

# Performance Analysis of Wide Band MC-CDMA systems in Indoor Wireless Radio Networks.

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## ABSTRACT

*In this paper we propose a new Wide band Multicarrier (W-MC) Code Division Multiple Access (CDMA) scheme that delivers a great immunity against multi-user interference (MUI) caused by interferers in the system and from which the classical MC-CDMA suffers considerably.*

*For the synchronous-case, the results show that the new system performance was comparable to a single-user system. This exceeds enormously the performances obtained for MC-CDMA. The asynchronous Wide Band MC-CDMA scheme is also analyzed and the performances are always best. This is reflected by the Bit error rate (BER) of the systems with either equal-gain combining (EGC) and maximum-ratio Combining (MRC) equalization techniques.*

## 1. INTRODUCTION

With a surging increase in demand for personal wireless radio communications within the past decade, there is a growing need for technological innovations to satisfy these demands. Future technology must be able to allow users to efficiently share common resources, whether it involves the frequency spectrum, computing facilities, databases, or storage facilities. The multicarrier technique has grown an important alternative for wireless indoor communications. One large advantage of this technology is its robustness in case of multipath propagation. Multicarrier Code Division Multiple Access (MC-CDMA) is one representative of the multicarrier technique [1], [2]. It has been proposed combined with classical modulation [3]- [6] and performances of different detection strategies have been analysed. It has been shown that MC-CDMA has better spectral efficiency compared to direct-

sequence code division multiple access (DS-CDMA) [7]. MC-CDMA has also been combined with M-ary orthogonal modulation. The results indicated that M-ary modulation significantly outperforms binary phase shift keying (BPSK) modulation [8].

In a multi-user synchronous MC-CDMA system  $M$  users have access to the same additive channel using preassigned signature waveforms and a set of orthogonal subcarriers. For each subcarrier, the received signal is the sum of  $M$  transmissions and an Additive White Gaussian Noise (AWGN). Much work has been done in designing a novel receiver structure or proposing a new scheme to effectively minimise the interference caused by other user transmissions.

The aim of this paper is to take advantage of a recently developed technique based on MC-CDMA [9]. Indeed, this technique has been improved by introducing another degree of orthogonality in addition to the orthogonality of the pseudo-random codes and the subcarriers. Our proposed Wide Band MC-CDMA system is based on suitable sequence arrangements obtained by cyclic rotation of a set of orthogonal sequences; An arrangement is assigned for each user. And from there, each user will see to transmit, on each subcarrier, a sequence that is orthogonal to sequences of the other users transmitting on same subcarrier. Hence, in addition to the orthogonality between the Pseudo-Random codes and the subcarriers another orthogonality is used within each subcarrier. This technique is equivalent to transmit DS-CDMA signals at different frequencies as in [10] but the proposed system differs by the added orthogonal sequences distribution. The idea behind this is to further enhance classical MC-CDMA capability to combat Multiple Access Interference.

The paper is organised as follows. Section 2 presents the W-MC-CDMA transmitter model and the

distribution method of the common set of orthogonal sequences. Section 3 deals with the receiver model where it is assumed that  $m=0$  is the desired user. In section 4 the channel model is presented. Section 5 concerns the analysis of the system performance where the BER is derived for two type of equalisations; Equal Gain Combining (EGC) and Maximum Ratio Combining (MRC). Last, the results are discussed in section 6.

## 2. TRANSMITTER MODEL

Shown in Fig.1 is the transmitter model of an W-MC-CDMA system. The input data symbols,  $a_m(k)$  of duration  $T_b$ , are assumed to be binary antipodal where  $k$  denotes the  $k$ th bit interval and  $m$  denotes the  $m$ th user. The  $i$ th branch (subcarrier) of the parallel stream is multiplied by a sequence,  $c_m(i)g_m^i(t - iT_c)$ , where  $g_m^i(t) \in \{h_0(t), h_1(t), \dots, h_{N-1}(t)\}$  and  $c_m(i) \in \{-1, 1\}$ , and then modulated to a subcarrier spaced apart from its neighbouring subcarriers by  $F/T_b$  where  $F$  is an integer number.  $c_m(0), c_m(1), \dots, c_m(N-1)$  represents the Pseudo-Random code of the  $m$ th user with  $T_c$  as chip duration. The property of the codes that is desired is for the codes of different users to be orthogonal, i.e.,

$$\sum_{i=0}^{N-1} c_n(i)c_m(i) = N\delta_{n,m} \quad (1)$$

where  $\delta_{n,m}$  is the Kronecker symbol.

$\{h_0(t), h_1(t), \dots, h_{N-1}(t)\}$  can be any set of orthogonal sequences (Walch-Hadamard, Wavelets,...) where each sequence is of length  $T_c = T_b/N$ . The chip duration of any sequence  $h_i(t)$  is  $T_h = \frac{T_c}{L} = \frac{T_b}{NL}$ . Consequently, the processing gain is  $G = NL$  instead of  $N$  as for the conventional MC-CDMA. For Walch-Hadamard sequences, we have

$$\begin{aligned} \langle g_m^i(t - iT_c), g_n^j(t - jT_c) \rangle &= \\ \int_{iT_c}^{(i+1)T_c} g_m^i(t - iT_c) g_n^j(t - jT_c) dt & \\ = \int_{jT_c}^{(j+1)T_c} g_m^i(t - iT_c) g_n^j(t - jT_c) dt & \\ = T_c \delta_{m,n} = \begin{cases} T_c & \text{for } i = j \text{ and } m = n \\ 0 & \text{for } i \neq j \text{ or } m \neq n \end{cases} & \end{aligned} \quad (2)$$

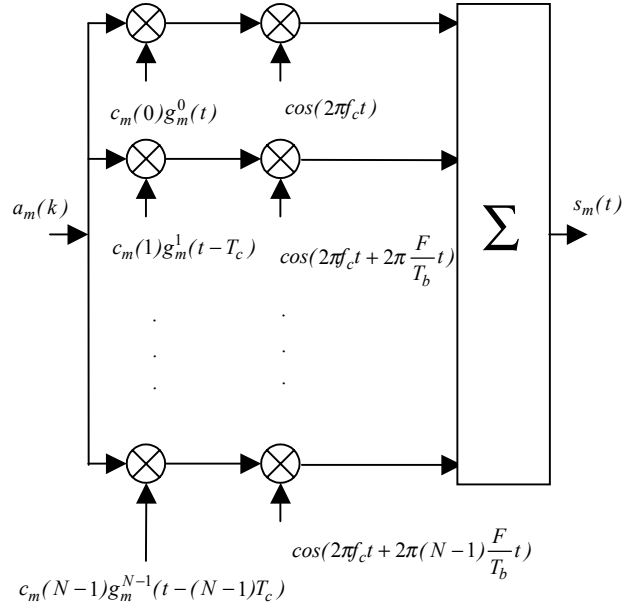


Fig.1. The W-MC-CDMA Transmitter Model

The different users share the same set of orthogonal sequences,  $\{h_0(t), h_1(t), \dots, h_{N-1}(t)\}$ , with different arrangement of these sequences, over the whole set of subcarriers, for each user. Thus, for each subcarrier, active users use orthogonal sequences. Assuming that there are  $(M=N)$  active users sharing the same noisy channel, the sequence arrangements over the users is presented in Table.1.

Subcarrier	User 0 ( $g_0^i(t - iT_c)$ )	User 1 ( $g_1^i(t - iT_c)$ )	User (2) ( $g_2^i(t - iT_c)$ )	...	User (N-1) ( $g_{N-1}^i(t - iT_c)$ )
$\cos(2\pi f_c t)$	$h_0(t)$	$h_{N-1}(t)$	$h_{N-2}(t)$	...	$h_1(t)$
$\cos(2\pi f_c t + 2\pi \frac{F}{T_b} t)$	$h_1(t)$	$h_0(t)$	$h_{N-1}(t)$	...	$h_2(t)$
$\cos(2\pi f_c t + 4\pi \frac{F}{T_b} t)$	$h_2(t)$	$h_1(t)$	$h_0(t)$	...	$h_3(t)$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	...	$\vdots$
$\cos(2\pi f_c t + 2\pi(N-2)\frac{F}{T_b} t)$	$h_{N-2}(t)$	$h_{N-3}(t)$	$h_{N-4}(t)$	...	$h_{N-1}(t)$
$\cos(2\pi f_c t + 2\pi(N-1)\frac{F}{T_b} t)$	$h_{N-1}(t)$	$h_{N-2}(t)$	$h_{N-3}(t)$	...	$h_0(t)$

Table.1. Sequence arrangements

The transmitted signal, for each user, consists of the sum of the outputs of the  $N$  branches. This process yields a multicarrier signal with subcarriers containing the PN-coded symbol.

The transmitted signal corresponding to the  $k$ th data bit of the  $m$ th user is

$$s_m(t) = \sum_{i=0}^{N-1} a_m(k) c_m(i) g_m^i(t - iT_c) \cos(2\pi f_c t + 2\pi \frac{F}{T_b} t) \times P_{T_b}(t - kT_b) \quad (3)$$

where  $P_{T_b}(t)$  is defined to be an unit amplitude pulse that is non-zero in the interval of  $[0, T_b]$ .

### 3. RECEIVER MODEL

When there are  $M$  active users, the received signal is

$$r(t) = \sum_{m=0}^{M-1} \sum_{i=0}^{N-1} \rho_{mi} a_m(k) c_m(i) g_m^i(t - iT_c - \tau_m) \times \cos\left[\left(2\pi f_c + 2\pi i \frac{F}{T_b}\right)(t - \tau_m) + \theta_{mi}\right] + n(t) \quad (4)$$

where the effects of the channel have been included in  $\rho_{mi}$  and  $\theta_{mi}$  and  $n(t)$  is an AWGN with one-sided power spread spectral density of  $N_0$ . Each user,  $m$ , is delayed by  $\tau_m$  with respect to the desired user  $m=0$ . Thereafter, It is assumed that  $0 \leq \tau_m \leq T_c$ .

The receiver model is shown in Fig.2 where it is assumed that  $m=0$  corresponds to the desired signal. With this model, there are  $N$  matched filters with one matched filter for each subcarrier. The output of each filter contributes one component to the decision variable,  $Z_0$ . Each matched filter consists of an oscillator with a frequency corresponding to the frequency of the particular modulated subcarrier that is of interest and an integrator. In addition, a phase offset equal to the phase distortion introduced by the channel,  $\theta_{0i}$ , is included in the oscillator to synchronise the receiver to the desired signal in time. To extract the desired signal's component, the orthogonality of the sequences  $g_m^i(t)$  of all the active users is used. For the  $i$ th subcarrier of the desired signal, the corresponding chip,  $c_0(i)$ , and sequence,  $g_0^i(t)$ , from the desired user's code and sequence set are multiplied with it to undo the code and the sequence set.

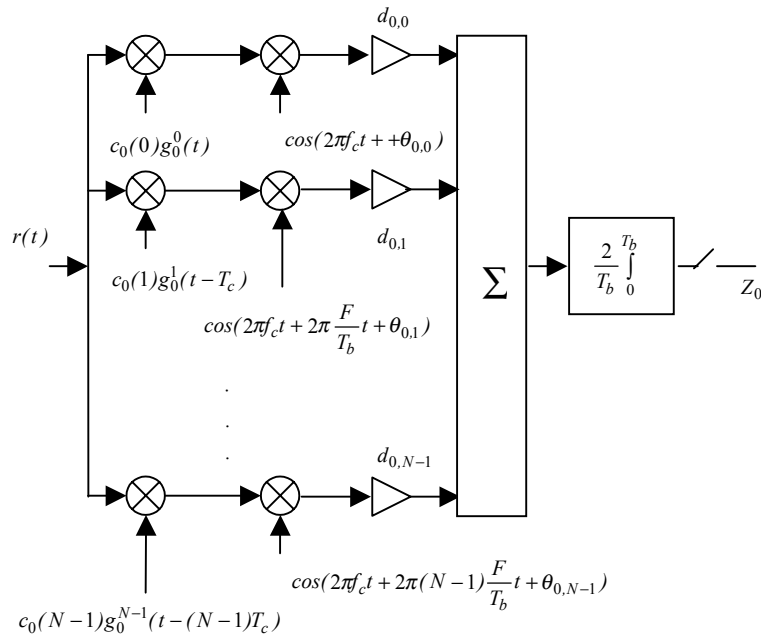


Fig. 2. Wide Band MC-CDMA Receiver model

Symbol-synchronism is not necessary for W-MC-CDMA to operate, and it is possible to let the users transmit completely asynchronously ( $\tau_m \neq 0$ ).

Applying the receiver model of Fig.2 to the received signal given in Eq.(4) yields the following decision variable for the  $k$ th data symbol

$$Z_0 = \sum_{m=0}^{M-1} \sum_{i=0}^{N-1} \frac{2}{T_b} \int_{kT_b}^{(k+1)T_b} \rho_{mi} a_m(k) d_{0,i} \times c_m(i) c_0(i) g_m^i(t - iT_c - \tau_m) g_0^i(t - iT_c) \times \cos \left[ (2\pi f_c + 2\pi i \frac{F}{T_b})(t - \tau_m) + \theta_{mi} \right] \times \cos \left[ (2\pi f_c + 2\pi i \frac{F}{T_b})t + \hat{\theta}_{0i} \right] dt + \eta \quad (5)$$

where  $\hat{\theta}_{0i}$  denotes the receiver's estimation of the phase at the  $i$ th subcarrier of the desired signal and the corresponding AWGN term,  $\eta$ , is given as

$$\eta = \sum_{i=0}^{N-1} \frac{2}{T_b} \int_{kT_b}^{(k+1)T_b} n(t) d_{0,i} c_0(i) g_0^i(t - iT_c) \times \cos(2\pi f_c t + 2\pi i \frac{F}{T_b} t + \hat{\theta}_{0i}) dt \quad (6)$$

Assuming perfect phase correction, i.e.,  $\hat{\theta}_{0i} = \theta_{0i}$  and synchronous detection of the desired user ( $\tau_0 = 0$ ), we have

$$Z_0 = a_0(k) \sum_{i=0}^{N-1} \rho_{0,i} d_{0,i} + \sum_{m=1}^{M-1} \sum_{i=0}^{N-1} \rho_{mi} a_m(k) d_{0,i} c_m(i) c_0(i) I_m^i(\tau_m, \tilde{\theta}_{mi}) + \eta \quad (7)$$

The first term of the right hand side of Eq. (7) is the desired user signal, the second term is due to multi-user interference and the last one is the AWGN term.  $I_m^i(\tau_m, \tilde{\theta}_{mi})$  is given by

$$I_m^i(\tau_m, \tilde{\theta}_{mi}) = \frac{2}{2T_c} \int_{iT_c + \tau_m}^{(i+1)T_c} g_m^i(t - iT_c - \tau_m) g_0^i(t - iT_c) \times \cos \left[ (2\pi f_c + 2\pi i \frac{F}{T_b})(t - \tau_m) + \theta_{mi} \right] \times \cos \left[ (2\pi f_c + 2\pi i \frac{F}{T_b})t + \hat{\theta}_{0i} \right] dt \quad (8)$$

Without loss of generality we suppose that  $\tau_m = \ell_m T_h$  where  $0 \leq \ell_m \leq L - 1$ . For  $\ell_m = 0$  ( $\forall m$ ), one has the synchronous situation which does not contain any MUI term and the decision variable reduces to

$$Z_0 = a_0(k) \sum_{i=0}^{N-1} \rho_{0,i} d_{0,i} + \eta \quad (9)$$

$I_m^i(\ell_m, \tilde{\theta}_{mi})$  can be evaluated using Eq.(2) as

$$I_m^i(\ell_m, \tilde{\theta}_{mi}) = \frac{1}{L} \cos(\tilde{\theta}_{mi}) \sum_{\ell=\ell_m}^{L-1} g_m^0(\ell) g_m^i(\ell - \ell_m) \quad (10)$$

where  $\tilde{\theta}_{mi} = \left[ \theta_{mi} - \hat{\theta}_{0i} - (2\pi f_c + 2\pi i \frac{F}{T_b})\tau_m \right]$  considered as a random variable uniformly distributed on  $[0, 2\pi]$ .

#### 4. CHANNEL MODEL

The effects of the channel for a single subcarrier are characterised by two parameters: an amplitude scaling,  $\rho_{mi}$ , and phase distortion,  $\theta_{mi}$ , of the  $m$ th user at frequency  $f_c + iF/T_b$ . In addition, it is assumed that the  $\rho_{mi}$  and  $\theta_{mi}$  remain approximately constant over the symbol duration,  $T_b$ , corresponding to a flat fading channel. For a Rayleigh fading channel,  $\rho_{mi}$  are independent and identically distributed (IID) Rayleigh random variables of the form

$$f_{\rho_{mi}}(\rho_{mi}) = \frac{\rho_{mi}}{\sigma_{mi}^2} e^{-\frac{\rho_{mi}^2}{2\sigma_{mi}^2}}, \text{ for } \rho_{mi} \geq 0 \quad (11)$$

with  $\overline{\rho_{mi}^2} = \frac{1}{2} E(\rho_{mi}^2)$  (each user having a total local-mean power of  $\overline{\rho_m} = N \overline{\rho_{mi}}$ ).

The phase effects,  $\theta_{mi}$ , are assumed to be IID random variables uniformly distributed on the interval  $[0, 2\pi]$ .

#### 5. PERFORMANCE ANALYSIS

Using Eq.(7) and (9), we first obtain the BER, i.e.,

$$BER = \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{\frac{1}{2} \left( \sum_{i=0}^{N-1} \rho_{0,i} d_{0,i} \right)^2}{\sigma_{\beta_{int}}^2 + \sigma_{\eta}^2}} \right) \quad (12)$$

where  $\sigma_{\eta}^2$  is the variance of the AWGN  $\eta$  and  $\sigma_{\beta_{int}}^2$  is the variance of the MUI term which is a gaussian random variable.

In order to evaluate the performance of our W-MC-CDMA system, the BER has been calculated for two equalisation techniques namely EGC where the gain factor of the  $i$ th subcarrier is chosen to be

$$d_{0i} = 1, \quad (13)$$

and MRC with

$$d_{0i} = \rho_{0i} \quad (14)$$

For these equalisation techniques, and using the law of large number for approximations [4], the corresponding BER are

$$BER_{EGC} = \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{\pi}{4 \left( \frac{1}{LN} \right)^2 \sum_{m=1}^{M-1} \sum_{i=0}^{N-1} \left( \sum_{\ell=\ell_m}^{L-1} g_m^0(\ell) g_m^i(\ell - \ell_m) \right)^2 + \frac{N_0}{p_0 T_b}}}} \right) \quad (15)$$

and

$$BER_{MRC} = \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{\pi}{4 \left( \frac{1}{LN} \right)^2 \sum_{m=1}^{M-1} \sum_{i=0}^{N-1} \left( \sum_{\ell=\ell_m}^{L-1} g_m^0(\ell) g_m^i(\ell - \ell_m) \right)^2 + \frac{N_0}{p_0 T_b}}}} \right) \quad (16)$$

It is noticed that in the synchronous case no MUI term is present and the BER can be written as

$$BER_{EGC} = \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{\pi}{4} \frac{p_0 T_b}{N_0}} \right) \quad (17)$$

and

$$BER_{MRC} = \frac{1}{2} \operatorname{erfc} \left( \sqrt{\frac{p_0 T_b}{N_0}} \right) \quad (18)$$

where it is shown that the synchronous W-MC-CDMA system is equivalent to a single-user system.

## 6. SIMULATION RESULTS

In order to compare the performance of W-MC-CDMA technique and that obtained for classical MC-CDMA [4], [11], plots of the BER for transmissions versus the number of interferers ( $M-1$ ) over a Rayleigh fading channel using EGC and MRC are shown in Fig.3 and Fig.4, respectively. It is assumed that all users are received with equal power and SNR is fixed to 10dB.

The average BER for conventional MC-CDMA (uplink situation) is evaluated for  $N=128$  ( $L=1$ ) and that for Wide Band MC-CDMA is evaluated for  $N=L=128$ .

Knowing that for each user,  $m \neq 0$ ,  $\ell_m$  is a random variable taking values in  $[0, \dots, L-1]$ . It is therefore not an easy task to calculate the BER of Eq. (15) and (16). The Most adequate manner, in evaluating this BER would be to look for values of  $\ell_m$  ( $m = 1, \dots, M-1$ ) in order that the error probability is maximum (maximum of  $\sigma_{\beta_{int}}^2$ ). This

situation corresponds to the worst-case performance. It is shown, from Fig. 3 and 4, that W-MC-CDMA outperforms considerably MC-CDMA for both EGC

and MRC. The new W-MC-CDMA scheme has considerably reduced the effect induced by the MUI as compared to MC-CDMA while it is completely cancelled if the users' symbols are well synchronised in time ( $\ell_m = 0$ ).

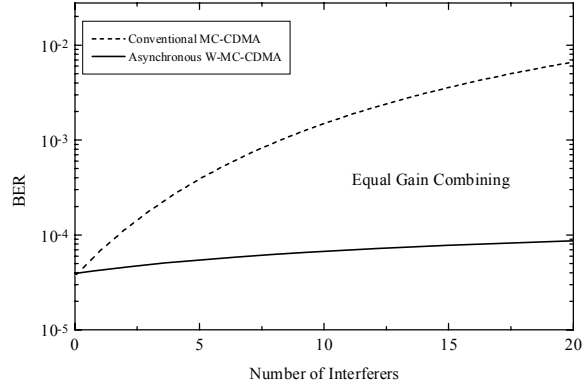


Fig.3: Maximum BER and Average BER for W-MC-CDMA and MC-CDMA, respectively. EGC Equalisation, SNR=10dB and N=L=128.

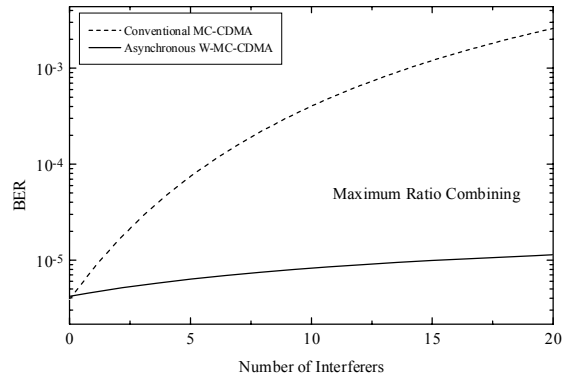


Fig.4: Maximum BER and Average BER for W-MC-CDMA and MC-CDMA, respectively. MRC Equalisation with SNR=10dB and N=L=128.

Plots of the BER, for synchronous W-MC-CDMA, versus signal to noise ratio ( $SNR = p_0 T_b / N_0$ ) over a Rayleigh fading channel using EGC and MRC are also shown in Fig.5 and Fig.6, respectively. The SNR is varied from -10 to 10dB. The average BER for conventional MC-CDMA (uplink situation) is evaluated for  $N=128$ , increasing number of users,  $M$ , and assuming that all users are received with equal power.

Fig. 5 and 6 show that our W-MC-CDMA system is independent on the number of users in the system whereas MC-CDMA is very sensitive.

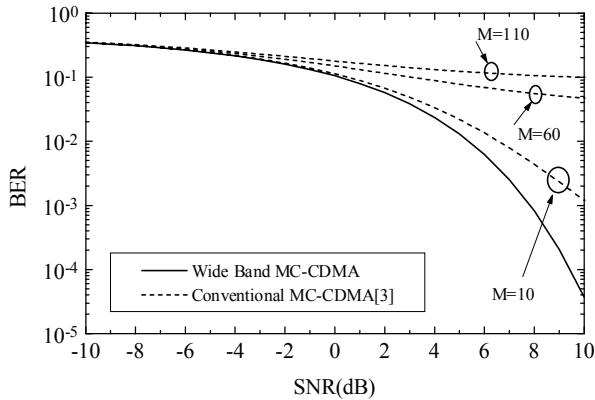


Fig.5: BER vs SNR for synchronous W-MC-CDMA and MC-CDMA. EGC Equalisation with  $N=128$ .

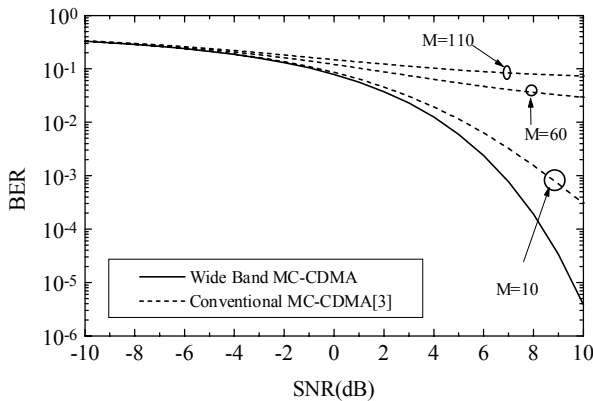


Fig.6: BER vs SNR for synchronous W-MC-CDMA and MC-CDMA. MRC Equalisation with  $N=128$ .

## 7. CONCLUSION

A new Wide Band MC-CDMA scheme has been presented. Results show that it is a very promising technique being able to be used, successfully, in indoor wireless radio networks. Compared to the classical MC-CDMA [3], Wide Band MC-CDMA is more effective because it is less sensitive to the number of users in the system.

The improvements in the BERs, could not be obtained without the introduction of the set of orthogonal sequences. This has introduced a new degree of orthogonality within each subcarrier thing that does not exist in the classic MC-CDMA.

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