Power Efficiency Improvement in CE-OFDM System With 0 dB IBO for Transmission over PLC Network

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Abstract

Orthogonal frequency division multiplexing (OFDM) OFDM has been adopted for high speed data transmission of multimedia traffic such as HomePlug A/V and Mobile WiMax. However, OFDM also has a drawback of a high PAPR (peak-to-average-power-ratio). Due to this high PAPR amplifier usually does not act in dynamic range. One potential solution for reducing the peak-to-average power ratio (PAPR) in an OFDM system is to utilize a constant envelope OFDM (CE-OFDM) system. Furthermore, by utilizing continuous phase modulation (CPM) in a CE-OFDM system, the PAPR can be effectively reduced to 0 dB, allowing for the signal to be amplified with a power efficient non-linear power amplifier with Input Back-Off (IBO) of 0 dB. This paper describes a CE-OFDM based modem for Power Line Communications (PLC) over the low voltage distribution network. Relying on a preliminary characterization of a PLC network, a complete description of the modem is given. Also CE-OFDM is compared with conventional OFDM under HomePlug 1.0 in the presence of power amplifier nonlinearities, considering different values of IBO.

Key words: OFDM, CE-OFDM, PAPR, IBO, PLC, BER.

1. INTRODUCTION

Indoor power line channels are frequency and time selective, with remarkable disparity even among different locations in a specific site. The frequency selective characteristics of indoor power line channels in the frequency band up to 30 MHz have been reported in [1, 2]. Recent studies have extended the analysis up to100MHz [3]. Time variations have a twofold nature: long-term changes caused by the connection and disconnection of electrical appliances and periodic short-term changes, synchronous with the mains, due to the time-variant behavior of the impedance and the noise emitted by the electrical devices. Regarding the noise, it is composed of the following terms: colored back ground noise, impulsive components and narrowband interferences [4].

The orthogonal frequency division multiplexing (OFDM) transmission scheme is suitable for frequency-selective channels because of its ability to cope with this feature by dividing the available bandwidth into N equally spaced narrowband sub-channels [5, 6, 7]. A data stream is distributed to subcarriers (each subcarrier is centred in one sub-channel) and transmitted in parallel. OFDM has two primary drawbacks: The first is a high sensitivity to time variations in the channel caused by Doppler, carrier frequency offsets, and phase noise. The second is that the OFDM waveform has high amplitude fluctuations, a drawback known as the (PAPR) problem. Without sufficient power back-off, the system suffers from spectral broadening, inter-modulation distortion, and, consequently, performance degradation. . There are several techniques for PAR reduction in OFDM systems has been proposed in literature [8, 9, 10].

Constant Envelope OFDM (CE-OFDM) provides one solution to the high PAPR issue in OFDM [11, 12, 13]. The idea of constant envelope OFDM with phase modulation (OFDM-PM) system was introduced. In [14] an approach is presented which transforms the high PAPR OFDM waveform into a 0 dB PAPR CE-OFDM-based waveform called OFDM phase modulation. The significance of the 0 dB PAPR achieved by using phase modulation (PM) is that the signal can be amplified with power efficient nonlinear power amplifier. Although the CPM has low spectral efficiency, it features low system complexity and favorable performance due to low PAR and robustness to amplitude variation and impulsive noise [15], which causes bit errors in data transmission, due to connected electrical appliances such as transformers, industrial switches etc. in the PLC network. The CPM decreases the side lobe of the power spectrum by means of continuously connecting the phase that contains the information. The CE-OFDM-CPM approach described in this paper is based on the phase modulator transform technique. In essence, the OFDM waveform is used to phase modulate the carrier. The OFDM-PM signal can be viewed as a type of digital FM, whereby the modulating phase signal is a real-valued OFDM baseband waveform. In this paper a CE-OFDM modulation will be introduce in order to create a complete picture of PLC channel. Our simulation model is based on the measurements in the real PLC transmission environment.

The paper is organized as follows. In section (2 and 3), we propose a detailed description of the transmitter and the receiver. In section 4, Measurement and simulation results are shown, the effect of load impedance on the Bit Error Rate (BER) performance is investigated. CE-OFDM-CPM is then compared with conventional OFDM under *homeplug 1.0* in the presence of nonlinear power amplification. The effect of the modulation index and modulation order on the BER performance is investigated.

2. CE-OFDM-CPM SIGNAL DESCRIPTION

Consider the baseband OFDM waveform:

$$m(t)=\sum_{i}\sum_{k=1}^{N} I_{i,k}\,q_k\left(t-iT_B\right) \qquad (1)$$

Where { $I_{i,k}$ } are the data symbols and { $q_k(t)$ } are the orthogonal subcarriers.

The CE-OFDM signal is obtained through a simple transformation of OFDM. The OFDM signal is phase modulated onto a carrier signal to obtain a constant envelope signal with 0dB PAPR. This is implemented through a straight forward modification of a standard OFDM system as shown in Figure 1.

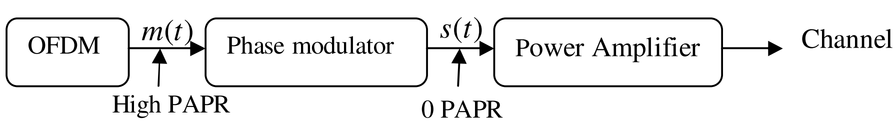

FIGURE 1: The modification of an OFDM system to obtain CE-OFDM

The baseband CE-OFDM signal is,

$$s(t)=Ae^{j\phi(t)} \qquad (2)$$

Where *A* is the signal amplitude. The phase signal $\phi(t)$ with the embedded OFDM signal is given as:

$$\phi(t) = \theta_i + 2\pi h c_N \sum_{k=1}^{N} I_{i,k} q_k \left(t - iT_B\right), \quad iT_B \le t < (i+1)T_B \qquad (3)$$

Where $\qquad \theta(t) = \phi(iT - \varepsilon) - \phi(iT + \varepsilon), \quad \varepsilon \to 0$

The real data symbols $I_{n,k}$ modulate the orthogonal OFDM subcarriers $q_k(t)$. The phase memory θ_i may be used in conjunction with a phase unwrapper at the receiver to ensure a continuous phase at the symbol boundaries and hence better spectral containment [15]. Here h refers to modulation index; N is the number of sub-carriers. The normalizing constant, c_N, is set to where σ_I is the variance of the data symbols, and consequently the variance of the phase $c_N = \sqrt{\frac{2}{N\sigma_I^2}}$ signal will be $\sigma_\phi^2 = (2\pi h)^2$. Assuming that the data is independent and identically distributed, it follows that $\sigma_I^2 = \frac{M^2 - 1}{3}$.

The signal energy E_s and the bite energy E_b are

$$E_s = A^2 T_B \,, \qquad E_b = \frac{E_s}{N \log_2(M)} \qquad (4)$$

To guarantee continuous phase, the memory terms set to

$$\theta_i = K \sum_{l=0}^{\infty} \sum_{k=1}^{N} [I_{i-l,k}\, A_b(k) - I_{i-1-l,k}\, A_e(k) \qquad (5)$$

Where $\qquad K = 2\pi h c_N \,,\; A_b(k) = q_k(0) \,,\; A_e(k) = q_k(T_B - \varepsilon) \,,\; \varepsilon \to 0 \,.$

The benefit of continuous phase CE-OFDM is a more compact signal Spectrum. The CPM decreases the side lobe of the power spectrum by means of continuously connecting the phase that contains the information. CPM features low system complexity and favorable performance due to low PAR and robustness to amplitude variation and impulsive noise [16].

3. PM RECEIVER

A practical receiver such as the PM receiver can be used for CE-OFDM. It consists of a phase demodulator to undo the transformation followed by a standard OFDM demodulator as shown in Figure 2. Although this results in a sub-optimum receiver, it provides for a simple and practical receiver implementation.

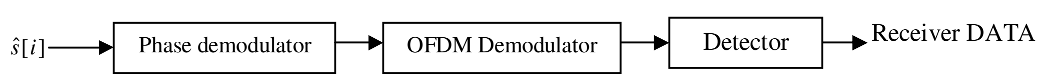

FIGURE 2: The modification of a standard OFDM receiver to obtain a CE-OFDM receiver

The CE-OFDM-CPM is a modulation format that can be viewed as a mapping of the OFDM signal onto the unit circle. The resulting signal has a constant envelope leading to a 0 dB PAPR. The OFDM signal is transformed through continuous phase modulator to a low-PAPR signal prior to the PA and at the receiver, the inverse transform by a phase demodulator is performed prior to OFDM demodulation as shown in Figure 3. The phase demodulator receiver is a practical implementation of the CE-OFDM-CPM receiver and is therefore of practical interest. However, it isn't necessarily optimum, since the optimum receiver is a bank of MN matched filters one for each potentially transmitted signal.

The phase demodulator receiver essentially consists of a phase demodulator followed by a conventional OFDM demodulator. The received signal is first passed through a front-end band pass filter, which limits the bandwidth of the additive noise [14]. An arg(·) operation to calculated the phase of the received samples, and a phase unwrapper to eliminate of phase ambiguities. This receiver is shown to be insensitive to phase shifts caused by the channel. It is shown that with the introduction of memory, CE-OFDM is made phase-continuous and,

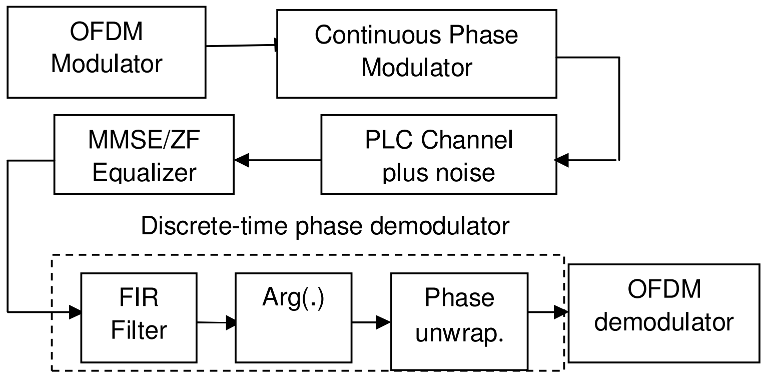

FIGURE 3: CE-OFDM-CPM block diagram

consequently, has a more compact spectrum. An additional bonus of the non-coherent receiver is it demodulates continuous phase CE-OFDM signals with no added complexity.

4. MEASUREMENT AND SIMULATION RESULTS

4.1. Measurement Results

We have made frequency response measurements for in-building power line channels in the frequency range of (1–100 MHz). As can be seen in figure 5, the frequency response exhibits considerable frequency dependent variation, due to the specific wiring configurations encountered. The frequency dependent channel fading is the result of reflections and multipath propagation. One main source for reflection and multipath propagation is impedance discontinuity. At impedance discontinuities part of the transmitted signal is reflected. The received signal is an addition of the reflected signal and original signal. The signal can be constructive or destructive, in which case signal fading may be generated. There are many possible reasons for impedance discontinuity, such as change of gauge of wires connected to each other, connected loads or branch wires, etc.

4.2. Influence of Load Impedance

This study is emphasized here because, it is common that the loads at the termination of branched lines are not always line characteristic impedance or resistive, rather it could be a case dependant arbitrary load, like, low or high impedance (R type) compared to line characteristic impedance and practical load impedance (RL type) representing transformers, machines, etc.

Domestic appliances connected to the power line network have impedances that are going to be decisive on the transfer function: the signal will either be absorbed by these impedances, or reflected on the network. These impedances vary with frequency and their impact of the transfer function will be significantly different.

Now, we consider the topology shown in figure 4 for studying the effect of load on the transfer function, which can be altered when connecting new load. The load impedances at point D in figure 1 were varied as 20 Ω, 50 Ω, 100 Ω, 200 Ω and characteristic impedance. The length of the branch BD is 10m.

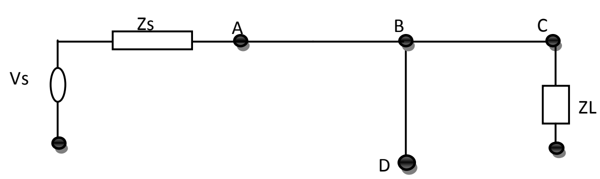

FIGURE 4: Power line network between sending and receiving ends

Figure 5 gives the transfer functions magnitudes measured by network analyzer in downlink from a household for the configurations below and between 1 MHz and 100 MHz. In the presence of load impedances on the network, the channel attenuation is faster, especially in the case of 50 Ω where it reaches a value of -16 dB at 1 MHz.

For the load impedances less than channel characteristic impedance the position of notches is unchanged with no attenuation. It is interesting to observe that when the load impedance lowers the notches are at 40dB. As the load increase the peaks are increase and the notches decrease.

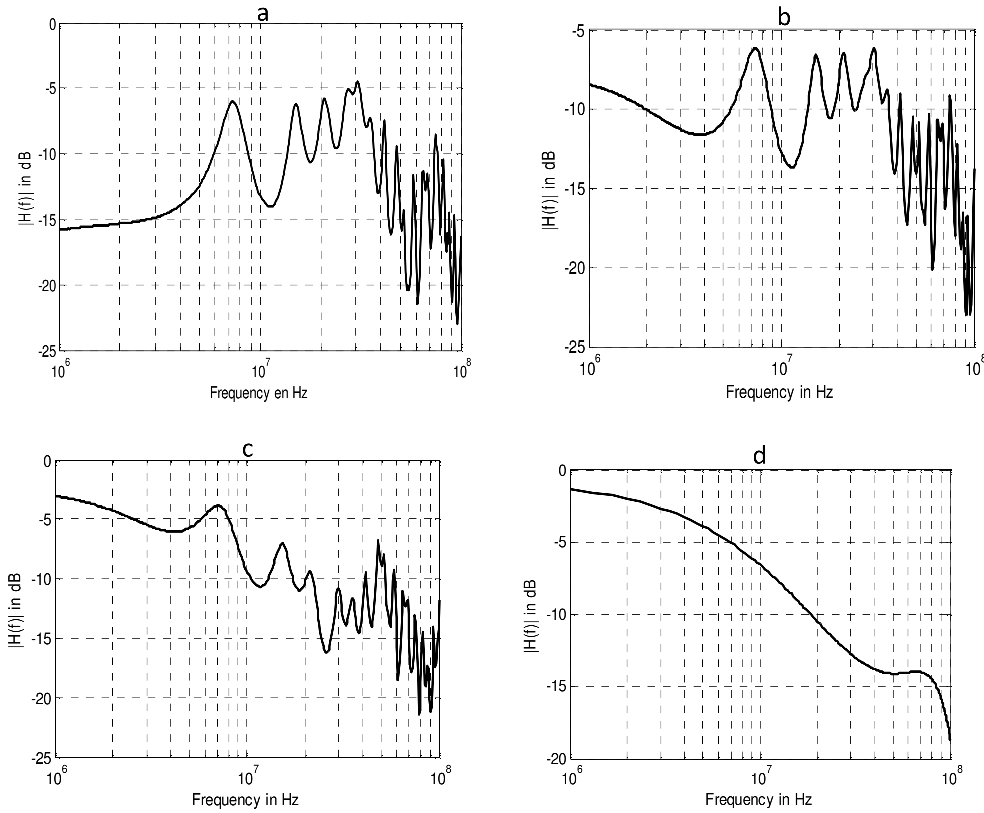

FIGURE 5: Experimental measurements of frequency response magnitude, (a) 50 Ω, (b) 100 Ω, (c) 200 Ω and (d) characteristic impedance

4.3. Simulation Results

The BER performance of CE-OFDM-CPM over PLC channel is evaluated using computer simulation. The parameters of the representative CE-OFDM-CPM system used for this study are demonstrated in Table I. The simulation results are performed with L = 15 length Hamming window FIR, having a normalized cutoff frequency f_c = 0.4.

M	Modulation order	4
$2\pi h$	Modulation index	0.3, 0.6, 0.8
N	Number of subcarriers	512
A	signal amplitude	1
J	Oversampling factor	4
N_B	Samples per symbol	2048
N_g	Samples per guard interval	384
N_F	Samples per frame	2432

TABLE 1: CE-OFDM-CPM parameters system

4.3.1. Effect of Impedance Loads on BER Simulation

The signal-to-noise ratio (SNR) is defined as E_b/N_0, where E_b is the received energy per information bit and N_0 is the mono-lateral power spectral density.

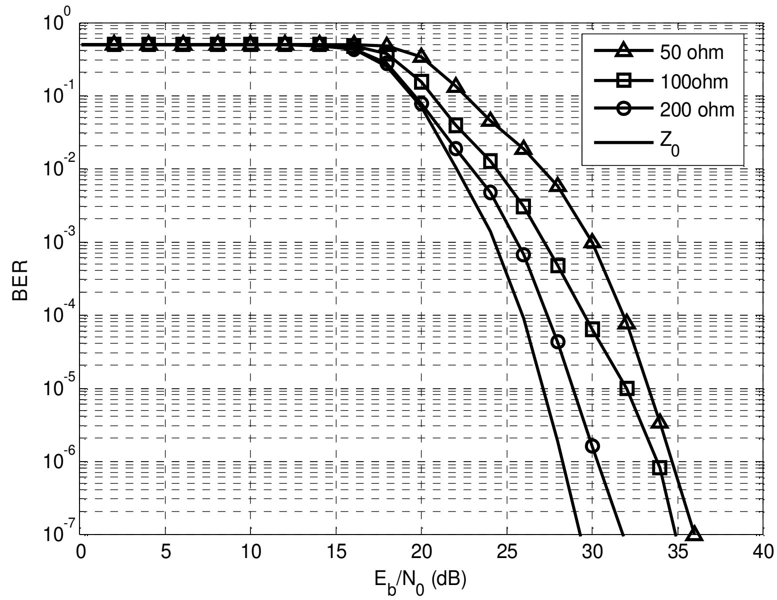

FIGURE 6: Simulation results for the CE-OFDM-CPM system with 4-QAM modulation for PLC channel for various load branch impedances ($2\pi h = 0.6$, M=64)

Figure 6, shows the performance of the CE-OFDM-CPM system for various load impedance cases. It is observed that the good performance can be obtained when the channel is terminated in characteristic impedances wherein the bit error probability is 10^{-7} at a E_b/N_0 per bit of 29 dB. The power is 32dB, 35dB and 36dB for 200 Ω, 100 Ω, and 50 Ω respectively. However, as the load impedance approaches a short circuit a degraded system performance is found. This is due to the fact that at short circuit, higher deep notches exist in the system. It is shown that the performance of PLC channel can be affected due to multipath phenomena. We have shown that the variations in the load terminations of those branches result in poor channel performances. On the other hand for lower terminal impedances in the range of few Ohm the channel shows a degraded performance. The findings presented in the paper can be used to improve the channel performance at design phase using interleaved coding techniques, channel precoding and channel equalizations methods, etc.

4.3.2. Effect of Modulation Order and Modulation Index on BER Simulation

Figure 7, shows simulation results for M = 4, 8, 16, 32, 64 and 128. The bit error rate is plotted against the E_b/N_0. There are two main observations to be made. The first, for a fixed modulation index, CE-OFDM-CPM has improved spectral efficiency with increase modulation order M at the cost of performance degradation. For example consider 2πh = 0.3, the spectral efficiency is 2, 3, 4, 5, 6 and 7 b/s/Hz for M = 4, 8, 16, 32, 64 and 128 respectively. The second, from figure 7, it can be seen that with M increasing the system requires augmenting the E_b/N_0 in order to achieve a certain BER. For example consider 2πh=0.8, if M=4, to achieve BER of 3.10^{-7} the E_b/N_0 need to be only about 23dB. And if M=8, 16, 32, 64 and 128 to achieve the same BER, the E_b/N_0 need to be 26 dB, 33 dB, 37 dB, 42 dB and superior to 50 dB respectively. So M should not take too large value when E_b/N_0 is limited. However, the larger M is, the higher the maximum data transmission rate of the system is.

In the case of 2πh=0.8 it can be seen that, if let BER≤ 10-6, the system can achieve about 32Mbit/s and 112Mbit/s data transmission rates when the SNR are about 22 dB and 48 dB respectively.

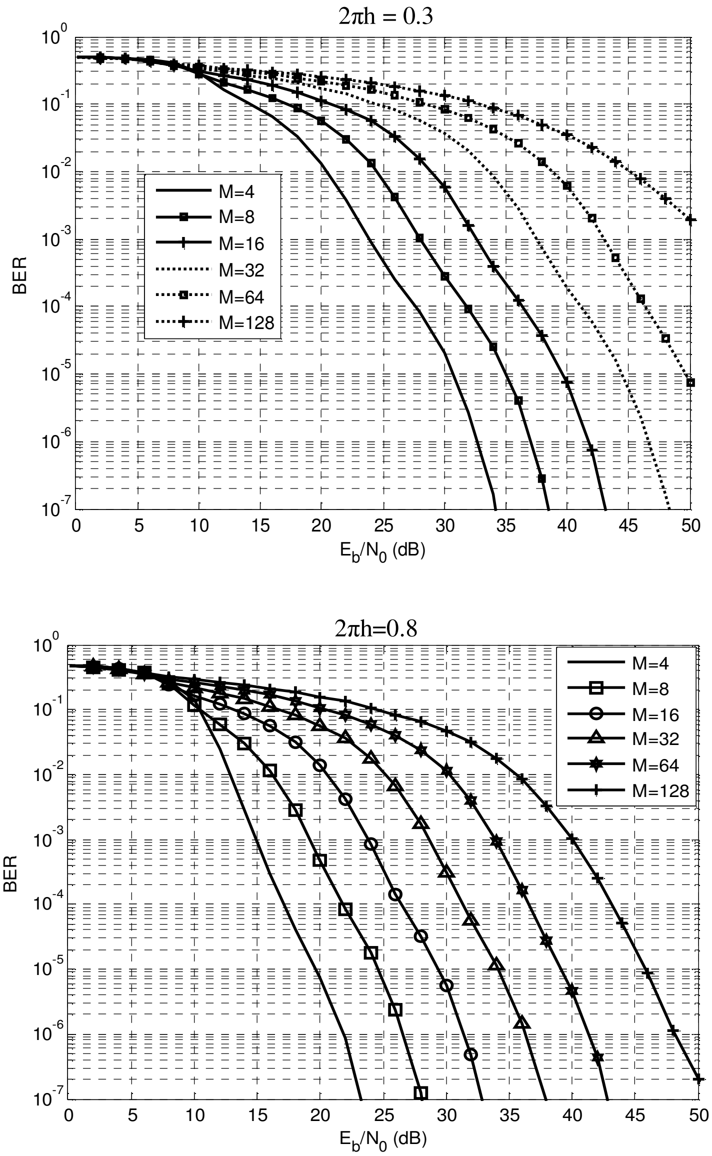

FIGURE 7: BER of CE-OFDM-CPM systems in PLC channel. (N=512, J=4, MMSE)

4.3.3. OFDM versus CE-OFDM

➢ *Solid-State Power Amplifier Model*

The nonlinear AM/AM characteristic of the solid-state power amplifier (SSPA) used in our simulations has been modeled by a memory less block with input-output relationship given by [17],

$$s'(t) = g[s(t)] = \frac{g_c \cdot |s(t)|}{\left(1+\left(\frac{|s(t)|}{s_{sat}}\right)^{2p}\right)^{\frac{1}{2p}}} e^{j\arg\{s(t)\}} \qquad (7)$$

Where g_c is the amplifier gain associated to a given peak-power P_p, the parameter p controls the smoothness of the transition from the linear region to the saturation region and s_{sat} is the saturation amplitude parameter, i.e., s_{sat} indicates at which amplitude the transition between linear and saturation region is located. The amplifier IBO is defined as

$$IBO = {s_{sat}^2}\Big/{\sigma_s^2} \quad (8)$$

so that the reference power is determined by the saturation parameter s_{sat}. Following this IBO definition, IBO=0 dB represents a condition in which the power of signal at the input of the SSPA is $\sigma_s^2 = s_{sat}^2$, i.e., the input signal is characterized by dynamic greater than s_{sat}, driving heavily the SSPA into the saturation region. For CE-OFDM, the PAPR is 0 dB, and nonlinear distortion is avoided. CE-OFDM-CPM operates at IBO=0 dB, maximizing the range and efficiency of the PA [18]. For OFDM, *s(t)* is Rayleigh distributed [19] resulting in a large PAPR. To avoid nonlinear distortion, large back-off is required, reducing range and PA efficiency [20], [21].

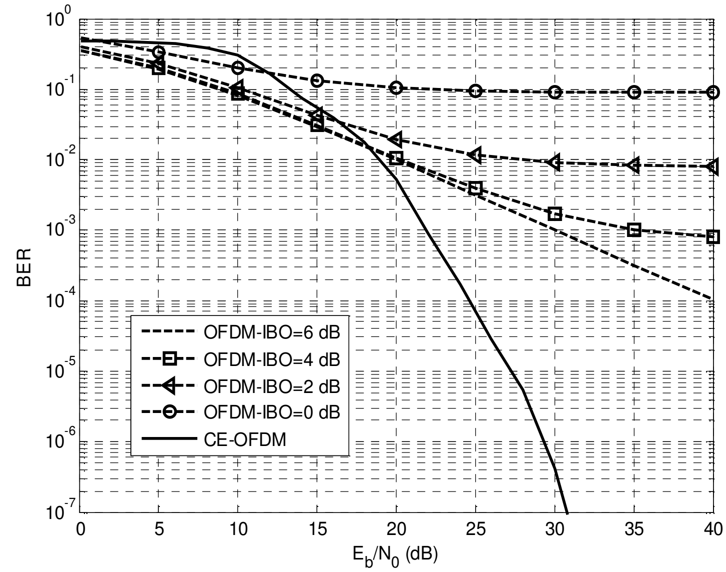

FIGURE 8: CE-OFDM-CPM versus OFDM under *HomePlug 1.0*

in power amplifiers (PA), the most efficient operating point is at the PA's saturation point, but for signals with large PAPR the operating point must shift to the left keeping the amplification linear. The average input power is reduced and consequently this technique is called input power back-off (IBO). At large back-off the efficiency of a power amplifier is very low. Such efficiency is detrimental to mobile battery-powered devices which have limited power resources. Here we assume that we need IBO 0=dB. In our simulation we considered AM/AM characteristic to model SSPA with peak-power P_p=10 W, g_c =5, *p=3* and S_{sat}=1.18w.

In figure 8, the performance of CE-OFDM-CPM is compared with the conventional OFDM over PLC channels under *HomePlug 1.0*, considering different values of IBO. In this case 2πh=0.8 and M=16. Over the region 0dB≤ E_b/N_0 ≤15dB and for (IBO> 0dB), the OFDM system performs better than the CE-OFDM-CPM system. However At high E_b/N_0, CE-OFDM-CPM is shown to outperform OFDM. On the other hand, one can conclude that for IBO value of 0 dB the CE-OFDM-CPM system outperform the OFDM system: this is justified by the fact that the SSPA operates at a nonlinear point such that the OFDM signal is heavily distorted. As a consequence, the BER curves obtained with the OFDM system are affected by (i) errors generated by thermal noise,(ii) signal distortion.

Making a direct comparison between CE-OFDM-CPM and conventional OFDM is difficult due to the various parameters involved (M, 2ph, IBO, etc.), and due to the fact that system requirements vary from system to system. For example, if power amplifier efficiency is the most important requirement, then the input power back-off of 0dB should be chosen. At this back-off level, the OFDM system has a very high irreducible error floor due to the power amplifier distortion, while the CE-OFDM-CPM system is relatively unaffected. Alternatively, if operation at low E_b/N_0 is important, then CE-OFDM-CPM may not be well suited due to the threshold effect.

5. CONCLUSION

In this paper a transformation technique that eliminates the PAPR problem associated OFDM is developed. The phase modulation transform results in 0 dB PAPR constant envelope signals ideally suited for nonlinear, efficient amplification. The main advantage of the CE-OFDM-CPM is to reduce the PAPR to 0 dB which improves power efficiency and improvement in BER performance is achieved over conventional technique.

Results of BER simulations for different channel response are presented. As the terminal impedances on the branches increase to line characteristic impedance, the signal attenuation and distortions tend to reduce. CE-OFDM is shown to compare favorably to conventional OFDM in PLC channels when the impact of nonlinear power amplification is taken into account. CE-OFDM-CPM is also shown to suffer from the FM threshold effect, however. Potential solutions to this problem, including threshold extension with phase locked loops, are discussed.

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