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Performance Evaluation of an adaptive OFDM-based PLC System with an Impulsive Noise Environment

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Abstract:

Power Line Communication (PLC) is an interesting approach in establishing last mile broadband access in rural areas. PLC provides a ready medium for broadband internet connectivity and as well as monitoring and control functions for both industries and homes. In fact, PLC network is the most expansive network in the world reaching every room. However, it provides an available channel that is hostile when used for communication purposes. This hostility is due to the many problematic characteristics of the PLC from a communications perspective. They include reflections due to impedance mismatch, multipath due to the cable joints, as well as the different types of noise inherent in the channel. In this paper, we are interested by the impact of impulse noise on the performance of an adaptive OFDM based PLC system. The article presents a design of the PLC model, which is composed of communication model, model of power line and noise model. The communication model is realized as an adaptive OFDM system, power-lines are modelled like a multipath channel. Noise model is modelled as white noise in addition to the impulsive noise, the mathematics behind the impulse is utilized in an attempt to fully characterize the impulsive noise. The impedance mismatching is considered and, with the channel model, are estimated at the receiver. On the resulting PLC communication model was shown comparison of different modulation technique with the adaptive system. Different schemes were simulated to compare the bit error rate (BER) for different impulsive noise parameters.

Key words: power line, OFDM, impulsive noise, impedance mismatch, modelling, modulation, and channel estimation.

1. Introduction

Most of us today have a wireless network in our homes to enable us to enjoy unfettered access to the internet and share data between PCs and networked peripherals like printers. More recently the trend towards connecting into home entertainment devices using ethernet ports to connect to TVs, Blu-ray players, and gaming devices has become increasingly common place. Kaspersky Labs estimates that the current number of UK homes with a wireless LAN installed is around 57 per cent. Ofcom estimates that 1.5 million households (out of a total of approximately 22 million households) have deployed PowerLine Technology to connect them up. The most interesting aspect regarding PLC is the ability to use existing infrastructure for signal transmission, reducing deployment costs. Until recently the biggest problem for PLC was the low distance coverage and low data rate which was eliminated with the introduction of new standards.

The PLC is a need to use distribution lines of electricity for the control signals, IP telephony transfer, and remote data acquisition [Mlynek 2008], [Achmad 2007], and [Koinakis 2009]. It comes up almost simultaneously with electrical power network developing. This technology becomes more and more important. The PLC technology should be as an alternative to other existing data channels [Orgoň 2007].

PLC technologies are mainly classified into two; narrowband and broadband depending on the frequency band of operation. Broadband PLC operates in the frequency range between 1MHz to 300 MHz. Narrowband PLC operates in the frequency range between 3 kHz to 500 kHz. PLC networks also form part of local area networking solutions [Berger 2013] [Ferreira 1996]. However, the PLC channel is a hostile environment for use as a communications media. This is primarily so because, the channel characteristics are highly varying with frequency, time, loads and topology. The channel is also plagued with different sources of noise which are difficult to effectively describe parametrically. The main noise types in PLC include background noise, narrowband interference and impulse noise. Also the signal is attenuated as it traverses the channel from the transmitter to the receiver. This attenuation is mainly dominated by frequency selective fading. The proper choice of modulation techniques, channel estimation techniques, and impedance mismatching correction methods for the PLC channel is a thorny issue [Berger 2013], [Ferreira 1996] [Zwane 2014], [Lazaropoulos 2012], [Zimmermann 2002], [Mulangu 2011] and [Mulangu 2012]. The biggest threat to PLC performance is noise; and impulsive noise is the most dominant. This noise and its impact on the performance of an adaptive OFDM based system is the main focus of this paper.

2. Impulsive Noise

Impulsive noise is the most severe form of noise in PLC channels. It is mainly caused by the switching ON/OFF of electrical appliances or faults in the network. It is classified into three main categories [Zimmermann 2002]:

1- Impulsive noise that is synchronous with the mains frequency and is periodic: This type of impulsive noise is cyclostationary and is synchronous with the mains frequency. It is generated by silicon controlled rectifiers in different power supplies.
2- Impulsive noise that is periodic but asynchronous with the mains frequency: This category of impulsive noise is generated by periodic impulses whose repetition rates are between 50 to 200 kHz.
3- Asynchronous impulsive noise: This kind of impulsive noise is very unpredictable and is the most dominant. It exhibits

no regular occurrence and mainly arises from transients that originate from the connection or disconnection of electrical appliances from the power line network. The impulses can last for between some microseconds and a few milliseconds with a random occurrence. The power spectral density for this kind of noise can go as high as 50 dB above the background noise. It is also sometimes referred to as sporadic impulsive noise.

The four basic parameters that describe impulsive noise are the impulse width t_w, arrival time t_{arr}, inter-arrival time t_{IAT} or the impulse distance t_d and the impulse amplitude, A. The impulse width is the time duration that an impulse event lasts. The inter-arrival time is defined as the time difference between the start of two consecutive impulse events. The impulse distance is the time between the end of an impulsive event and the beginning of another. Thus, it defines the frequency of occurrence of the impulsive noise. The three basic impulsive event time parameters are related by the following expression:

$$t_{IAT} = t_w + t_d = t_{arr,i+1} - t_{arr,i} \qquad (1)$$

And, using a general impulse function *imp(t)* with unit amplitude and unit width, a train of impulses can be described by [Zimmermann 2000]:

$$n_{imptrain}(t) = \sum_{t=1}^{N} A_i . imp\left(\frac{t - t_{arr,i}}{t_{w,i}}\right) \qquad (2)$$

where $n_{imptrain}(t)$ is the train of impulses. The parameters A, t_w and t_{arr}, can be used to derive secondary parameters that are crucial in analysis of impulse noise and studying its behavioural characteristics over time. One of these secondary parameters is the impulse rate, given by [Zimmermann 2002]:

$$r_{imp} = \frac{N_{imp}}{T_{win}} \qquad (3)$$

where N_{imp} is the number of impulses that occur within a given window of observation T_{win}. Another key aspect would be the actually disturbed time, which can be determined from the "disturbance ratio"; which by definition is the ratio of the sum of the widths of all impulses generated within a window of observation, and the length of the window, that is [Zimmermann 2002]:

$$disturbance\ ratio = \frac{\sum_{i=1}^{N_{imp}} t_{w,i}}{T_{win}} \qquad (4)$$

3. System Model

For a creating of the complete PLC communication system, there is necessary to create model of channels as well as noise model and a transmitter and a receiver models. The complete PLC model will be created from particular models. There will be possible to create analysis of a concrete power line based on the simulations of this system with various models of lines. The analysis will be possible to judge in term of possibility to using of various combinations of PLC technologies, security transfer, modulations etc. So that there will be obtained to best parameters of data transfer in mentioned systems. It is necessary to create the channel models for the PLC simulation. There are more possibilities of power line model creating. First of them is the power line model as environment with multipath signal propagation. The parameters of this line are obtained from a distribution network topology or based on metering. Second of them is model, which applies chain parameter matrices to describing the relation between input and output voltage and current by two-port network.

In design of PLC system, it is necessary to bear in mind the character of transmission medium and interferences which the PLC communication is influenced. It is necessary to find useable guard interval, modulation technique and encryption to ensure of security and fool proof communication with smallest error rate between data source and receiver. The PLC communication system is possible to divide to particular parts for purpose of modelling:

1- PLC communication model
2- Models of power lines,
3- Noise model.

3.1. The PLC communication model: Adaptive OFDM

The model of PLC communication is created by a transmitter, receiver and channel block. It serves for a creating of a source and destination of data communication for subsequent simulations of lines model which they are replaced by block of channel. The basic PLC communication model with OFDM system is shown in the Fig.1

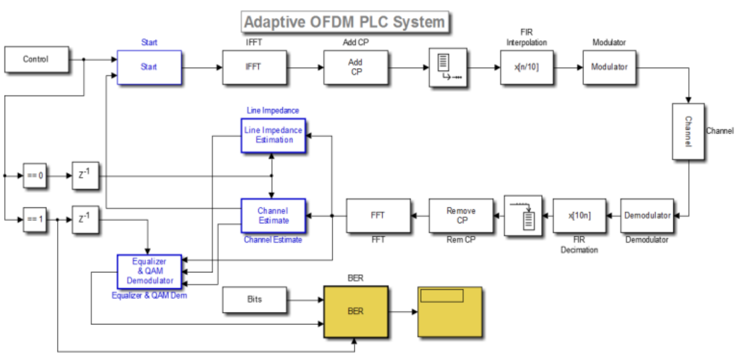

Figure 1: The Adaptive OFDM based PLC system.

The control block is used only for enabling or disabling some functionalities of the system, like the estimation/equalization schemes, the start block is responsible of generating the random stream of bits and selecting the corresponding mapping in each sub-carrier with respect to the SNRs estimated by the channel estimation block. No error correcting code is used which in addition to an interleaver can improve the performances presented below. A stream of symbols is resulting from the mapping; this serial data obtained is converted to parallel and the pilots are added which are necessary to include to the transmission in case of continuous channel estimation. The estimation is important for determination of amplitude and phase of map's constellation each of subcarrier. The estimation of the channel in an OFDM system requests a inserting of known symbols or a pilot structure to the OFDM signal. The number of parallel streams resulting from the data and pilots should match to the number of carriers. IFFT block transforms data from frequency to time domain. A protect interval is used in OFDM to prevent of ISI (inter symbol interference). A cyclic prefix (CP) is created by a few of last samples of OFDM symbols. CP creates a protect interval between adjacent transferred OFDM symbols in time area. This is a way how to keep orthogonally carries. Again, the parallel streams are converted into serial, and an interpolation filter is used to convert the digital signal into analog to be upconverted by the modulator to a certain carrier frequency, here, f_c = 46.5 MHz.

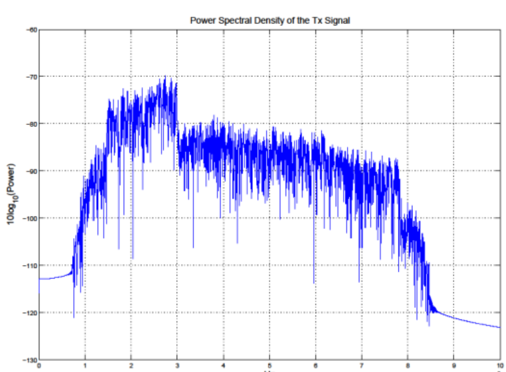

Figure 2: The transmitted signal

Figure 2 shows the power spectral density of the transmitted signal. The variation in the power level presented in Fig.2 is due to the different level of mapping, so different power level, used in the transmitted signal.

After the channel which is considered as a multipath channel in addition to the noise sources added, the receiver's blocks will do the inverse work of the transmitter's blocks. So the demodulator will down-convert the signal into baseband, and the decimation filter is used to digitize the signal. The cyclic prefix is removed and the signal is transformed into frequency domain. The most important blocks here are: the line impedance estimation, the channel estimation, and the equalization & detection blocks.

The line impedance estimation block works only in the first channel use, where all the data sent from the transmitter are known at the receiver and used for this estimation. This block is represented in Fig. 3, it is very simple where we should make a certain division with the known data (Training) and after that an average is done to obtain the impedance estimated on each sub-carrier. These impedances are forward to the channel estimation block and the equalization & detection block for the next channel use.

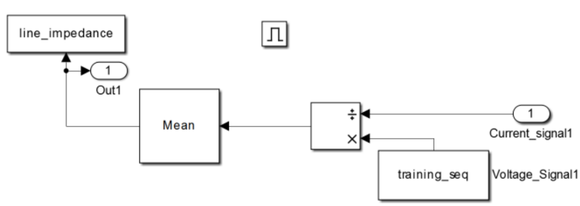

Figure 3: The block diagram of impedance estimation.

For the second channel use, the impedance estimator will be disabled and the channel estimator block and the equalizer block can work normally starting from this second channel use until the end of the connection. In this time, the signal contains information data and a small training sequence used by the channel estimator represented in Fig. 4.

The channel estimation block is responsible of estimating the channel taps and estimating the SNR on each sub-carrier. The estimation of the channel taps is done simply by doing a division between the known training sequence and the corresponding received sequence, since we work here in the frequency domain. For the SNRs estimation, we are obligate to work in each sub-carrier trying to separate the noise from the desired signal, and compute the power of desired signal divided by the power of the estimated noise. When we obtain these SNRs, they will be sent back to the transmitter and saved at the receiver for the next use, which choose the mapping level on each subcarrier in corresponding to the SNRs received and a certain threshold chosen by the method represented by $S(i)$ in Fig. 5 and memorized in the start block at the transmitter.

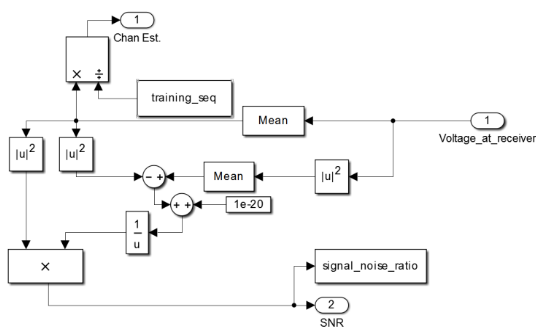

Figure 4: The block diagram of channel estimation

Since we work in the frequency domain here after the FFT, so the equalizer's work is very simple, it has just to divide the received sequence by the estimated channel (make sure that the estimated channel is in frequency domain). The resulting sequence is than demapping with a different de-mapper on each sub-carrier. Finally the bit stream outputted by the de-mapping is compared with the random bits generated at the transmitter and the BER is calculated.

The transmission rate (or spectral efficiency) of each transmission is basically determined by the modulation and channel coding combination. Three main modulation schemes are considered here: i) Quadrature Phase Shift Keying (QPSK), ii) 16-Quadrature Amplitude Modulation (16-QAM) and iii) 64-

QAM. In each case, the modulation efficiency is equal to the number of bits per symbol that can be sent. If the channel coding is used the efficiency is multiplied by the coding rate. According to a fixed Target BER, which accounts for application or service types, the minimum SNR threshold is set to achieve the desired mapping scheme as shown in the Fig. 5. We note here that the target BER chosen for those values are assumed to be equal to 10^{-3}, but in general it may to take a positive value depending on the service offered.

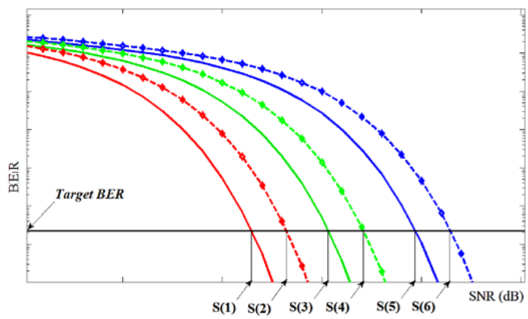

Figure 5: SNR thresholds selection for different mapping

3.2. PLC Channel and Additive Noise Model

Besides simulation of communication system characteristic, it is necessary to identify possible sources of interference and noise because the power line has a significant attenuation of signal and various noises. Therefore the data transfer has a high error rate without any checking algorithm. The fundamental influence on data transmission over power lines are mainly the negative characteristics of power networks. These characteristics can be summarized in:

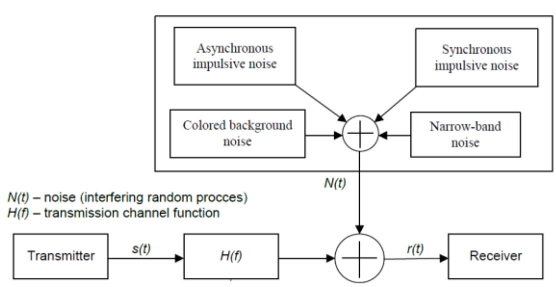

Figure 6: PLC channel model.

1- Mismatched impedance
2- Attenuation on the communication channel
3- Noise and Noise changing in time.

Figure 6 shows a simplified block model of the PLC channel, in which the described characteristics and parameters are included. The parameters of interference, except noise, are represented as a time variable linear filter described by the frequency parameters. Noise is depicted as additive random process. This model captures the whole range of parameters which are necessary for a model of the communication system with corresponding characteristics, although this model is schematically simplified in the figure. The impulse response of the linear filter and the noise can be either estimated from the measurement or derived from the theoretical analysis. Here, they are computed by a huge number of measurements and the average of all taken measurements is considered as a representative model for the linear filter and the summation of different type of noise presented in Fig. 6. The impulse response and the frequency response of the linear filter is represented in Fig.7 and figure 8 shows an one shot time domain value of the noise considered here.

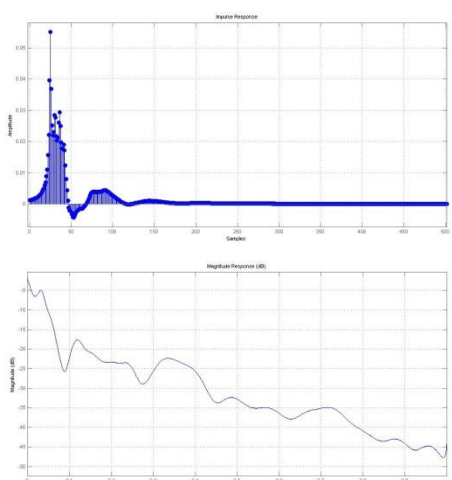

Figure 7: The time variable linear filter model used

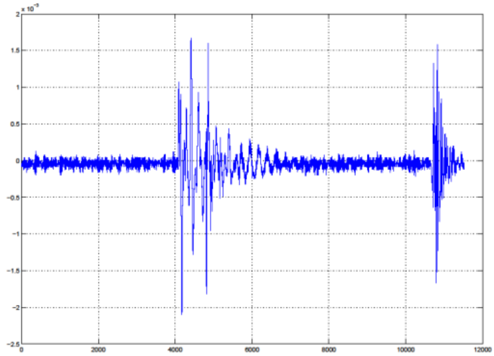

Figure 8: One shot time domain representation of noise

4. Simulations Results and Analysis

A key performance index to evaluate the performance is the BER given a received SNR over the considered channel presented above. We consider a received SNR from 0 up to 100 dB and examine the BER. The received signal to noise ratio is considered here as E_b/N_0 where E_b is the received energy per bit, and N_0 is the total noise power spectral density. Monte Carlo simulation by MatLab is used to obtain the results shown in the following figures; in despite that the block diagrams shown before were done using Simulink. For the evaluation, three mapping levels, QPSK, 16QAM, and 64QAM are considered and finally, compared with the adaptive based OFDM system over a PLC channel.

4.1. Comparison of different mapping level

The testing of different types of modulations for data communication over power line has been accomplished on created model. Figure 9 shows a comparison of the QPSK, 16QAM, 64QAM, and 256QAM modulations in OFDM system. Here, the amplitude of the impulsive noise is considered equal to 1 (A=1); in despite that it can be much smaller than this value. The idea behind this assumption was to compare the effect of the modulation alone.

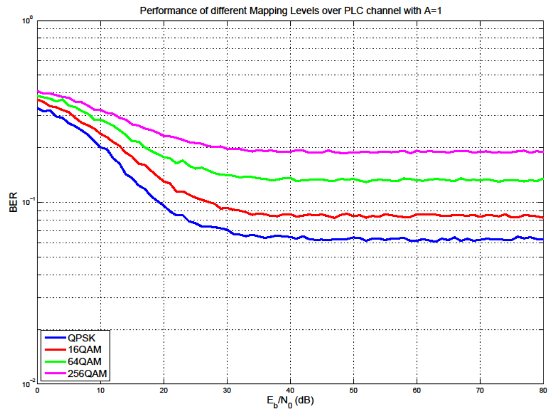

Figure 9: Performance of different mapping levels (*A*=1)

The results in Fig. 9 show that the performance of all mapping levels are very bad, this because of our assumption, in despite that the performance of QPSK is much better than the others, and the performances decrease when the mapping level increase. This conclusion can be done easily when we compare these mapping levels over AWGN channel, so it was expected. But the error floor beginning from 30 dB for each curve was not expected and it can be justified by the presence of the impulsive noise all time and whatever the SNR is, so when the SNR is large the power of AWGN noise is small but the power of the impulsive noise remains fixed, which mean that this error floor is the best performance in presence of this type of noise. However, these performances can be improved using an error correction code or using one of the criteria of adaptation when we fixed a certain threshold for the SNR per sub-carrier and if it is smaller than this threshold we don't transmit anything over this sub-carrier. Thus the total data rate of the system is decreased but we obtain a good improvement of the performance shown in Fig. 10 and 11. We remark in Fig. 10 that the performance of QPSK is much more improved than the other mapping levels, which indicates that working with QPSK is more preferable for all applications with these channel conditions, in despite that it gives the smallest data rate. In figure 11, we can show that at high SNRs the total data rate of the system using the threshold elimination (called with elimination; some sub-carriers are not used for transmission, so eliminated) remains lower than the data rate of the system without any sub-carrier elimination (called complete; all sub-carriers are used for transmission) which is fixed to the maximum possible with each mapping level with respect to the bandwidth and this loss is approximately between 26% and 28%, and we can remark also that this mapping level cannot respect the conditions of the threshold so they cannot send any data, thus in this interval of SNR we should use the BPSK modulation, whatever the loss obtained in the data rate.

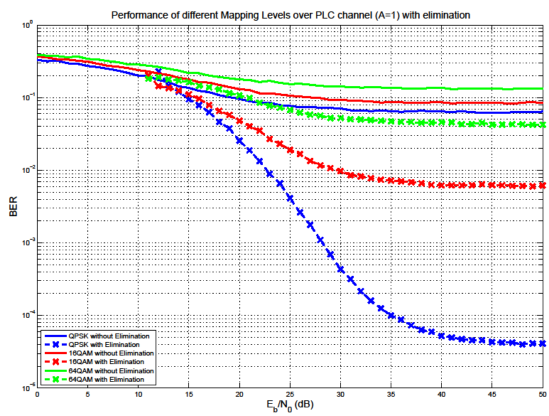

Figure 10: Performance of mappings (*A*=1) with Elimination

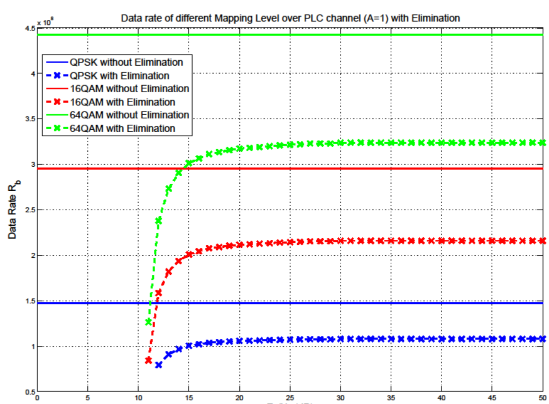

Figure 11: Data Rate of mappings (*A*=1) with Elimination

4.2. The effect of the impulsive noise amplitude

In this simulation, we want to study the effect of the impulsive noise amplitude, and the results shown in Fig. 12 and 13 confirm that the error floor presents in the curves is decreasing with the impulsive noise amplitude. We obtained a representative value of this amplitude during the measurements done for deducing the model of the PLC channel, and this value was approximately equal to 0.0316 (A^2 = 0.001). Figures 12 and 13 show the performance of considered mapping levels for both amplitudes A=1 and A=0.0316. Figure 12 represents the system without elimination and figure 13 represents the system with elimination.

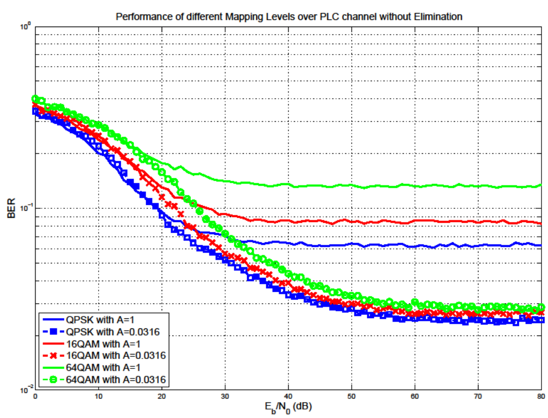

Figure 12: Performance of mappings (*A*=0.0316) without Elimination

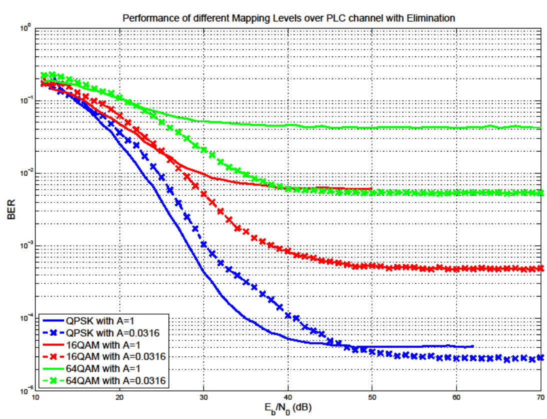

Figure 13: Performance of mappings (*A*=0.0316) with Elimination

Figure 12 shows that the performance of all mapping levels is improved, in despite that, the BER remains high, the curves are very close to each other, especially at high SNR. From Fig. 13, we can conclude two things; the first conclusion is that, with A=0.0316, the performances are improved for all mappings except the QPSK mapping where we remark that the curve converges slower to the error floor value which is smaller than the one with A=1; the second conclusion is common with Fig. 12 where the performances are approaching to each other.

4.3. Comparison with the adaptive OFDM system

Here, we will present the advantage adaptive system. The idea behind this work is to consider that we have a certain application which needs a minimum BER to work properly, so we consider this minimum BER as a target BER and we compute the threshold corresponding to the mappings used. When the SNR in a certain sub-carrier is bigger than or equal the threshold of 16QAM, for example, we can transmit over this sub-carrier this modulation, otherwise the mapping with lower level is used, and so on each sub-carrier and for every channel use. Here, the target BER is fixed to 10^{-3} and when this BER cannot be obtained the lowest mapping level is used. The PLC channel mode chosen is the more realistic one which corresponds to any practical use of a PLC system, it considers the presence of impulsive noise with amplitude A=0.0316. Figures 14 and 15 show the evolution of the BER and the data rate when the SNR is increasing, and to be fair these adaptive system performances are compared with the system with elimination. We remark clearly that, after 37 dB, the target performance is obtained, so the adaptive system will try to increase the data rate by carrying upper mapping level on the sub-carriers without affecting the BER; for these reasons, we obtained in Fig. 15 a data rate higher than the one of 64QAM and in the same time the BER performance of our system remains confirmed to the desired application, in despite that the BER of 64QAM is largely higher than the target one. As shown in Fig. 15, the data rate obtained is increasing with the SNR until a certain value which is nearly 390 Mbps for an acceptable probability of error.

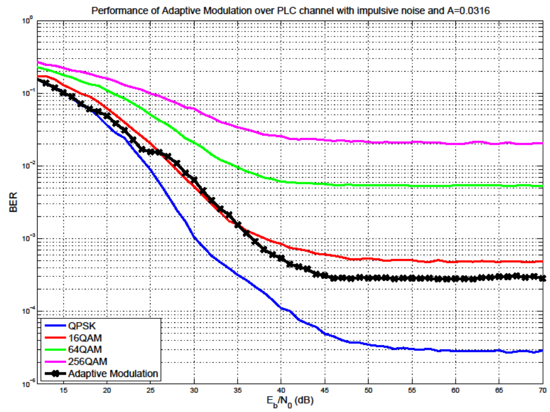

Figure 14: Performance of Adaptive Modulation (*A*=0.0316)

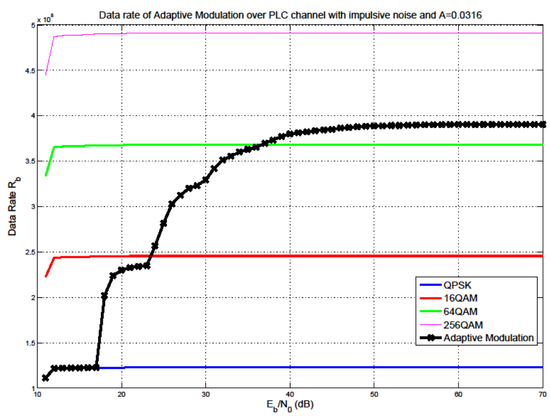

Figure 15: Data Rate of Adaptive Modulation (*A*=0.0316)

5. Conclusion

The progress in PLC technology has come about in the last decade. PLC technology is seemed as an alternative data channel. The article deals with design of the PLC communication system model. The model is composed of the OFDM communication model, the model of power lines and noise model. In this paper, an adaptive approach has been presented that assesses the impact of impulsive noise on an adaptive OFDM-based PLC system. The statistical properties of the impulsive noise have been utilized in their most basic form. The error statistics obtained show that the performance of the system is highly limited in the presence of the impulsive noise in the channel. We observe that a lower value of the amplitude translates to more frequent impulses and this improves the error performance of the system. Thus to improve on the system performance, an error correction code can be used, it is our case here, so the adaptive system should be implemented on the channel. We show two level of adaptive system; the first one is to do not use some sub-carriers for transmission if their SNR is below a certain threshold without changing the mapping level. The second level is to use this threshold to adapt the mapping level of the modulation with respect to the target performance desired. The results presented here show that we can obtain a good improvement with this technique. From the results of simulations it follows that an inappropriate choice of modulation can significantly affect the resulting signal. The error correction code is not used here. In the future work, we will design a corresponding channel code which will be adaptive and specific to this application. After that, the complex adaptive OFDM-based PLC system can be used for future standardization. The results of simulations based on the model will be compared with measurements in the future work.

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