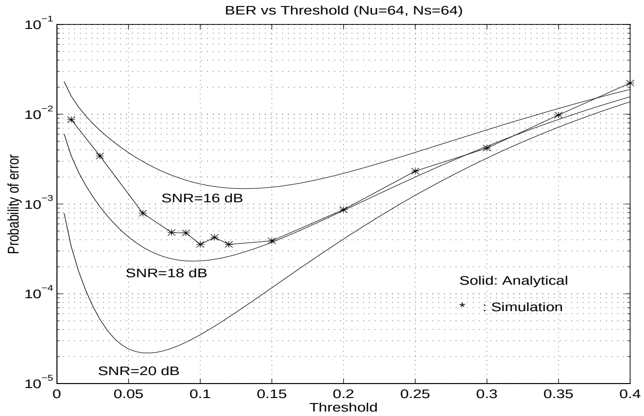

Figure 2: Probability of error of the TORC detector (zero-stage) as a function of the threshold.

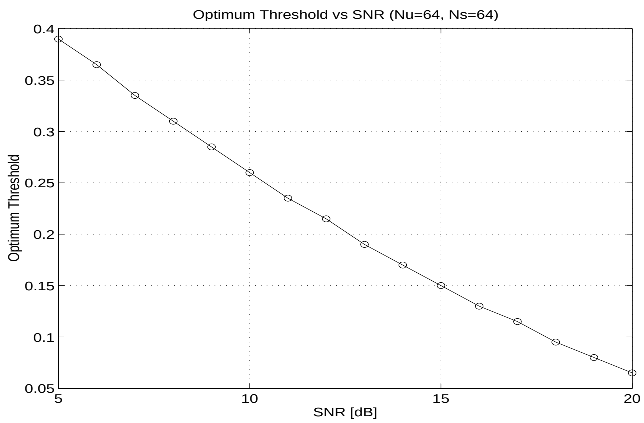

Figure 3: Optimum threshold as a function of SNR.

In Fig. 4, the probability of error is plotted as a function of SNR for the initial estimate using the TORC detector with threshold 0.065, and for the first and second stages of the Multi-Stage detector. We can see that although there is a difference of about 1 dB between the theoretical and the simulation results, they both agree that there is an improvement after the first stage of about 2 dB for high SNRs. Also it can be seen that the better the initial estimate, the larger the improvement in performance. At this point it should be added that the simulation results show that there is almost no improvement in the performance of the multistage detector after the first stage.

6 Conclusions

In this paper the performance of a Multi-Stage detector in the synchronous case of a multiuser MC-CDMA system operating in frequency selective Rayleigh channel, has been examined. In the zero stage, the TORC detector has been used and its performance was also examined analytically. It has been shown that even with only one stage the performance of the TORC detector can be improved by 2 dB for a BER 10^{-3}, an improvement which is even more significant for higher SNRs.

The proposed detector was found to combine satisfactory performance with low computational complexity. Its main drawbacks are the inherent delay and the need for centralized detection by each user.

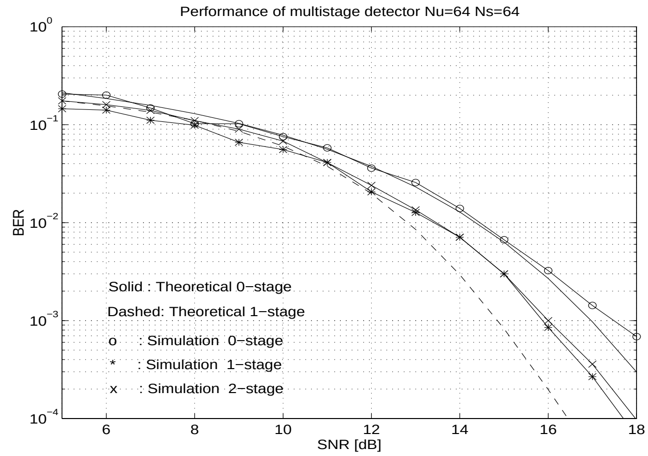

Figure 4: Probability of error of the zero, first, and second stages of the Multi-Stage detector as a function of SNR. The threshold of the TORC detector is $h_{THR} = 0.065$.

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