

**Comparison of Coded
Orthogonal Frequency Division Multiplexing and
Multicarrier Code Division Multiple Access
Systems for Power Line Communications**

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ABSTRACT

Orthogonal Frequency Division Multiplexing (OFDM) and Multicarrier Code Division Multiple Access (MC-CDMA) systems are comparatively evaluated for Power Line Communications (PLC) in a frequency-selective fading environment with additive colored Gaussian noise which is used to model the actual in-home powerline channel. OFDM serves as a benchmark in order to measure the performance of various MC-CDMA systems, since multicarrier modulation systems are considered the best candidate for this kind of channel. Both single-user and multi-user cases are taken into account, making use of the appropriate combiner schemes to take full advantage of each case.

System efficiency is enhanced by the application of different coding techniques, a fact which shows that powerful coding can make the difference under such a hostile

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medium. The impact of block interleaving is investigated, while the simulation examines how different modulation schemes fair under the imposed channel conditions as well. The performance of the system is assessed by the commonly used Bit Error Rate (BER) vs. Signal to Noise Ratio (SNR) diagrams and there is also a comparison regarding throughput efficiency among all the tested systems. As stated in the results section, a promising PLC application is attained.

I. INTRODUCTION

The idea of using power lines to provide power as well as information is quite old, since the powerline grid seems to be a very convenient medium to serve both needs. The utility commodities worldwide have been using the grid for controlling, measuring, maintaining charging and receiving payments since late 1800's and the first patents on these applications are dated in that time [1]. However, the technology had not been extensively used for transferring information to homes and small businesses due to high cost, low speed, low functionality and other barriers. But more recently the almost global strive for the liberalization of telecommunications services has added new dimensions to the potential applications of established wireline infrastructures including those of the incumbent telecommunications companies, particularly the local loop, originally designed to link telephones to the local telephone office. In parallel, the ever-increasing need for low-cost broadband services and access to Internet has worked as a driving force leading to further research in the field of powerline communications for deploying modern and quite demanding qualified services.

PLC certainly is a cheap way to communicate, since no new wires are required, offering an existing last mile infrastructure; it can support the social needs for access to digital services from anywhere at any time till helping to avoid the digital division in the society. But still, there is doubt whether it is possible to attain high data rates at an acceptable BER for the last mile

access and to become a strong competitor for other cable-based communication systems like xDSL [2] and cable networks that have been around for a while, or it will target exclusively the in-home networking market.

The powerline channel used for wideband transmission has been under extensive study during the last years. Research in the scientific community worldwide covers topics as: the study of the grid structure in the different parts of the world [3], measurements and modeling of the communications channel, transmission, modulation and coding techniques [4-6], study of access techniques and networking issues on the grid [7], development of appropriate tools for deploying simulations of various multimedia services [8], etc. Specifically in the field of measurements and channel modeling, research is split into two broad categories, the first one covering the study of the grid in the public areas [9], while the second is focusing on the in-house grid [10-12], attempting for an effective implementation of modems and prototypes. As a result of the excessive trials on channel modeling one can find in the literature several channel models due to the peculiarities of the communication channel. Since each link exhibits its proprietary unique profile, due to individual network structure, dominant effects of signal propagation and an individual noise spectrum, the links can be assigned to groups depending on the length, type of cable, number of branches, the structure of the specific national grid, the split-phase systems, etc. On top of the physical variation we can consider the obstacles this channel imposes; high levels of interference and attenuation, impulsive noise, multipath fading and fluctuating impedance are the main problems existing in the in-house grid but their effect is even more intense over the powerline last mile. There is, however, a lack of a widely accepted channel model. Among the several models proposed in the literature we have selected an appropriate one for our study as explained in the following chapter taking into consideration published as well as our own measurements [2], in order to have a good insight into the variations of the channel.

One of the main problems seems to be the maximum power, which will be allowed for transmission over the channel. Such constraints arise in order to limit electromagnetic radiation

emitting from power lines due to the length of the cables and the lack of shielding which would result in interference for short and medium wave radio. Recent standardization activities treat this problem of EMC and pose strict guidelines for the power and transmission schemes on the grid [13] but this topic of standardization is still open and careful studies on possible transmission techniques are needed in order to help the decision procedures for future standards. Anyway, these power restrictions hinder any attempt to fight back against the already unfriendly medium, described above.

Despite these difficulties several communication techniques have been suggested for application on the powerline channel and there is a good list of references in relevant Conferences and Journals. For a successful modem design the object is to define a desirable modulation scheme that provides low bit error rates at low received SNR that performs well in multipath and fading conditions, occupies an affordable bandwidth, and it is easy and cost effective to be implemented. Simple ASK and FSK techniques are not sufficient for modern applications. M-ary non-coherent FSK and m-ary DPSK are considered more suitable, especially for narrowband applications. Spread Spectrum schemes, MSK modulation and multicarrier techniques are proposed. Generally the study of the medium voltage is easier since the use of that part of the grid is appropriate for broadband applications and in our days it is being transformed into a high quality fiber network. The study of low voltage network is the open and challenging question in the current research community. Frequency hopping [14] / M-ary multilevel FSK [15] system has also been studied aiming at relatively low-bitrate applications. MMFSK modulations were originally designed to cope with the interchannel tone disturbances in a multiple access mobile system and are now considered suitable for Power Line Communications because of their robustness to impulsive noise disturbances [16].

Code Division Multiple Access (CDMA) mainly in the form of Direct Sequence CDMA has already been examined thoroughly [17] for low and medium voltages, for different categories of services. Besides, comparisons between CDMA and Orthogonal Frequency Division Multiplexing (OFDM) applied on the medium voltage power grid [18], among OFDM,

Single Carrier, and Spread Spectrum for high data rate PLC [4,19], and between OFDM and Direct Sequence Spread Spectrum (DS/SS) for power line data transmission [20] have been carried out as well. Furthermore, a lot of research has been performed [6,21] comparing multi-user CDMA techniques (DS-CDMA, MT-CDMA and MC-CDMA); although this work does not refer to powerline communications, it provides a clear view of the advantages of the MC-CDMA over the other two multi-user CDMA schemes, as regards the BER performance, especially for a large number of users. Results on the performance of these techniques and useful guidance for selecting the most appropriate technique for any examined application are found in the literature helping the network designer to optimize his/her application at a considerable degree of confidence.

Multicarrier transmission seems to be the most promising modulation scheme for powerline communications [4], called forth to counter the frequency-selective features of the channel as well as the non-gaussian behaviour of the noise. Discrete Multi-Tone has also been suggested [5] to improve the power distribution aim for a better overall performance, using adaptive loading to cope with the frequency-dependent nature of the channel, a common feature with PSTNs, where DMT has been employed as part of the ADSL system.

Moreover, advanced coding techniques should be realized in such a system, using processing power to provide coding gain and, in turn, reduce the required power to achieve the same BER. Reed-Solomon codes, repetition coding, block coding are different forward error correction techniques proposed for applications currently. Convolutionally coded PSK - OFDM with IO-NMLSE decoding [22] is one proposal for improving the performance of the system. Turbo coding is a fairly new coding technique, which has not been tested yet on a grid like power line, and its contribution to our system is going to be examined. The Turbo coding technique was introduced in 1993 [23], producing exceptional coding gain results in Rayleigh fading and AWGN channels [24]. In the version used in this work Turbo coding is employed, comprising two concatenated convolutional codes.

In this work the characteristics of a powerline in-house network are simulated in order to measure the efficiency of an OFDM and an MC-CDMA system described in more detail below. This study examines the effects that coding and interleaving bring about in an attempt to reduce the required power while maintaining the same overall performance.

One of the most important reasons to employ OFDM is the efficient way it deals with multipath delay spread. By dividing the input data stream in N_s subcarriers, the symbol duration increases N_s times, which reduces the relative multipath delay spread, relative to the symbol time, by the same factor. To eliminate intersymbol interference almost completely, a guard time prefix greater than the maximum delay spread is introduced in each OFDM symbol. In the guard time the OFDM symbol is cyclically extended to avoid intercarrier interference. This scheme is also easy to implement by using modern DSP processors capable of utilizing the FFT algorithm which is commonly used to form the OFDM symbol.

The MC-CDMA scheme is similar to that of a normal OFDM scheme. The main difference is that the former one transmits the same symbol in parallel through many subcarriers, whereas the latter transmits different symbols. All the carriers in total are $N=P \cdot K_{mc}$, where P is the number of the primary carriers and K_{mc} is the number of the subcarriers. At the receiver a combining scheme takes place, to decide which symbol was transmitted; this scheme can be Orthogonality Restoring Combining, Equal Gain Combining, Maximal Ratio Combining or Minimum Mean Square Error Combining, according to [6]. Note, that when setting K_{mc} to 1, the modulation scheme becomes the same as OFDM with P carriers. So the MC-CDMA system can be considered as a combination of an OFDM scheme and a CDMA one. The major advantage of the MC-CDMA is that since it can lower the symbol rate in each subcarrier, longer symbol duration is created, so it makes it easier to quasisynchronize the transmissions, as well as to have more tolerance in fading channels. Furthermore, MC-CDMA does not require a RAKE receiver for optimal reception due to its inherent frequency diversity which is taken advantage of in the combiner.

The outline of this paper is as follows. In Section II, the channel model of the simulation is analyzed. The system structure and analysis is described in section III. The performance evaluation of the system and extensive simulations results are depicted in Section IV. Section V concludes this paper and presents the final remarks.

II. CHANNEL MODEL

Modeling the power line channel is not an easy task because of its unpredictable nature with frequency, time of day, geographic location and rural environment. The main parameters of interest are the impedance, attenuation and noise.

Absolute impedance of the power distribution system up to 30 MHz has been carefully studied in several countries in [25], showing similar results between European countries and the US. The main problem lies in the enormous fluctuation in the frequency range of interest though this fluctuation is relatively reduced in the range from 1MHz to 30 MHz.

Indoor and outdoor powerline channel attenuation has been examined in [9] considering the lower part of the spectrum. These reports show that an attenuation level of 40-100 dB/Km of distance can be expected but it has a strong frequency dependence thus leading a frequency-selective channel behavior.

Noise on power lines is also varying with frequency, location and time. It exhibits a decaying spectrum with increasing frequency. This behavior was investigated and it was found that the background noise spectrum decays by about 29 dB / decade from 10 KHz to 100 MHz. Another major source of noise is impulsive noise caused by unpredictable switching operations which lead to noise bursts of various durations and levels. Less than 1% of these noise impulses has a duration of 500 μ sec and 0.2% exceeds 1 msec [26] while their level is around 40-50 dB above the background noise level. Furthermore, there is noise synchronous to the mains frequency caused by rectifiers and also narrowband noise dependent on location and time, basically due to short and medium wave radio stations.

The aforementioned qualities of the powerline channel have been integrated in channel and noise models. Two attenuation models have been proposed so far for PLC applications: The Hooijen's model and IEC-1334-1-4 standard for narrow band communications [27]. Several channel models covering the frequency range up to 30 MHz also exist in literature. An echo model and a series resonant circuit model were developed in [28] to produce the channel impulse response/transfer function regarding the in-home channel. In [29] a multipath model is used for 0.5 to 20 MHz, also referring to the in-home powerline grid. The resulting transfer function comprises a weighting factor which describes the reflection and transmission factors of the path, the attenuation term and the delay term. In [30] a simpler two-parameter model is presented for 1-15MHz considering a macroscopic approach; attenuation increases as frequency increases and the model parameters depend on cable characteristics, distance and frequency. This sort of model has been applied in the telephone line channels. In general, a ubiquitous model cannot be easily implemented since the change of loads in a line would greatly alter the transfer function. Network topology (distance the signal travels, number of branches and their length) also plays a major role as the number of paths (which form the multipath channel profile) and signal attenuation may drastically change, thus resulting to a totally different model.

In our simulation the channel model (echo model) from [28] is used, which is based on channel measurements from the in-house network to portray the channel transfer function. The general structure of the in-house channel can be seen in figure 1. The signal is received through a multipath environment. The transmitted signal reaches the receiver not only on a direct path, but also delayed and attenuated. Hence, the channel simulation is based on an N-path propagation model (impulse response), each path has a different gain, delay and phase shift given by:

$$h(t) = \sum_{v=1}^N |\rho_v| \cdot e^{j\phi_v} \cdot \delta(t - \tau_v) \quad (1)$$

where N is the total number of paths, $|\rho_v|$ and ϕ_v are the amplitude and the phase of the attenuation factor respectively, and τ_v is the delay time of the signal received by the v^{th} path. It can clearly be seen that for each path a set of only three parameters has to be defined. Hence, the entire model with N paths is completely defined by $3*N$ parameters. These parameters (5-path impulse response) provided by the channel model, are focalized on table 1 keeping them constant throughout the entire simulation.

Though, channel models show some similarities as far the approach used is concerned (even though their results may differ), there is great differentiation regarding the noise model that should depict the actual powerline noise. We can distinguish proposals for background noise and impulse noise, the Middleton model [31] being the most applied one for broadband power line systems, when having impulsive noise. There are also models based mainly on measurements [30] a fact which reinforces the notion that impulsive noise cannot really be modeled in a unique way [32]. Background noise is mainly represented as filtered white Gaussian noise [28], despite the fact that its statistical distribution is almost Gaussian [30]. Narrowband noise is usually represented by cosines in the frequencies where narrowband interference was observed. Again, models usually depend on measurements and these measurements cannot be global since noise amplitude shows a great fluctuation at different time intervals and may even change when measured at different outlets.

The simple noise model described in [28] is utilized to represent background and narrowband noise, which are the main types of noise on power lines; impulsive noise has been left out since its behaviour cannot be accurately predicted due to the fact that it relies heavily on impulsive noise sources connected to the system or near it. The noise model is based on sources of White Gaussian noise, which are defined separately for M adjacent, non-overlapping frequency bands. Each segment is defined by its bandwidth and its noise amplitude. Due to this fact, the noise amplitude is set through M linear filters by means of a multiplication with a constant factor, for each path. The distribution of the amplitudes of the summation of the M

filter outputs is a Gaussian distribution as well, because only linear operations are carried out. In the noise model applied in this work, 5 segments are used (M=5).

III. SYSTEM STRUCTURE AND ANALYSIS

The general layout of the simulated system can be seen below in figure 2; it represents an OFDM and an MC-CDMA model. The baseband signal to be transmitted in each case can be expressed as:

$$s(t) = \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}+1} d_{i+\frac{N_s}{2}} \exp\left(j2\pi \frac{i}{T}(t-t_s)\right), t_s \leq t \leq t_s + T$$

$$s(t) = 0, t < t_s \wedge t > t_s + T$$
(2)

for the OFDM scheme, where d_i are the incoming to the OFDM block information data, N_s is the number of subcarriers, and T the symbol duration.

And for the MC-CDMA scheme:

$$s_{MC}^j(t) = \sum_{i=-\infty}^{+\infty} \sum_{p=0}^{P-1} \sum_{m=0}^{K_{MC}-1} a_{j,p}(i) d_j(m) p_s(t - iT_s') e^{j2\pi(Pm+p)\Delta f'(t-iT_s')} \quad (3)$$

where j refers to the j^{th} transmitting user, $a_{j,p}(i)$ is the input information sequence after being converted to P parallel data sequences, $d_j(m)$ is the spreading code with length K_{MC} , T_s' is the MC-CDMA symbol duration ($T_s' = PT_s$), T_s is the subcarrier symbol duration, $\Delta f'$ is the minimum subcarrier separation ($\Delta f' = 1/(T_s' - \Delta)$), Δ is the guard interval inserted between symbols to avoid intersymbol interference caused by multipath fading, and $p_s(t)$ is the rectangular symbol pulse waveform defined as

$$p_s(t) = \begin{cases} 1, & (-\Delta \leq t \leq T_s' - \Delta) \\ 0, & \text{(otherwise)} \end{cases} \quad (4)$$

In the OFDM scheme the signal is modulated through $N_s=512$ carriers; whereas in the MC-CDMA scheme the signal uses $P=128$ primary carriers, and $K_{mc}=4$ subcarriers (512 carriers in total), equally spaced throughout the measured frequency range (1-30MHz). A different spreading length is also tested; $K_{mc}=16$ subcarriers (spreading length 16) and $P=32$ primary carriers in order to confirm the gain provided by spreading. A single-user case is considered so that the focus lies on the efficiency of the scheme to counter the channel properties, not interference caused by other users. Also, multi-user scenarios with various numbers of users are assumed, to examine the efficiency of the system in a more realistic environment.

The modulation schemes under test are the commonly used Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK) and 16-Quadrature Amplitude Modulation (16-QAM). The coding techniques were chosen to be some representative codes of the Block codes, Cyclic codes, Convolutional codes and Turbo codes; four codes have been applied to the aforementioned system: Hamming (7,4), Cyclic Golay (23,12), Convolutional code (3,1) with generator polynomials [171,133,165], using a hard-decision Viterbi decoding, and a Turbo code analyzed below. The selection of codes was based on the fact that Hamming is an easy-to-implement linear Block code, Cyclic Golay is a powerful cyclic code, Convolutional codes are widely used in wireless channels with very good performance results, and Turbo coding is a new coding technique which has not been tested yet on a PLC environment. Block Interleaving with depth 8 has also been tested to face bursts of errors caused by deep fading in conjunction with high levels of noise [33].

In the case of Turbo codes [24,34-35], the information data is encoded twice using two Recursive Systematic Convolutional (RSC) encoders, one of which receives an interleaved version of the original data, thus making the two sequences almost statistically independent of each other. Only the parity bits are used in conjunction with the original data sequence. Moreover, the parity sequences can be punctured in order to increase the coding rate. The

decoding procedure is more complex; two RSC decoders are used with soft-input and soft-output decoding algorithms. There are three main algorithms on which the decoding procedure is based, namely, Log-MAP (Maximum A Posteriori) [36], Max-Log-MAP, and SOVA (Soft Output Viterbi Algorithm) [37]. The Turbo decoder operates in an iterative process, with each RSC decoder producing a soft output-estimation of the information data and an extrinsic output which provides information about the surrounding bits. After the first iteration the extrinsic data are fed to the decoders in the form of feedback in order to achieve a better estimation of the information data. As a result, every iteration improves the overall BER performance although this gain is gradually reduced after 8 or more iterations. It is obvious that the number of iterations is a tradeoff between performance and implementation complexity.

The parameters chosen for the implementation of the Turbo coding in our system are centralized in the following: two Convolutional codes (2,1) using generator polynomials [171,133]. Also, the decoding scheme is based on the Log-MAP algorithm, using 8 iterations. The parity bits are punctured, so that the coding rate becomes 1/2.

Finally, it should be mentioned that perfect channel estimation is assumed at the receiver. In the real-world scenario of imperfect channel estimation, system performance would generally deteriorate; QAM modulation suffers more from this hindrance because amplitude level fluctuations directly affect the detector, leading to very poor performance results. BPSK can deal with this issue more efficiently, making use of the guard interval. However, if the guard interval is less than the maximum delay spread, system performance drops sharply. The channel combiner at the receiver employs Maximal Ratio Combining (MRC), except for the case of 16-QAM and whenever Turbo coding is applied, where the system uses Orthogonal Restoring Combining (ORC). This is due to the fact that MRC does not restore the signal to the original level, which can have detrimental effects on multi-level modulation schemes, such as QAM, because the decision boundaries used in the detector would not be correct any more. The same notion applies for the Turbo-coded cases where the soft-decoding procedure requires the

original signal level. Despite that fact, MRC was chosen for the rest of the cases because it outperforms ORC.

To sum up, the OFDM - BPSK system can provide a gross throughput of 29Mbps minus the amount of bandwidth used for the guard time interval, which is one quarter of the transmitted bits. This overhead lessens throughput by about 20% which equals to 23.2 Mbps, when uncoded data is used. BPSK in conjunction with Hamming code (7,4) and Golay code (23,12) lowers this bit rate to about half (about 13.25 Mbps and 12.1 Mbps respectively) and Convolutional code (3,1), allows the system to transmit at 7.7 Mbps (1/3 of the uncoded data bit rate). The last code, Turbo code, provides a bit rate of 11.6 Mbps (it is actually lower than that since every frame of approximately 32768 bits long and 4 bits are overhead data but that is an insignificant amount of bandwidth loss).

On the other hand, MC-CDMA is even more bandwidth consuming, as it uses a frequency spreading to achieve better results. Bit Rate is reduced by 4 and 16 times for spreading length of 4 and 16, respectively. Coding lowers throughput by the same factors as above, leading to a transfer rate as low as 480Kbps in the case of MC-CDMA with 16 subcarriers and convolutional encoding rate 1/3. However, if more than one user is considered the cumulative bit rate is augmented by the number of users occupying the system; that is for 4 users in the 16-subcarrier MC-CDMA system total rate is equal to the 4-subcarrier MC-CDMA system, while in the 16-user scenario the system has the same bit rate as OFDM. This comparison is going to be carried out in the following section.

Apart from BPSK it is quite obvious that the application of QPSK modulation can double throughput and 16-QAM can quadruple it although performance in terms of Bit Error Rate is undermined.

IV. PERFORMANCE EVALUATION AND RESULTS

For the performance evaluation of the proposed system, a code has been developed in Matlab. The figures presented below were created by running multiple simulations, in order to minimize the statistical errors and to assure the validity of the results. The system was evaluated by simulating a transmission of about 2^{26} (67108864) data bits to obtain performance results for each of the tested systems. The multiparametric nature of the code should be mentioned here. These parameters can be focalized on the following: number of primary carriers and number of subcarriers as regards the MC-CDMA scheme, coding techniques, modulation techniques, bits per symbol, interleaving depth, number of users, and the length of the considered frames (number of OFDM or MC-CDMA symbols in one frame) are the major parameters with which we tested our system for several values and combinations. The Bit Error Rate (BER) performance of the aforementioned systems for a wide range of Signal to Noise Ratios (SNR) is presented in this section.

The system simulation includes the comparison of three modulation schemes (BPSK, QPSK and 16-QAM), combined with three multiplexing techniques (OFDM, MC-CDMA with frequency spreading 4 and MC-CDMA with frequency spreading 16). In 16-subcarrier MC-CDMA three-user scenarios are examined (1, 4 and 16 users), thus yielding a total of 15 diagrams. Each diagram compares the performance of the following coding techniques: Hamming, Cyclic Golay and Convolutional, as well as the effect of block interleaving. In addition, as regards the BPSK modulation, Turbo coding is also examined for all the multiplexing techniques.

The BPSK - OFDM scheme is examined in figure 3. It appears that a simple Block code like Hamming (7,4) with correction capability of one error per codeword produces much better results compared to the uncoded transmission. Even though a decrease in terms of SNR to attain the same BER was expected, this simple code provides a better improvement than it could give in some other environment, like the wireless channel. Cyclic Golay code (23,12) offers a slightly better advantage, while Convolutional coding is even better, reaching a BER of $3 \cdot 10^{-6}$ at less than 6.5dB. The efficiency of the codes is illustrated, teamed up with block interleaving of

degree 8. Interleaving combined with the Hamming or Golay code incurs a gain of over 1 dB to the BER performance compared to the system without interleaving. In the case of Convolutional coding, interleaving barely boosts the system performance. Turbo coding on the other hand has a tremendous effect on the system; there is a very sharp drop after -2.5 dB which can reach a BER of $2 \cdot 10^{-6}$ with little more than 1dB.

In figure 4 the BPSK - MC-CDMA scheme is investigated; in contrast to OFDM which uses all 512 carriers to transmit different symbols, this system uses 4 subcarriers and 128 primary carriers. The results of the simulation are analogous to the ones above; the Hamming code adds up a total gain of 3db at a BER of $2 \cdot 10^{-6}$. About the same improvement is achieved from the comparison of Golay code with Hamming. Convolutional code is again far more beneficial as it can reduce the required SNR by an extra 5dB (compared to Golay) at a BER of $2 \cdot 10^{-6}$. Apart from these common features, MC-CDMA differentiates itself from OFDM; it appears that Hamming code can be more advantageous when combined with interleaving, than in the case of OFDM. The interleaved Cyclic Golay code remains better than the same code without interleaving. Still, the presence of interleaving in Convolutional coding cannot be clearly observed. However, Convolutional coding is still the most prevalent of the conventional coding techniques (excluding Turbo code). Turbo coding appears to offer the same overall performance gain as in the OFDM case. Again, it can be observed that the curve descends very rapidly, because of the number of the iterations; as the number of iterations increases the BER drops even more sharply as explained in section III.

Regarding the next simulated system, i.e. BPSK - MC-CDMA with 16 subcarriers and 32 primary carriers, the obtained results are depicted in figures 5, 6 and 7 for 1, 4 and 16 users respectively. In figure 5, there is a slightly different response; while the improvement over the system using Hamming code is still about the same (4dB at $2 \cdot 10^{-6}$), Cyclic Golay coding provides better results compared to the MC-CDMA system with spreading length equal to 4 and to the OFDM scheme. In addition, the superiority of the Convolutional code over Cyclic Golay is now decreased. As regards interleaving, the only code combined with it, that provides a great

benefit to the system, is the Hamming code. The other two interleaved codes examined here offer a far inferior improvement. Interleaving in conjunction with Golay coding improves performance by 0.5dB at a BER of $2 \cdot 10^{-6}$, while with Convolutional coding there is hardly more than 0.3dB enhancement at a $2 \cdot 10^{-6}$ BER. Yet the two curves can be now clearly distinguished. As expected, Turbo coding is the most powerful coding technique among the tested ones, leading to a BER of $2 \cdot 10^{-6}$ at -12.5dB.

For the 4-user scenario (figure 6) there is a similar response though a deterioration of 4-5dB can be observed when comparing the 1-user with the 4-user case regardless of the coding scheme which is, of course, attributed to the multi-user interference. This figure shows similar properties to 4-subcarrier MC-CDMA; in the figure under test, the different coding scheme curves are equally spaced. Results show that the multi-user scheme is more efficient by about 1.5-2 dB excluding convolutional coding. Interleaving shows the same properties as described above. For the Turbo coding case, it can be seen that the 17dB gain with reference to the uncoded curve remains, as in the three previous figures.

The last scenario (figure 7) which considers 16 users in the system is quite different. When uncoded data is used the BER is reduced very slowly after the SNR threshold of 10 dB. The number of users here is quite large and multi-user interference seems to prevail against the channel properties. The application of coding, however, overcomes this problem, though it is evident that more than 10 extra dB are required to achieve the same BER. This scheme is throughput-equivalent to OFDM and this time apart from the uncoded case it is apparent that results do not present major differences.

Figure 8 depicts the efficiency of the QPSK - OFDM system. Compared to BPSK, there is a 3-4dB increase of required power to maintain the same BER. Hamming coding shows the same behavior as before. Golay coding, though, seems more favored by the presence of interleaving than in the BPSK version. Convolutional coding with interleaving does not offer any improvement at all.

The QPSK - MC-CDMA system with 4 subcarriers and 128 primary carriers is presented in figure 9. While the results for the Hamming and Golay codes are analogous to the BPSK's scheme, with a worsening of 3-4dB, again, Convolutional coding is less advantageous here. Interleaving offers a clear, but fair improvement when using Hamming or Golay code, while Convolutional is slightly benefited by the presence of interleaving and the distance between convolutional coding and interleaved Golay coding has diminished.

In figures 10, 11 and 12 the QPSK - MC-CDMA system with 16 subcarriers and 32 primary carriers is tested, for 1, 4 and 16 users loaded on the simulated system, respectively. In figure 10 the Hamming code gives a noticeable improvement to the system, of about 3 dB at a BER of $2 \cdot 10^{-6}$. Golay code is slightly less beneficial compared to the MC-CDMA system with spreading length 4 and to the OFDM scheme. In addition, Convolutional code reaches a BER of $2 \cdot 10^{-6}$ at about -1.5dB.

The 4-user scenario examined in figure 11 is analogous to the latter one, with obviously worse results, for all the applied coding techniques, as expected due to the multiplicity of the users. Interleaving appears to offer minor improvements to the coded curves compared to the single-user figure. Again, these results are generally better than the ones provided by the 4-carrier single user MC-CDMA, a system with the same throughput.

As regards the 16-user scenario, presented in figure 12, all the results are even worse, and the uncoded curve cannot reach a low BER; this sort of behavior is parallel to the BPSK figure. Comparing OFDM and the case that 16 users are loaded on the 16-subcarrier MC-CDMA system, results that the former is slightly better than the latter, at about 2-4dB for all the curves, with the exclusion of the uncoded case, of course.

In the case of 16-QAM combined with OFDM as illustrated by figure 13, transmitted power generally has to be increased by almost 5 dB compared to QPSK or 9 dB when compared to BPSK. This scheme seems to behave more like QPSK than BPSK. Both Hamming and Convolutional coding do not seem to obtain any significant gain from interleaving, yet interleaving appears to be quite beneficial to Golay coding. This is quite normal due to the fact

that interleaving greatly affects a code with a larger codeword length (23 compared to 7 for Hamming and 3 for Convolutional) and this effect is further exploited when a larger symbol size is used. In general, Convolutional coding shows a superior performance in comparison to the rest of the codes but the efficiency of all the applied codes is quite clear if the uncoded case is taken into account.

Figure 14 examines the MC-CDMA 4-subcarrier system employing 16-QAM, which is a multi-level modulation scheme, unlike BPSK and QPSK which only have one modulation level. Moreover, Maximal Ratio Combining is used in the MC-CDMA BPSK and QPSK receiver, while Orthogonal Restoring Combining is employed for the 16-QAM - MC-CDMA receiver which can better counter the channel inhibitions but also augments the effect of noise. Thus, it is apparent that the difference in performance among the codes is reduced in 16-QAM.

Figures 15, 16 and 17 exhibit the performance results of 16-subcarrier MC-CDMA simulated system for 1, 4 and 16 users correspondingly. The first one is slightly different from the previous scheme (4-subcarrier MC-CDMA); in this case the interleaved Golay curve presents a greater advantage compared to the uninterleaved one (1.5dB extra gain).

The same system loaded with 3 more users produces almost identical results with an overall performance impairment of 5dB (figure 16). Comparison with 4-subcarrier MC-CDMA offers a small advantage to the multi-user system. Finally, figure 17 depicts the 16-user case; the general inclination of the curves does not show great variations when paralleled to the two previous cases apart from the expected multiple user interference burden (an extra 5dB compared to 4 users or 10dB for the single-user case). 16-QAM can clearly overcome the saturation that BPSK and QPSK have shown, mainly regarding the uncoded curve, which fails to reach an acceptably low bit error rate. This is indirectly attributed to the combiner scheme as described above. 16-subcarrier MC-CDMA and OFDM performance results are almost indistinguishable apart from Golay coding curves, where the multiple-user scheme prevails, a fact which is related to the codeword length.

There is one more throughput comparison to be taken into account; the 16-QAM scheme with 4 users loaded on the 16-subcarrier MC-CDMA system provides throughput equivalent to the BPSK one with 1 user loaded on the 16-subcarrier MC-CDMA. There is no actual comparison as regards the modulation scheme, however since the BPSK scheme is far superior due to the multi-level nature of 16-QAM which is quite unfavourable in the channel of choice. Similar conclusions erupt from the comparisons of the 16-QAM with 16 users and the BPSK with 4 users, and also the BPSK single-user with 4 subcarriers MC-CDMA and the 16-QAM single-user with 16 subcarriers MC-CDMA.

As a general comment on interleaving, it can be seen that, in spite of the fact that there is no impulsive noise model specifically used for the simulation, interleaving can be beneficial against narrowband interference and corruption of multiple bits caused by fading. As the simulation passes from OFDM to MC-CDMA using a higher spreading factor each time interleaving gradually begins to add up to all of the codes, since the combining that takes place at the receiver uses multiple subcarriers, i.e. multiple neighboring bits to decide about only one. Thus, interleaving now affects a greater number of data bits, a fact which boosts Hamming and even Convolutional coding (in the case of spreading length 16). On the other hand, the application of frequency spreading turns out to be highly advantageous for Golay coding, in general. Its performance is now much closer to convolutional coding so it is expected that interleaving will not be able to offer any more significant help.

V. CONCLUSION

This paper examines the BER performance of a coded OFDM and two coded MC-CDMA systems over the powerline in-house network. BPSK, QPSK and 16-QAM have been examined, combined with Hamming, Cyclic Golay, Convolutional and Turbo codes. Interleaving is also evaluated as a means to improve this performance. Multiple-user scenarios have been investigated for the MC-CDMA scheme.

The single-user MC-CDMA scheme with 16 subcarriers and 32 primary carriers is the most efficient of the presented systems, with regard to the BER performance. Nevertheless, there is a significant tradeoff between BER performance and throughput efficiency. As the number of users increases to attain the OFDM throughput, this advantage diminishes. As a final remark on the simulations, Turbo coding was by far the most advantageous technique. Yet, this efficiency comes at an enormous cost of complexity, especially when the number of iterations increases.

Finally, the overall conclusion coming out of this comparison is that Power Line Communications can profit from the application of the presented techniques.

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VII. TABLES AND FIGURES

N (PATH)	 P 	Φ IN RAD	T IN MS
1 st	0.151	0.691	0.110
2 nd	0.047	-0.359	0.154
3 rd	0.029	0.591	0.205
4 th	0.041	2.913	0.311
5 th	0.033	1.012	0.427

Table 1: Parameters of the channel model

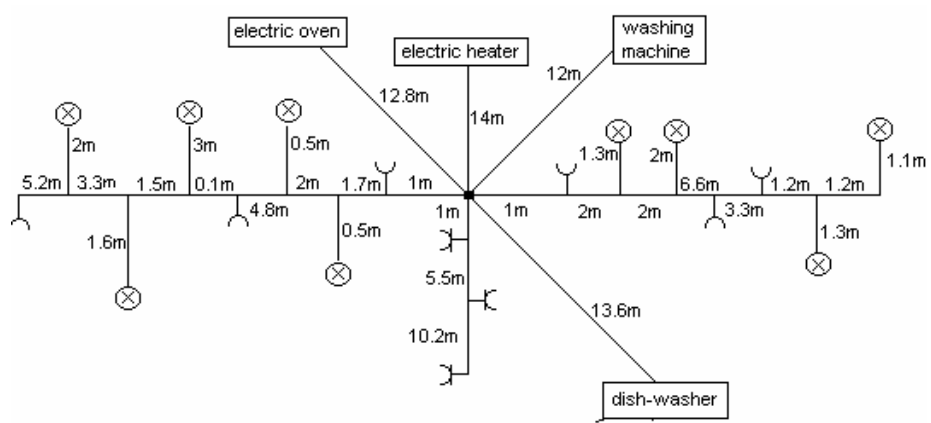


Figure 1: In-house channel typical topology

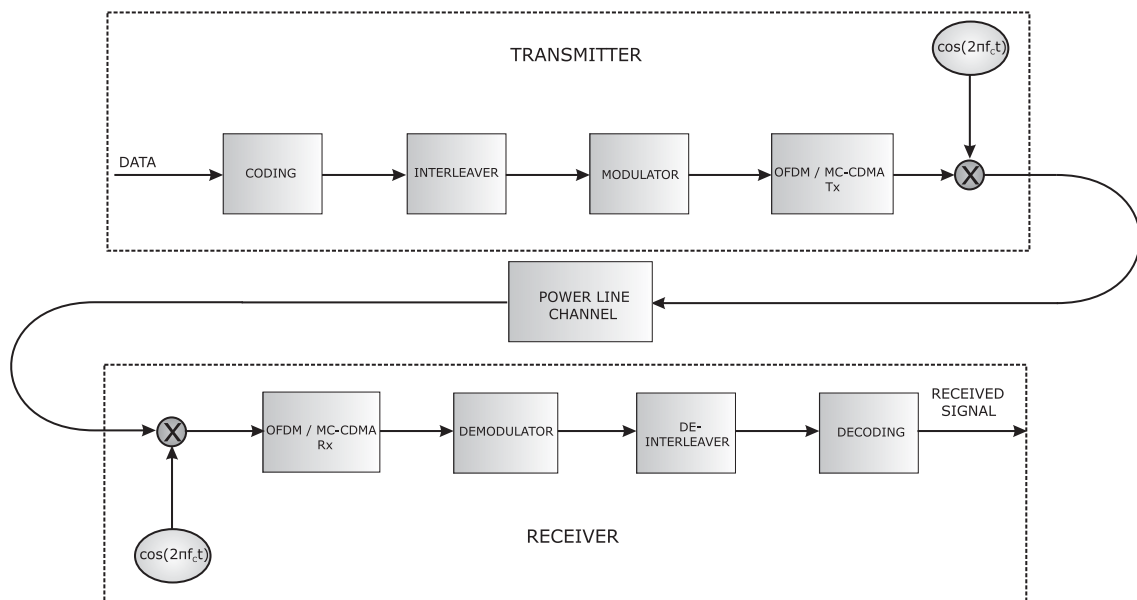


Figure 2: System Block Diagram

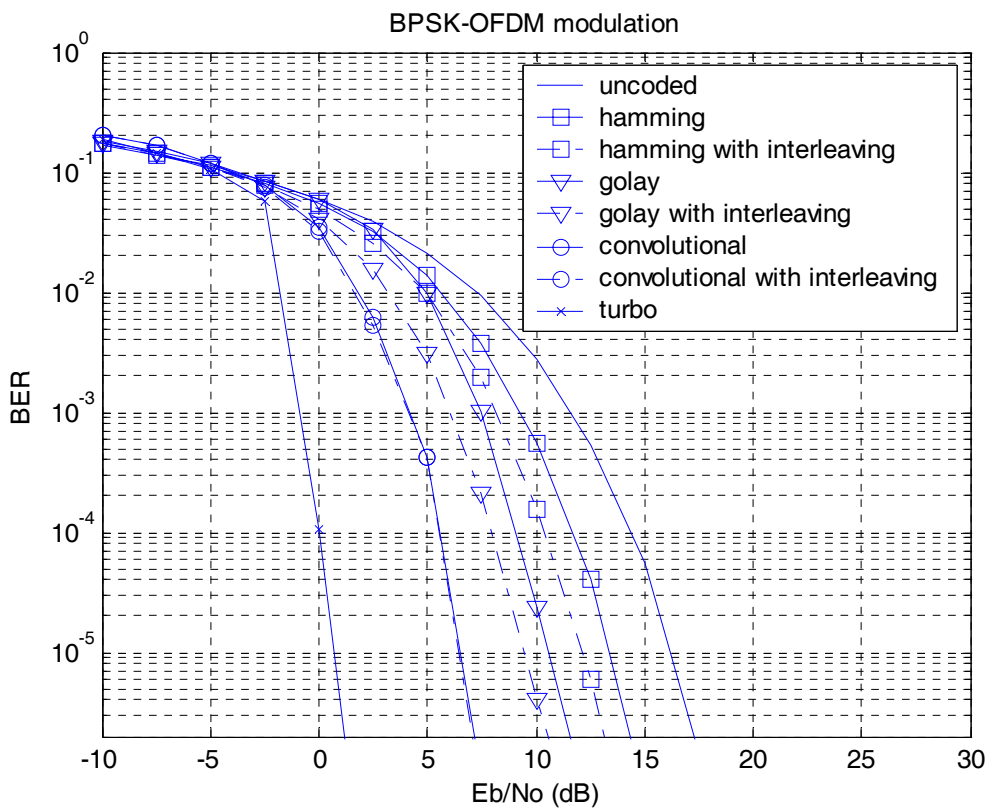


Figure 3: OFDM - BPSK modulation

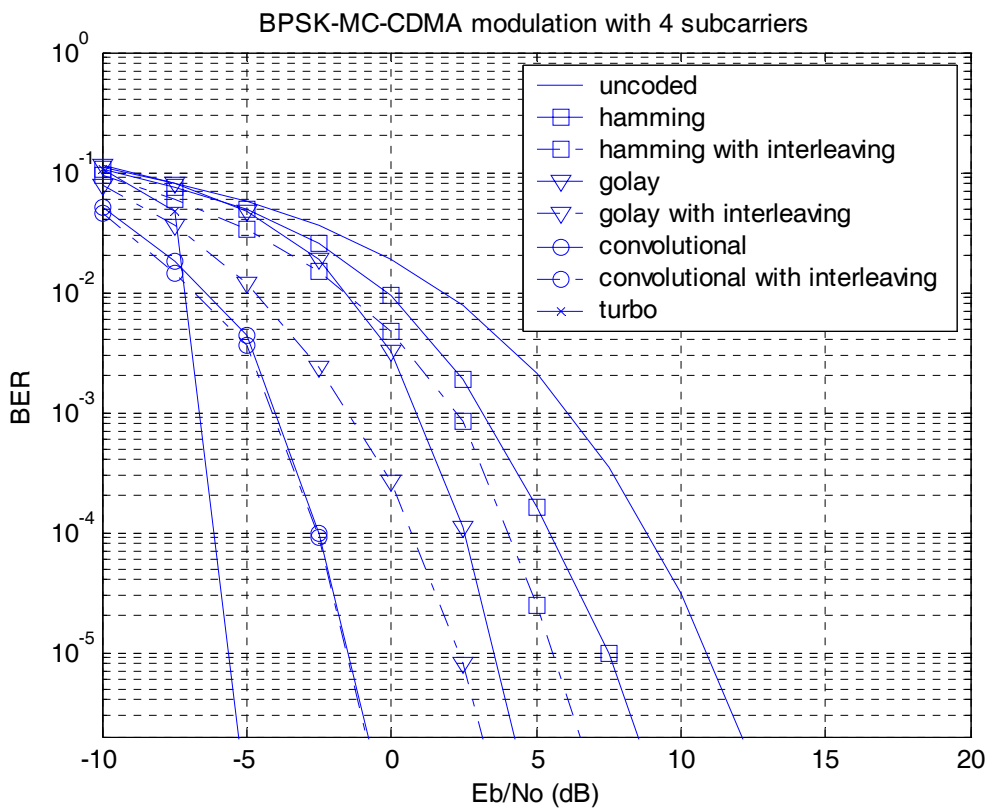


Figure 4: BPSK – MC-CDMA modulation using 4 subcarriers and 128 main carriers
with a single user

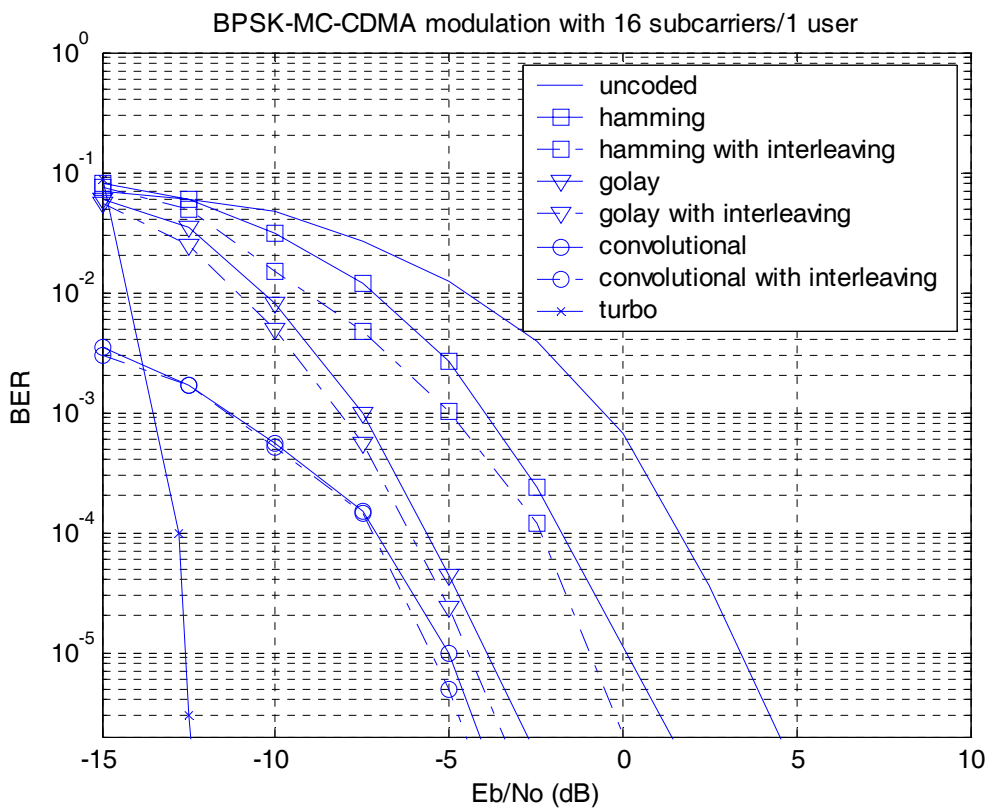


Figure 5: BPSK – MC-CDMA modulation using 16 subcarriers and 32 main carriers with a single user

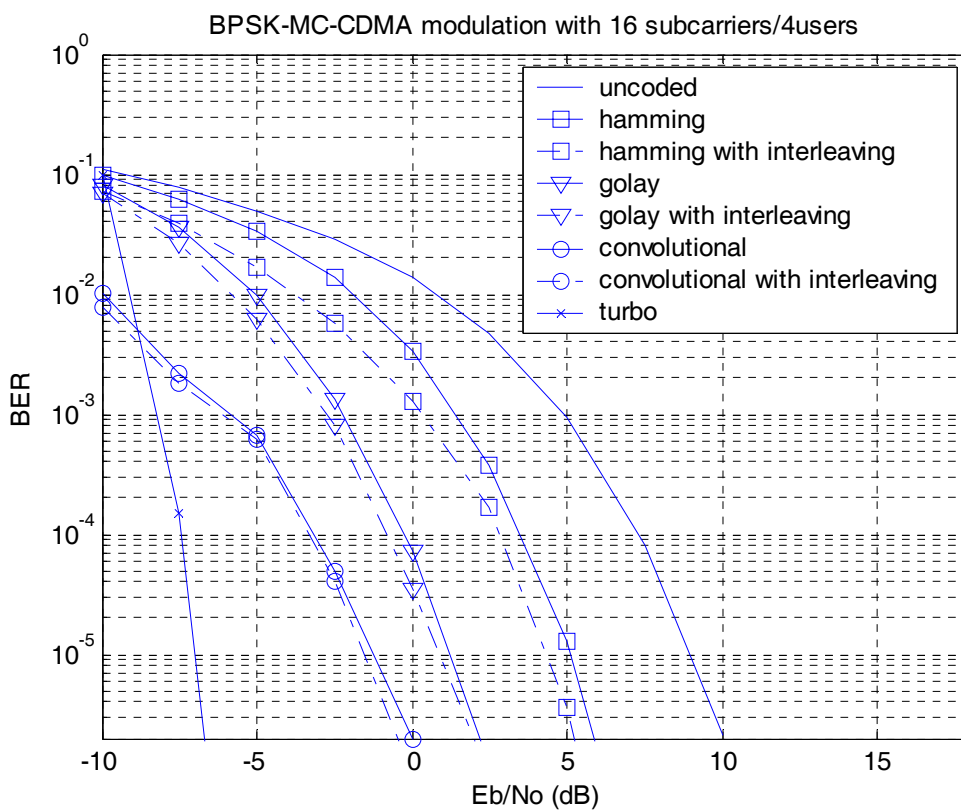


Figure 6: BPSK – MC-CDMA modulation using 16 subcarriers and 32 main carriers with 4 users present

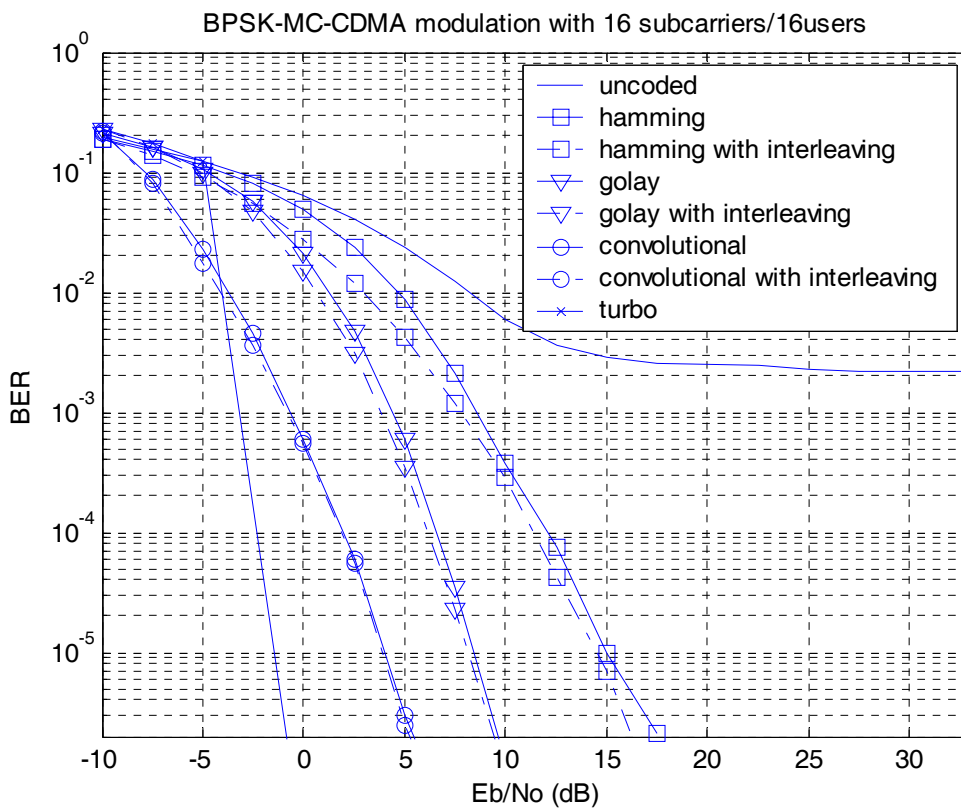


Figure 7: BPSK – MC-CDMA modulation using 16 subcarriers and 32 main carriers
with 16 users present

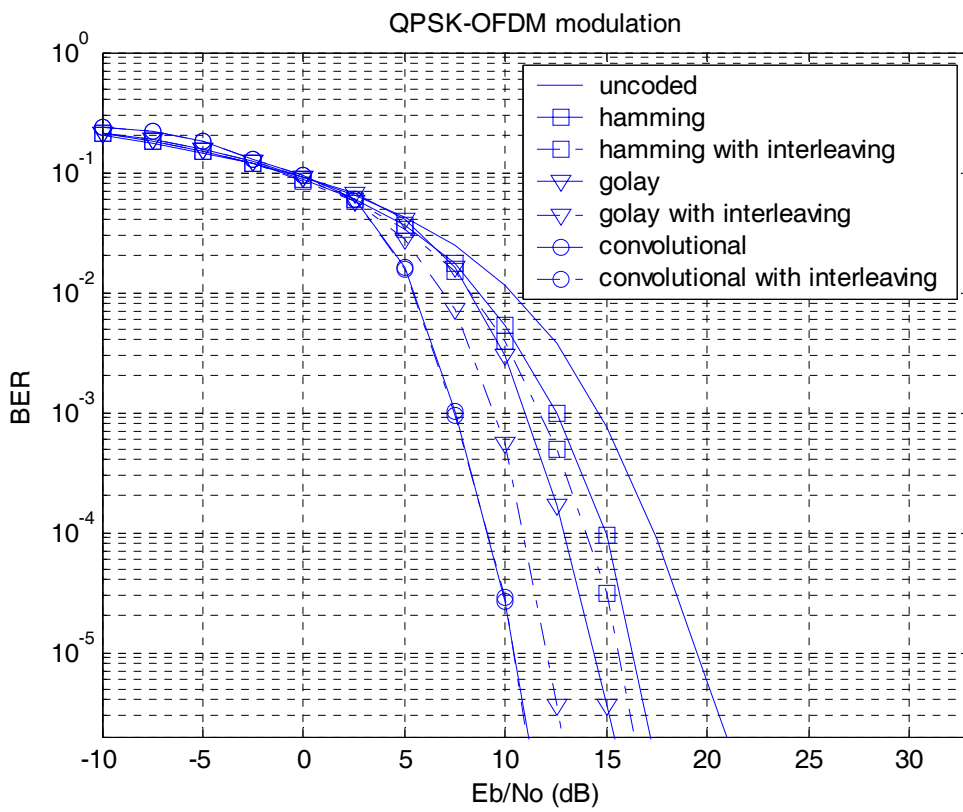


Figure 8: QPSK – OFDM modulation

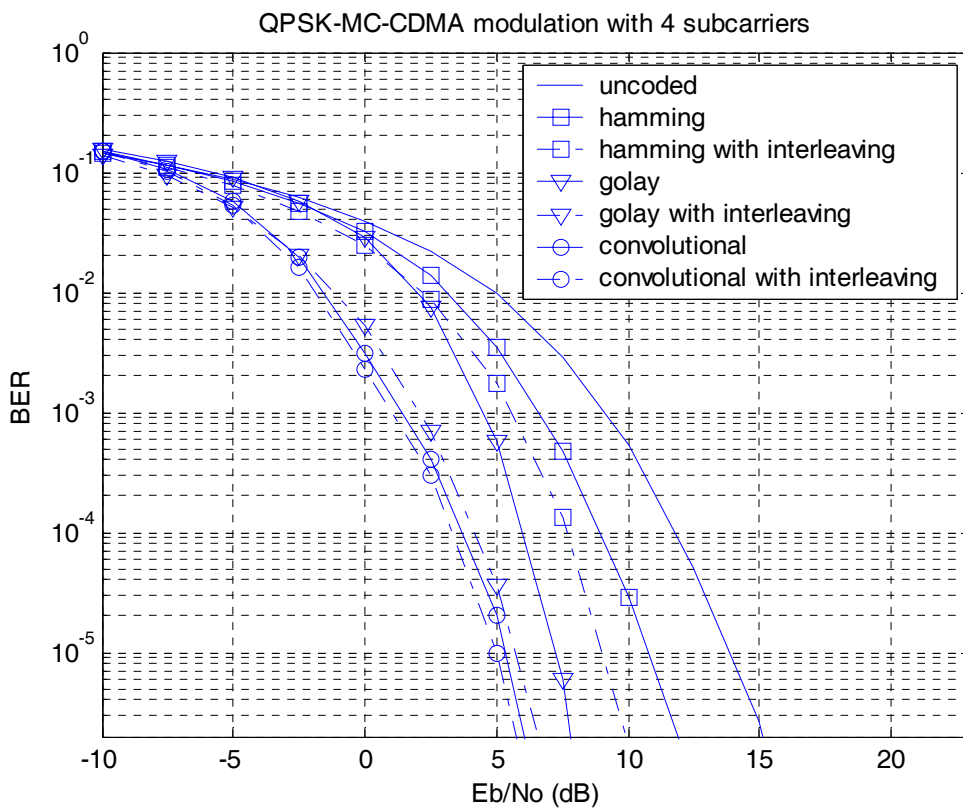


Figure 9: QPSK – MC-CDMA modulation using 4 subcarriers and 128 main carriers
with a single user

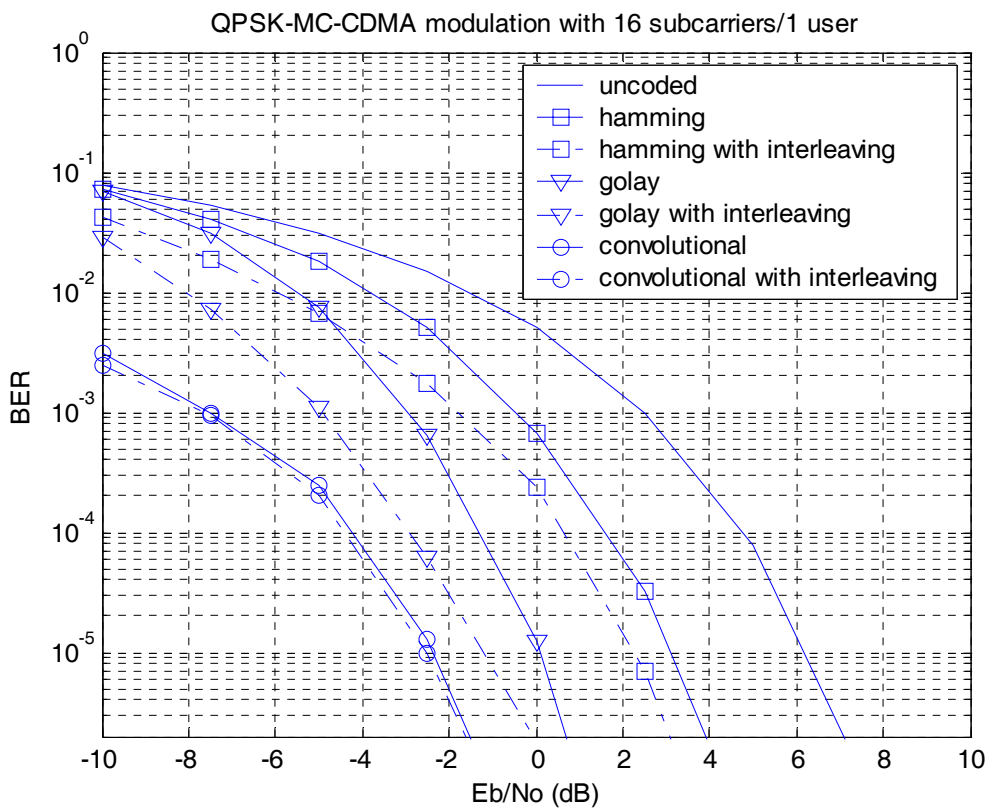


Figure 10: QPSK – MC-CDMA modulation using 16 subcarriers and 32 main carriers
with a single user

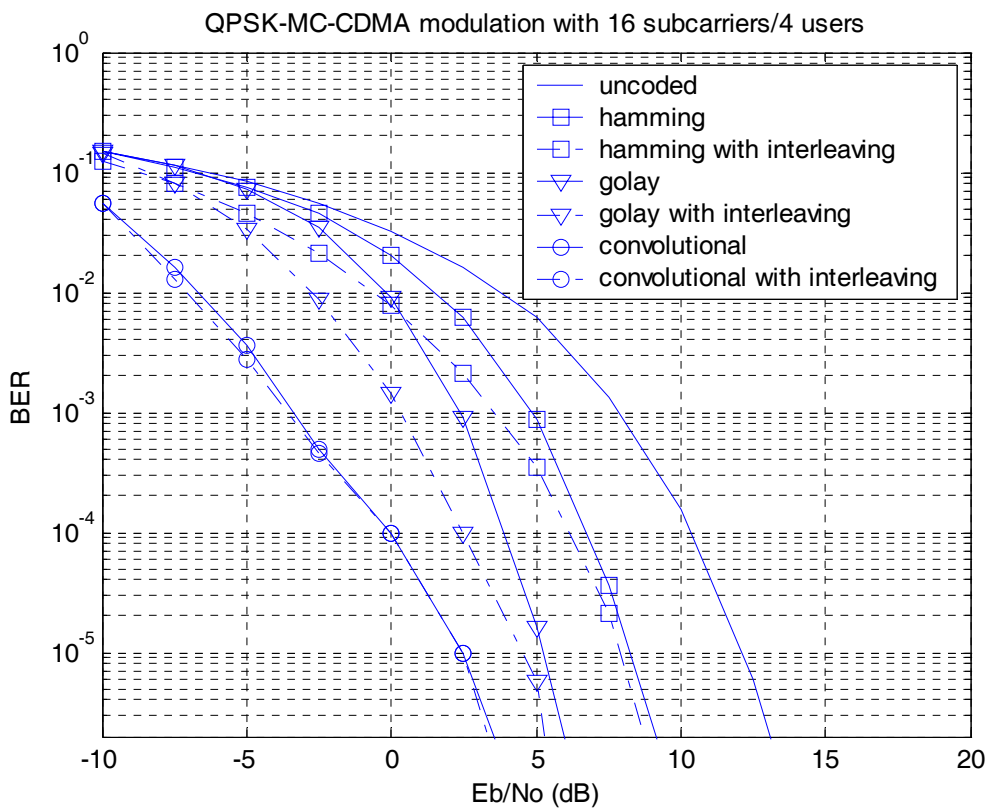


Figure 11: QPSK – MC-CDMA modulation using 16 subcarriers and 32 main carriers with 4 users present

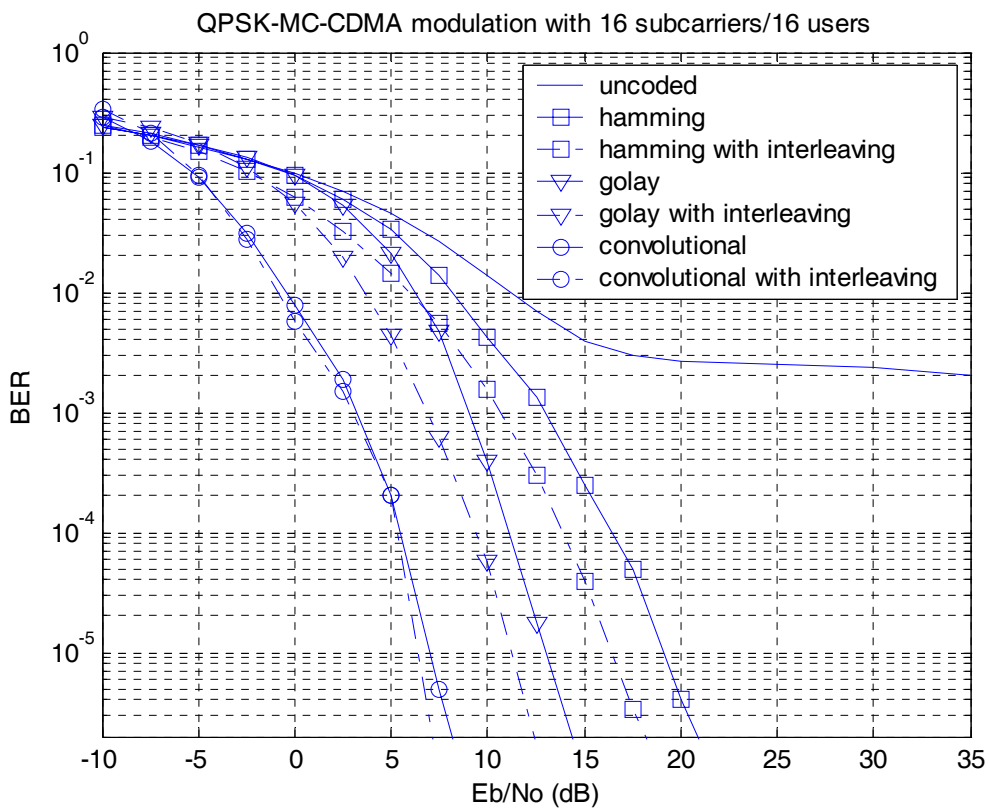


Figure 12: QPSK – MC-CDMA modulation using 16 subcarriers and 32 main carriers with 16 users present

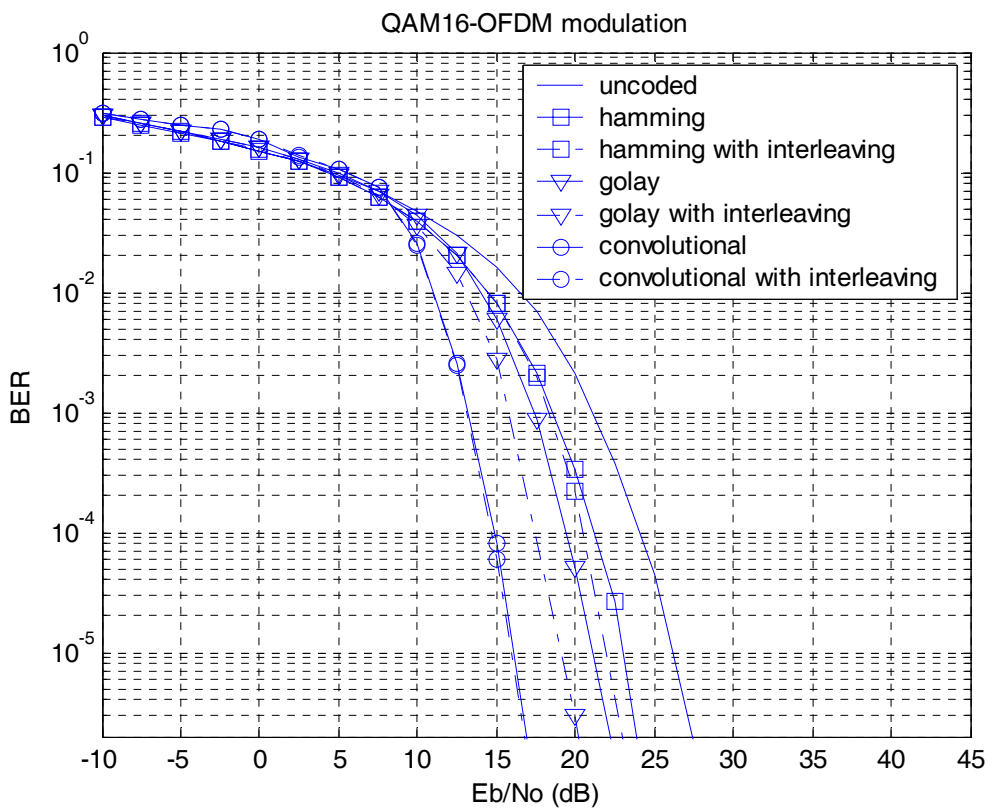


Figure 13: 16-QAM – OFDM modulation

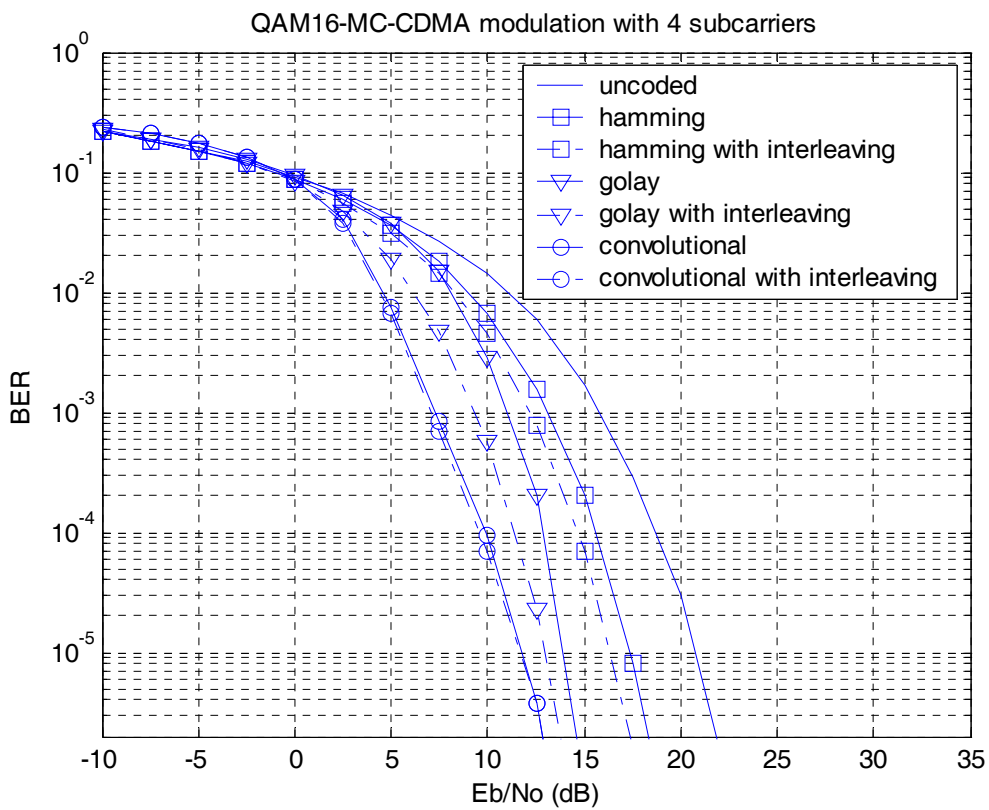


Figure 14: 16-QAM – MC-CDMA modulation using 4 subcarriers and 128 main carriers with a single user

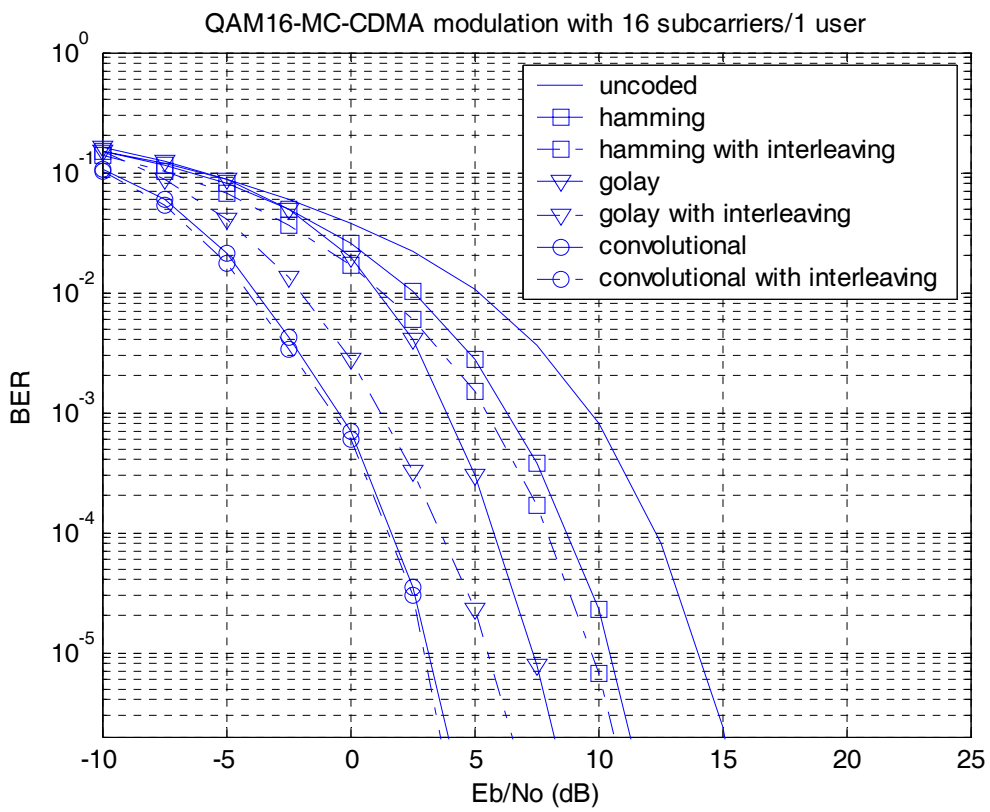


Figure 15: 16-QAM – MC-CDMA modulation using 16 subcarriers and 32 main carriers with a single user

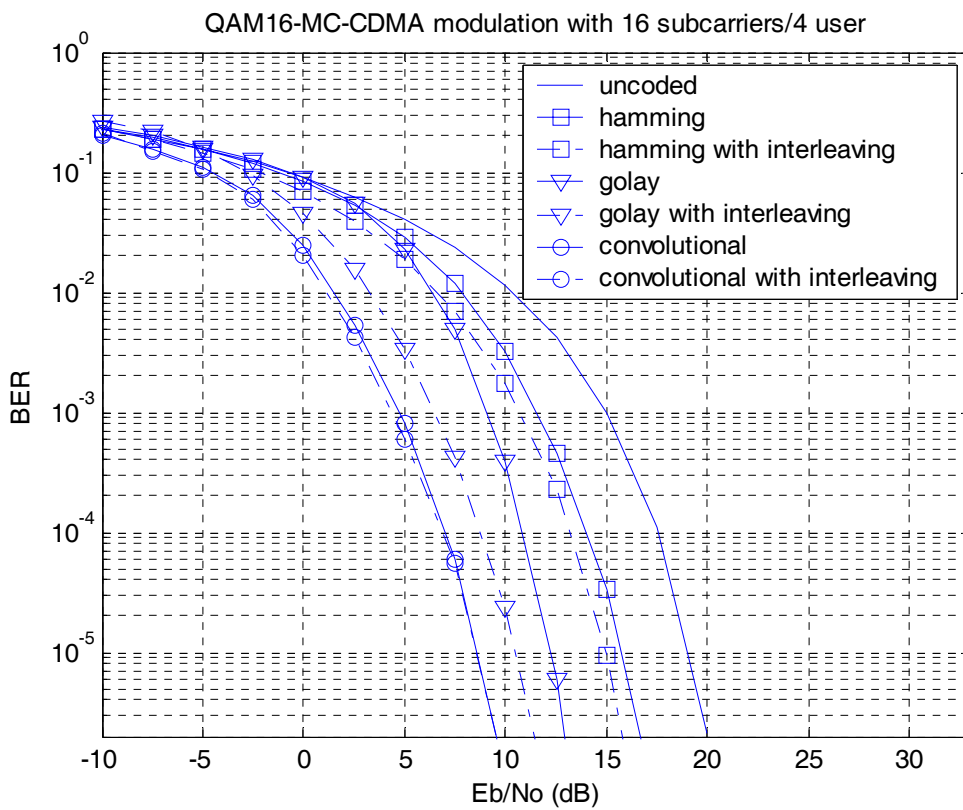


Figure 16: 16-QAM – MC-CDMA modulation using 16 subcarriers and 32 main carriers with 4 users present

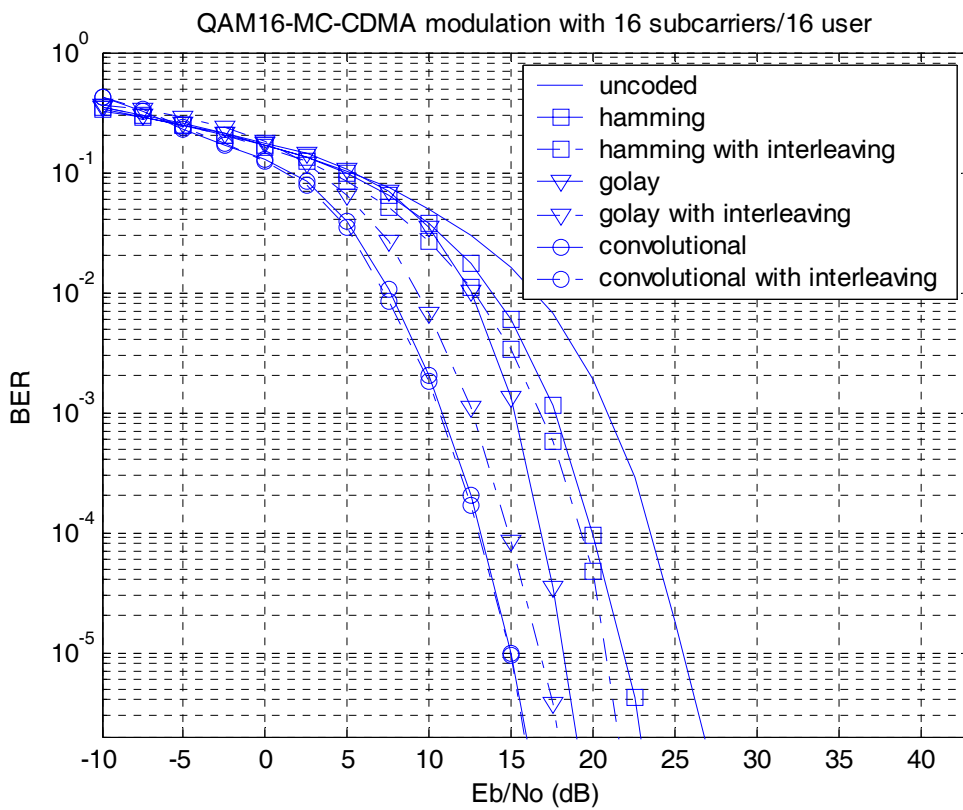


Figure 17: 16-QAM – MC-CDMA modulation using 16 subcarriers and 32 main carriers with 16 users present