Modeling the Noise on the OFDM Power-Line Communications System

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***Abstract*—Power-line communications (PLC) have gained a lot of scientific interest over the past years. In this paper, a practical noise model is proposed that best describes the noise conditions on an orthogonal frequency-division multiplexing PLC system. The noise present on a power-line system is divided in five categories which are grouped into two classes: 1) the generalized background and 2) the impulsive noise. In this paper, all of the components comprising the noise are precisely depicted on a computer simulation system. The statistical properties regarding all component parameters are taken into account and used in our model. By this way, the real conditions on a PLC channel can be portrayed in the most precise way. This model is tested on a PLC channel and its performance in terms of bit-error rate versus the E_b/N_0 value is obtained. For reasons of completeness, we examine how two of the model's components affect the system's performance by altering their vital parameters. In order to accomplish this, we take various values for these parameters and we check their influence on the system. Furthermore, we apply a popular noise model, such as Middleton's noise model and we compare the performance obtained by both noise models.**

***Index Terms*—Background noise, impulsive noise, noise model, orthogonal frequency-division multiplexing (OFDM), power-line communications (PLC).**

I. INTRODUCTION

POWER-LINE communications have gained a lot of scientific interest the last years and tend to be a promising way of information exchange. The main advantage when implementing power-line communications (PLC) is that there is no need for extra infrastructure, which can be both expensive and time consuming. On the other hand, the main drawback is that the power-line network was originally not designed for supporting the communication signal's transmission. There is a continuous altered load, due to the number of appliances connected to the network, which changes with time. As a result, the telecommunication signal undergoes severe degradation caused by interference and impulsive noise.

An accurate channel model needs to be employed in order to investigate the power line channel's characteristics. Several attempts have been made by the scientific community towards this direction. One of the first channel models was introduced by Hensen and Schulz, according to which, the attenuation was proportional to the frequency growth, [1]. Later on, Philipps' channel model was built, taking into account the multipath phenomenon occurring in a power-line network, whereas each component is multiplied by a factor depending on its path, [2]. Zimmermann and Dostert, [3] introduced a model, according to which, not only is the multipath scenario considered, but also the attenuation added to the signal due to the wire's length. Furthermore, Galli and Banwell proposed a model, based on the multi-conductor configuration, according to which the power line can be represented by an equivalent circuit, [4]. There are also a lot of researchers that have developed several channel models, after being based on their own measurements, [5]–[7]. In this paper, Zimmermann's channel model has been utilized, since it is a straightforward method.

Many attempts have been made in order to approach the characteristics of the channel's noise, which deteriorates the signal. Similarly to the channel models, many researchers were based on their measurements in order to derive a noise model, [8]–[11]. A popular noise model is Middleton's model, [12], which indicates that the noise is categorized into background and impulsive, while the two components are added to form the total noise affecting the signal. However, according to [13], it does not describe the PLC channel's noise in the most accurate way.

Due to the increased number of researchers in the vast topic of PLC, there is a need for a simple, but yet accurate noise model. As a result, many investigators, which examine any feature on the subject of a power-line system except for noise, tend to use simple and effective noise models, like Middleton's noise model. Induced by this necessity for a practical and precise model, we propose a noise model that describes the noise in the most realistic way on an OFDM PLC system. Further on, we test its performance on a PLC channel.

When designing a noise model for the PLC channel, it is crucial to be acquainted with the statistical features of its parameters. A good statistical analysis of the impulsive noise characteristics has been made by Zimmermann in [14], whereas Benyoucef in [15] has explored the statistical properties of the background noise. The results derived from both of these studies, which are taken into account in this paper, are also pointed out in [16].

In order to complete our system, a coding scheme also needs to be employed. For this purpose, we implement Low Density Parity Check (LDPC) codes along with BPSK modulation. These codes, first introduced by Gallager, [17], have become the target of research and investigation the last years and they constitute a promising coding method for communication systems. In this paper a class of irregular LDPC codes is used, namely the Quasi—Cyclic LDPC (QC—LDPC) codes, [18].

Manuscript received June 29, 2009. First published December 08, 2009; current version published December 23, 2009. This work was supported by the Greek General Secretariat for Research and Technology (Program PENED 2003). Paper no. TPWRD-000301-2009.

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Digital Object Identifier 10.1109/TPWRD.2009.2035295

The rest of the paper is arranged as follows. Section II describes the PLC channel model, whereas in Section III the coding technique is illustrated. The proposed noise model is analyzed in Section IV. Section V describes the system's configuration and the computer results are displayed. Conclusions are drawn in Section VI.

II. CHANNEL MODEL

Regarding the channel model needed for the system's realization, Zimmermann's 15-path model [3] is applied. The multipath effect the signal undergoes is taken into account. The components reaching the receiver follow a different route and therefore they have a different amount of delay. The N dominant paths are the ones to be calculated through the model. The frequency transfer function is given by

$$H(f) = \sum_{i=1}^{N} \underbrace{g_i}_{weightingfactor} \cdot \underbrace{e^{-(\alpha_0+\alpha_1\cdot f^k)\cdot d_i}}_{attenuationportion} \cdot \underbrace{e^{-j2\pi f\cdot(d_i/v_p)}}_{delayportion}. \quad (1)$$

The delay portion in the above equation reflects that different signal components do not arrive simultaneously at the receiver. The factor d_i/v_p represents the time delay τ_i of each path, with τ_i

$$\tau_i = \frac{d_i \cdot \sqrt{\varepsilon_r}}{c_0} = \frac{d_i}{v_p} \quad (2)$$

where d_i is the length of the path, ε_r the dielectric constant of the insulating material, v_p the electromagnetic waves' phase velocity and c_0 the speed of light. The attenuation portion stands for the signal's attenuation due to cable losses. The weighting factor represents the reflections occurring on each path. The constants α_0, α_1 and k depend on cable parameters. The values of the parameters in (1), as well as the number of the dominant paths used, can be found in [3].

III. CODING TECHNIQUE

A. LDPC Code Characteristics

LDPC codes belong to a subgroup of Linear Block Codes, meaning that the uncoded word (u) consisting of k bits is transformed into a codeword (c) of n bits after the encoding procedure. These codes are characterized by their parity check matrix, H, which is a sparse matrix. In case a codeword is valid, (3) is true

$$H^* c^T = 0. \quad (3)$$

The size of the parity check matrix is determined by the code rate. Thus, if the code rate equals to k/n, then the parity check matrix will have a size of $(n-k)xn$. Another reason why the parity check matrix plays an important role in characterising LDPC codes is because a uniform or non-uniform column weight results in having regular or irregular LDPC codes.

$$H=\begin{bmatrix} 1&0&1&1&0&1&1&0&1&0&0&0\\ 1&1&0&0&1&0&0&1&1&1&0&0\\ 0&1&0&1&1&0&1&1&0&0&1&0\\ 1&0&0&1&0&1&0&0&1&1&0&1\\ 0&0&1&0&0&1&1&0&0&1&1&1\\ 0&1&1&0&1&0&0&1&0&0&1&1 \end{bmatrix}$$

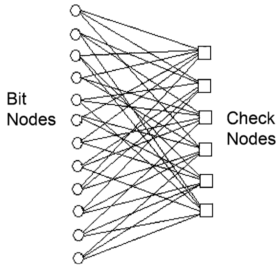

Fig. 1. Parity check matrix (H) and its corresponding bipartite graph.

An important aspect of LDPC codes is that their parity check matrix can be described via a bipartite graph. This graph constitutes of two groups of nodes, the check and bit nodes. The check nodes represent the rows in the parity check matrix, while the bit nodes represent the codeword bits. As a result, the size of the matrix defines the number of nodes present in the graph. The nodes are connected to each other in case there is an ace in the corresponding position of each row in the parity check matrix. For instance, if there is an ace in the fourth column and sixth row of the matrix, then the fourth bit node will be connected to the sixth check node, [19]. Fig. 1 illustrates an example of a parity check matrix and its corresponding bipartite graph.

B. Quasi—Cyclic LDPC Codes (QC—LDPC) Encoding Procedure

This class of LDPC codes, which is used in this paper, is characterized by a parity check matrix that consists of square blocks. These blocks could either be circulant permutation matrices based on the identity matrix or zero matrices. The feature that makes them preferable to random constructed codes is that they entail an easier implementation regarding the encoding procedure.

Equation (4) shows a permutation matrix P of size $q \times q$

$$P = \begin{matrix} 0 & 1 & 0 & & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \dots & 1 \\ 1 & 0 & 0 & & 0 \end{matrix}. \quad (4)$$

It is crucial that the parameter q is defined to be a prime number and that the inequality $q \geq k \geq j$ is not violated, otherwise the advantages of the coding technique will not be accomplished. The parameters k and j are related to the resulting code rate R, which is given by

$$R = 1 - \frac{j}{k}. \quad (5)$$

All non-zero circulant permutation matrices P^i are derived from the identity matrix (I), after shifting its columns to the right by i times $(0 \leq i \leq q)$. Defining the parity check matrix in such a way results in reduced memory needed for storage, since after positioning the aces in the first row of each block matrix P, then the rest aces can easily be located. In order to facilitate the encoding procedure, a parity check matrix in lower or upper triangular form is required. Therefore, we focus on a matrix having the form as shown in (6). This matrix is in upper triangular form whereas the code rate obtained is $1 - j/k$, [18]

$$H(q,j,k) = \begin{matrix} I & I & I & \dots & I & \dots & I \\ 0 & I & P & \dots & P^{(j-2)} & \dots & P^{(k-2)} \\ 0 & 0 & I & \dots & P^{2(j-3)} & \dots & P^{2(k-3)} \\ \vdots & \vdots & \vdots & \dots & \vdots & \dots & \vdots \\ 0 & 0 & \dots & 0 & I & \dots & P^{(j-1)(k-j)} \end{matrix}. \quad (6)$$

C. Decoding Procedure

In general an iterative algorithm, the so-called Belief Propagation Algorithm or Sum-Product algorithm, describes accurately the decoding procedure followed by LDPC codes. This algorithm is better comprehended via the code's bipartite graph. Several versions have been presented in the technical literature, whereas they all share a common basis, [20], [21]. According to this algorithm, each bit node sends a message to the check nodes with which it is connected, during each iteration round. This message is an estimation of the exact value of the corresponding codeword bit this node represents. Afterwards, all the messages received at each check node go under elaboration so that other messages are sent back to the neighbouring bit nodes, meaning that one iteration round is completed. Subsequently, the messages are further processed and the bit nodes send information back to check nodes, so that the algorithm is repeated. The messages exchanged between connected nodes entail extrinsic information only, which is the main feature of the algorithm. As a result, the message sent by a check node to one bit node is based on the information received by the check node from all the other bit nodes except for this particular bit node. The situation is similar when it comes to messages sent from bit nodes to check nodes. At the end of each iteration round and after the bit nodes' messages are processed, a codeword is produced. Whether or not the resultant codeword is correct this is checked at the end of each iteration round. The algorithm stops either after a predefined number of iterations is carried out or in case the correct codeword is already found during the algorithm's execution [20].

The nature of the exchanged messages can either be in log-domain [21] or not [20]. In this paper the messages sent at each iteration round are not in the log-domain since this would increase the system's complexity. However, another problem comes up, since the messages described in the original algorithm are not designed to work on a PLC environment. Therefore, instead of applying the variance of the Gaussian noise to the computations the algorithm indicates, the variance of the received symbol is calculated [22] and this value is inserted in the estimations.

IV. PROPOSED NOISE MODEL

In this section the proposed noise model is analysed and explained. In order that a proper model is derived, the characteristics of the noise present at the PLC channel should be examined. First of all, the noise that affects the telecommunications signal when transmitted through the PLC channel can be categorised into five categories, [8]. These are:

1) Colored background noise, which is caused by the summation of numerous noise sources with low power. It has a relatively low spectral density (PSD), which varies with frequency. Regarding time, it varies slowly over time, while it remains somehow constant in terms of minutes or even hours.
2) Narrow—band noise, which is caused by broadcast stations and consists mainly of sinusoidal signals with modulated amplitudes.
3) Periodic impulsive noise asynchronous to the mains frequency, which is caused by switching various power supplies on the network. The repetition rate is between 50 and 200 kHz, while its line spectrum is discrete and spaced according to the impulse repetition rate.
4) Periodic impulsive noise synchronous to the mains frequency, caused by power supplies like rectifier diodes, which occurs synchronously to the mains frequency. The impulses last some microseconds, while the repetition rate is 50 or 100 Hz.
5) Asynchronous impulsive noise, caused by switching transients to the network. Their occurrence is random, while their duration fluctuates from some microseconds up to some milliseconds. These impulses can be up to 10^5 times stronger than the background noise.

Noise types 1, 2 and 3 can be stationary for minutes even hours, therefore, they can be assumed to form altogether the background noise. On the other hand, noise types 4 and 5 can vary in terms of microseconds or milliseconds. These two classes of noise are considered to form the impulsive noise.

The background noise can be considered to be formed of the colored background noise and the noise due to the narrowband disturbers, since noise type 2 and 3 have a similar effect, [16]. Equation (7) depicts this statement

$$N_B(f) = N_{CBN}(f) + N_{ND}(f) \quad (7)$$

where N_B stands for the total background noise and N_{CBN} and N_{ND} represent the colored background noise and the noise caused by narrowband disturbers respectively.

The impulsive noise of type 4 is considered to be of minor importance compared to noise type 5, since the latter one is much stronger and therefore causes severer deterioration to the system's performance. Thus, when it comes to calculations, only noise type 5 is considered as the system's impulsive noise, [16].

The noise model that is proposed in this study, takes under consideration all of the above characteristics, therefore it depicts the noise present at a PLC channel in the most accurate way. In addition, it calculates the noise components in a simple and straightforward way, which makes it more appealing. It should be also noted here, that when it comes to the case of the OFDM transmission technique, the information data is transferred in terms of blocks, whereas each block implies simultaneous symbol transmission through various sub-frequencies. This means that, by definition, some data blocks are not affected by the impulsive noise. Our noise model takes into account this phenomenon, making it more realistic and close to the actual channel conditions.

A. Colored Background Noise

The colored noise is a component of the generaliZed background noise, as seen from (7) and can be expressed by

$$N_{CBN}(f) = N_0 + N_1 \cdot e^{-(f/f1)} \tag{8}$$

where N_0 is the constant noise density, $N_1 = N_0$ and f_1 the frequency of the narrowband disturber. For a residential environment, (8) gets the form

$$N_{CBN}(f) = 35 + 35 \cdot e^{-(f/3.6)} \tag{9}$$

where f_1 is expressed in MHz and N_0 in $\mathrm{dB}\mu\mathrm{V/Hz}^{1/2}$, [16]. In this study the system's performance is examined in terms of Bit Error Rate versus the E_b/N_0 value and compared to a popular noise model, Middleton's noise model. Therefore, various values of E_b/N_0 are applied to the system. For the noise modelling of the colored background noise, two options are available regarding the simulations. The first one requires that the signal power is adjusted to the particular E_b/N_0 value, while the noise power N_0 remains constant. The second one implies that E_b remains unchanged, whereas the noise power is adjusted to each E_b/N_0 ratio. The latter method seams more convenient for computer simulations, since the signal power does not need to alter. Although this condition is not in accordance to real conditions, it brings absolutely no effect to the final obtained system's performance, and it is used in our model. However, special care is taken so as the N_0 value corresponds to the various E_b/N_0 ratios. As a result, for every E_b/N_0 value and for all frequencies that constitute the OFDM symbol, we get a different value of the colored background noise.

B. Noise Due to Narrowband Disturbers

The noise due to narrowband disturbers is the second component of the generalized background noise and is given by

$$N_{ND}(f) = \sum_{k=1}^{N} A_k \cdot e^{-(f-f_{0,k})^2/2\cdot B_k^2} \tag{10}$$

where N is the total number of the disturbers, f_0 is the centre frequency and B_k is the bandwidth of the narrowband disturber, while A_k is its amplitude. There are 4 parameters to be defined when modelling this kind of noise. The parameter N follows a normal distribution with a standard deviation $\sigma = 5.47$ and mean value $\mu = 0.88$ for frequencies between 0–10 MHz, whereas for frequencies of 10–20 MHz, it is $\sigma = 3.94$ and $\mu = 0.35$, [15]. In order to find the number of narrowband disturbers in each subband, which would depict the actual situation in a PLC channel, we suggest the following steps:

1) Produce a large number of normally distributed numbers (i.e., 10000) with the equivalent characteristics for the mean value and standard deviation.
2) Discard the negative values
3) Take the mean value, which is the number of disturbers.

In this case, with these particular values of μ and σ we get for our system, number of narrowband disturbers for the subband of 0–10 MHz, $N_{B1} \approx 5$ and $N_{B2} \approx 3$.

For the bandwidth B_k (in MHz) each narrowband disturber occupies, the exponential distribution is applied, with $\lambda = 0.2$ and the minimum bandwidth $B_{\min}$ having the value of 0.23 MHz for frequencies of 0–10 MHz. Regarding frequencies of 10–20 MHz, the characteristics of the exponential distribution are a bit altered, with $\lambda = 0.18$ and the minimum bandwidth remaining at 0.23 MHz, [15]. Practically, for the system's realization, we produce N_{B1} exponentially distributed numbers with $\lambda = 0.2$ and N_{B2} exponentially distributed numbers with $\lambda = 0.18$, taking care that none of these numbers falls below the value of 0.23 MHz.

The centre frequency f_0 at which the narrowband disturbers broadcast also needs to be specified. For this purpose, we produce N_{B1} values at the subband of 0–10 MHz and N_{B2} values at the subband of 10–20 MHz with a uniform distribution.

The last parameter A_k (in dBm/Hz) remaining in order that the noise due to narrowband disturbers is specified, follows a uniform distribution for frequencies of 0–10 MHz with $a = 0.97$, $b = 54.4$ and a normal distribution for frequencies of 10–20 MHz, with $\sigma = 23.2$, $\mu = 9.6$, [15]. In addition, according to (9), $N_0 = 35\ \mathrm{dB}\mu\mathrm{V/Hz}^{1/2}$ or $5\ \mathrm{dBmV/Hz}^{1/2}$. Regarding computer simulations, and in order to define the noise due to narrowband interferers in a simple and straightforward way, it is advantageous to define their amplitude in terms of "how many times" or "how many dB" it is greater than the constant noise power N_0. Subsequently, a uniform distribution can be derived for the factor "how many dB" the narrowband disturbers' amplitude exceeds N_0 with $a = -3.75$, $b = 49.4$ for 0–10 MHz and a normal distribution for 10–20 MHz with $\sigma = 18.2$, $\mu = 4.6$. Baring this information in mind, in order to find the corresponding amplitude for the N_{B1} and N_{B2} narrowband interferers we perform the following steps:

1) Produce N_{B1} numbers with a uniform distribution having characteristics $a = -3.75$, $b = 49.4$. These numbers represent the amount in dB by which the amplitude of each narrowband interferer exceeds the constant noise power N_0 for the subband of 10–20 MHz.
2) Produce N_{B2} normally distributed numbers with $\mu = 4.6$ and $\sigma = 18.2$. These numbers stand for the amount in dB by which the amplitude of a narrowband disturber in the subband of 10–20 MHz surpasses the constant noise power.

However, since the number of narrowband interferers is low and the declination between the characteristic values of the distributions is great, the random factor that comes in the calculations cannot be tackled effectively. For reasons of completeness, we examine the cases where the aforementioned distributions have the values of $a = 5$, $b = 15$, $\mu = 2.5$, $\sigma = 12.5$ and $a = 5$, $b = 10$, $\mu = 1$, $\sigma = 7$ respectively. Apparently, the corresponding amplitudes have a lower declination between each other and lower values in general. By this way, we examine the case where the narrowband disturbers have a milder effect on the system. In Table I the values for the four parameters used in the system, describing the noise caused by narrowband interferers are illustrated. After having defined these four parameters, all we need to do is check for every frequency of the OFDM symbol the presence of a narrowband disturber and calculate through (10) the amount of the noise added to our OFDM symbol.

It should be noted here that the values shown for A_k in Table I denote "how many dB" the in question amplitude exceeds the background constant noise N_0.

TABLE I
PARAMETERS DESCRIBING THE NOISE CAUSED BY THE NARROWBAND INTERFERERS

Narrow – band Interferer	f_0 (in MHz)	B_k (in MHz)	A_k for $a=3.75$, $b=49.4$, $\sigma=18.2$, $\mu=4.6$	A_k for $a=5$, $b=15$, $\sigma=12.5$, $\mu=2.5$	A_k for $a=5$, $b=10$, $\sigma=7$, $\mu=1$
1	1.9879	0.3499	25.532	10.8106	7.2823
2	3.7589	0.235	30.1315	13.8889	8.8597
3	5.5267	0.2867	5.5028	10.4724	6.1557
4	6.9318	0.2515	14.1036	5.302	6.881
5	8.1593	0.3295	11.1519	8.1391	5.0925
6	11.6841	0.2394	16.2025	11.4483	8.4674
7	13.1106	0.3295	10.2676	4.9772	1.15
8	16.8944	0.2585	0.746	0.2052	0.3305

C. *Impulsive Noise*

The impulsive noise is the most important one when examining power lines as a communications medium, since it introduces most of the errors at the transmitted data and it is hard to predict. There are three parameters that define the characteristics of the impulsive noise, namely the impulse duration, the impulse amplitude and the interarrival time, meaning the time in-between two successive impulses. In an OFDM system, as it has been explained above in Section III, some blocks are affected by the impulsive noise, while some are not. It depends on which moment the impulse takes place, whether or not one particular block will be negatively influenced. Our attempt is to define which blocks are affected by the impulsive noise and at what extent. It should also be noted here, that one of the OFDM features is that the impulsive noise influence is spread to all the carrier frequencies. Therefore, even if an impulse occurs during the transmission of a specific block, all of the carrier frequencies will be affected. In order to analyze the proposed noise model, we will firstly point out the different cases regarding the occurrence of an impulse during the transmission of one particular block.

1) No impulse is present during the data block's transmission.
2) One impulse starts during the transmission of the data block.
3) One impulse starts during the transmission of the data block and ends before the transmission is completed.
4) One impulse that has started before the transmission of this particular data block, ends during this transmission.
5) One impulse that has started before the transmission of this particular data block, ends during this transmission while another impulse starts during the transmission of this data block.
6) One impulse affects the whole data block.
7) In one data block, two or more impulses occur.

The impulses influence one or adjacent data blocks, while some data blocks remain unaffected. At this point, the impulses' characteristics need to be defined and afterwards it should be defined which blocks are affected and which aren't.

The impulse duration is random and varies from some tens to some hundreds microseconds, whereas its amplitude follows an exponential distribution, [14]. It is convenient for computer simulations to define the amplitude of each impulse with respect to the constant noise power, by means of "how many times" or "how many dB" it exceeds N_0. The impulse amplitude could be even 40 dB above the N_0 power level. However, these values do not represent the majority of the impulses. Based on [14], we use an exponential distribution to generate the impulse power I_P divided by the constant noise power $N_0 (I_P/N_0)$ with $\lambda = 63$. By this way we obtain the quantity "how many times" the impulse amplitude surpasses the noise power N_0.

The interarrival time is also exponentially distributed with 90% of the samples falling beneath the level of 0.1 sec, [14]. We set the interarrival time with an exponential distribution of $\lambda = 0.015$ sec. For reasons of completeness we also set this parameter to be 0.04 and 0.005 sec in order to examine the system under heavier or milder impulsive noise conditions. In addition, we examine how a unique parameter impinges on the system's performance.

For the total number of the 1500 transmitted blocks for our OFDM system, we determine the number of impulses occurring and their characteristics. The proposed method of specifying the impulses and their characteristics consists of the following steps:

1) We set a large predefined number of impulses (some of them may not affect the sequence of the transmitted blocks).
2) We generate a sequence of numbers regarding the impulse duration, according to the impulse duration characteristics. Each of these numbers corresponds to one impulse defined in step 1.
3) We generate a sequence of numbers corresponding to the impulse amplitudes, with respect to their characteristics. Each one of these numbers is matched to one impulse defined in step 1.
4) We produce a sequence of numbers representing the interarrival time, relating to the interarrival time features. Each one of these numbers is assigned after the occurrence of one impulse, defined in step 1.
5) For every transmitted block, which has certain duration, we examine in which of the seven categories it falls as regards to the occurrence of an impulse during its transmission.
6) Depending on the absence or the presence of an impulse, its amplitude and the percentage of the time it affects the particular block, the equivalent amount of noise is added to our block data.

With this algorithm, the impulsive noise can be easily modeled, and above all, it depicts the actual situation at a PLC channel in the most accurate way.

V. SYSTEM'S CONFIGURATION AND SIMULATION RESULTS

In this section we describe the system's configuration and we also test the performance of the proposed noise model on a power-line channel. The BPSK modulation scheme is used along with LDPC codes of code rate 1/2. The main difficulty regarding the simulations was that a frequency channel model is used whereas the OFDM transmission technique implies that a cyclic extension of the symbol is necessary in the time domain. Therefore, cautious operations were required, when using the FFT and IFFT functions in order to transform the data from frequency to time domain and vice versa. The data block size used was set to 1784 bits. After the insertion of the parity bits during the encoding process and since the OFDM subcarriers' number is a power of 2, the resulting OFDM symbol consisted of 4096 sub-carriers. According to OFDM transmission theory, each carrier takes up a frequency spectrum of Δf Hz and the OFDM symbol lasts for T_S seconds without taking into account its cyclic extension, with

$$\Delta f = \frac{19,7 \cdot 10^6}{4096} = 4809.5703\,\text{Hz} \tag{11}$$

$$T_S = \Delta f^{-1} = 2.079188 \cdot 10^{-4}\,\text{sec.} \tag{12}$$

A cyclic extension of around 14.8% is used, which leads to a total OFDM symbol duration of T_{OFDM} seconds, with

$$T_{OFDM} = \frac{T_S}{0.852} = 2.44036 \cdot 10^{-4}\ \text{sec}. \tag{13}$$

The number of data blocks that were considered for the simulations had to be large, due to the characteristics of the impulsive noise. As it has been assumed, the impulsive noise influences consecutive blocks. In addition, having defined all the parameters that describe the impulsive noise and their statistical properties, the affected blocks can be determined in the sense of time length. However, in order to obtain more accurate results, the factor of randomness that is entailed in the simulations due to the random way the parameters acquire their final values, needs to be eliminated. Therefore, a large number of blocks are required. Nevertheless, more blocks leads in more simulation time needed. Thus, a trade off had to be made between the total simulation time and the number of data blocks which was set to 1500.

One of the parameters describing the impulsive noise present at a PLC channel is the interarrival time. This is considered to be one crucial parameter since it determines how frequent the impulses occur at the channel. As we have seen in the previous section, the interarrival time follows an exponential distribution, characterized by the value λ (*lamda*). As a result, this value λ plays a very important role in determining the impulses and further on the impulsive noise added to the telecommunications signal. We test how the performance is influenced in case this parameter takes various values. Therefore, we use three different values for λ, namely $\lambda = 0.015$, $\lambda = 0.04$ and $\lambda = 0.005$. In the latter case, the impulses occur with the highest frequency.

In addition, we have seen that concerning the background noise, and in particular the noise added due to narrowband disturbers, their amplitude follows a uniform distribution for the subband of 0 to 10 MHz in terms of "how many times" it is bigger than the constant noise power N_0. However, the parameters $a = -3.75$ and $b = 49.4$ indicate that it is very likely to have all narrowband disturbers with a high amplitude. This occurs, because the total number of interferers is not high enough to alleviate the factor of randomness by which the amplitude values are specified. Furthermore, for the second subband the in question amplitude follows a normal distribution with $\sigma = 18.2$ and $\mu = 4.6$, which could lead to all narrowband interferers having a large amplitude, for the same reason as for the first subband. In order to examine the effect this parameter has to the resultant system's performance, we test the case where the parameters of the uniform distribution are set to $a = 5$ and $b = 15$ and those regarding the normal distribution are $\sigma = 12.5$, $\mu = 2.5$. Additionally, we examine the occasion of having $a = 5$, $b = 10$ and $\sigma = 7$, $\mu = 1$ for the corresponding parameters. By this way, we can have a more detailed approach regarding the role of one single parameter to the resultant system's performance. In both cases, the amplitude values have a smaller declination between each other.

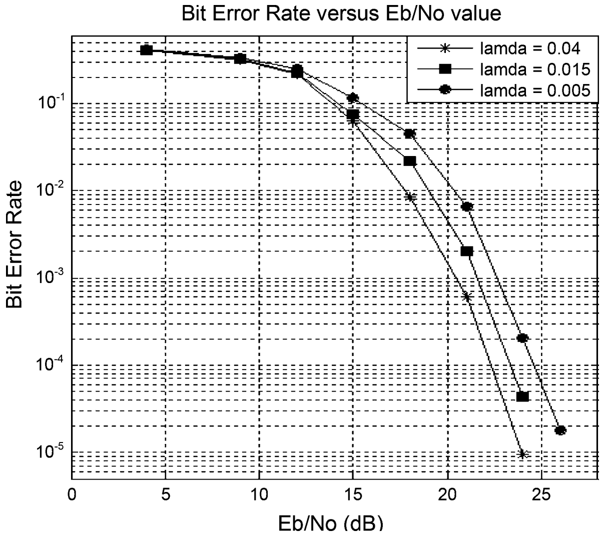

Fig. 2. Bit-error rate versus E_b/N_0 for the proposed noise model with the narrowband interferers amplitude having $a = -3.75$, $b = 49.4$ and $\sigma = 18.2$, $\mu = 4.6$ for the corresponding distributions.

In Fig. 2 the system's performance is illustrated when the narrowband interferers' amplitude has $a = -3.75$, $b = 49.4$ and $\mu = 4.6$, $\sigma = 18.2$ as corresponding distribution parameters.

Three curves are illustrated, each one having the impulsive noise interarrival time exponentially distributed but with dissimilar λ (*lamda*) values, in particular $\lambda = 0.04$, $\lambda = 0.015$ and $\lambda = 0.005$. First of all it is observable from Fig. 2 that all the curves follow the same trend. There is a sharp decrease in the achievable BER as the E_b/N_0 value increases, which is anticipated, since for a higher E_b/N_0 the signal quality becomes better compared to noise. However, the most important conclusion from Fig. 2 is that there is a great difference in the BER in case a single parameter is altered on the system, like the value describing the exponential distribution for the impulsive nose interarrival time. When the value λ has a great value (i.e., $\lambda = 0.04$), then the impulses produced by the system are infrequent, since the interarrival time becomes greater in general. Therefore, the data are less influenced by the destructive impulsive noise. On the other hand, the smaller the value λ becomes, the more deteriorated the performance turns to be. This can be explained since for more frequent impulses influencing the system, the more errors are introduced to the information data, which the system fails to correct. It is also important to notice that the difference in the resultant BER among the three curves is worthy of remark.

In Fig. 3 the system's performance is demonstrated when the narrowband interferers' amplitude has $a = 5$, $b = 15$ and $\sigma = 12.5$, $\mu = 2.5$ regarding the equivalent distribution parameters, whereas in Fig. 4 the respective parameters are set to $a = 5$, $b = 10$ and $\sigma = 7$, $\mu = 1$. Similarly to Fig. 2, all the curves follow the same trend showing a rapid decline in the BER as the E_b/N_0 value increases.

It is also clear from Figs. 3 and 4 that the alteration in the λ parameter regarding the impulsive noise interarrival time plays a significant role in defining the system's performance. Again,

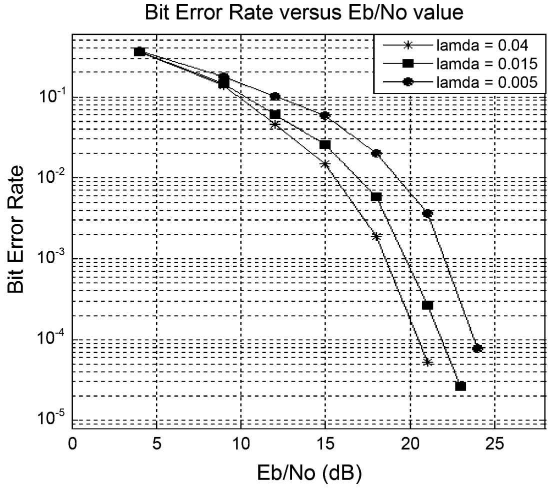

Fig. 3. Bit-error rate versus E_b/N_0 for the proposed noise model with the narrowband interferers amplitude having $a = 5, b = 15$ and $\sigma = 12.5, \mu = 2.5$ for the corresponding distributions.

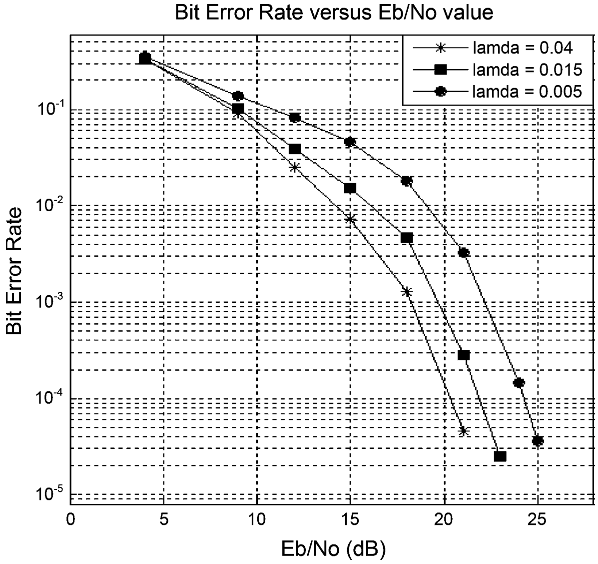

Fig. 4. Bit-error rate versus E_b/N_0 for the proposed noise model with the narrowband interferers amplitude having $a = 5, b = 10$ and $\sigma = 7, \mu = 1$ for the corresponding distributions.

with higher values of λ, the performance improves, whereas for smaller values of λ, the impulsive noise becomes more intense and the information data undergo severer degradation. By comparing Figs. 2–4, it is observable that the narrowband interferers' amplitude is a vital parameter and it affects evidently the obtained BER curves.

It is worth noticing that when the amplitude values are generally smaller and the declination with each other is also smaller, then the system's performance is enhanced. Although the total number of interferers is not great and the amplitude difference may not be that large, the BER diversity that comes in the system is noteworthy.

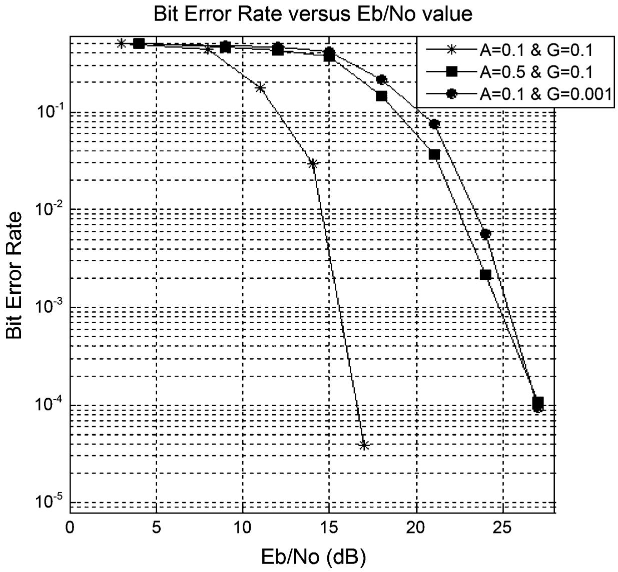

Fig. 5. Bit-error rate versus E_b/N_0 for Middleton's noise model with different values for the model's parameters.

For reasons of completeness, we compare our proposed model's performance on the power-line channel to the one obtained when a popular noise model is applied to the PLC channel, like Middleton's noise model. The same system conditions are applied. Middleton's noise model, [12], is mainly characterized by two parameters, the impulsive index A and Γ (or G), the background noise power to the impulsive noise power ratio. According to this model, the noise present at a power-line channel is distinguished between Gaussian background noise and impulsive noise. Each noise sample is given by

$$n = x_G + \sqrt{K_m} \cdot y. \tag{14}$$

x_G is the White Gaussian background noise with zero mean and variance σ_G^2, y corresponds to a White Gaussian sequence with zero mean and variance σ_I^2/A. The parameter K_m represents a Poisson distributed sequence whose pdf is characterized by the impulsive index A.

We take various values for A and Γ, in order to examine how these parameters affect the system's performance. Therefore, we set $A = 0.1$ and $\Gamma = 0.1$, which means that the impulsive noise power is ten times greater than the background noise. We also set $A = 0.5$ and $\Gamma = 0.1$ in order to examine how the impulsive index influences the system. Since the impulsive noise is said to be even 30 or 40 dB greater than the background noise, we set $\Gamma = 0.001$ and $A = 0.1$. By this way we obtain three different curves which help us comprehend the role of each parameter better. In Fig. 5 the system's performance is illustrated for the case when Middleton's model is applied to the PLC channel, while each curve represents the different values the parameters obtain.

It is noticeable form Fig. 5 that all curves experience a rapid fall in their BER values, for higher E_b/N_0 values. The impulsive index is a vital parameter, showing how frequent the impulses occur at the system. As a result, a higher impulsive index reveals the presence of many impulses, thus leading to a deteriorated performance. The factor Γ is also crucial, since for lower values, the destructive impulsive noise power becomes stronger compared to the background noise. Consequently, the signal's quality becomes poorer in terms of BER, as it can be observed from Fig. 5.

By comparing Figs. 2–5 we conclude that the system's performance obtained with Middleton's model for $\Gamma = 0.1$ is better than the rest cases. This can easily be explained since on this occasion the impulsive noise is only ten times stronger than the background noise, which is not the fact for the proposed model, where the impulsive noise power is considered to be of greater level. However, when we set $\Gamma = 0.001$, the resultant signal's quality in terms of BER becomes undoubtedly deteriorated.

By definition, when we set Γ to have a specific value, it is implied that the impulsive noise remains somehow static, in the sense that it is considered to be constantly 30 dB above the level of the background noise. The same goes for the parameter A when setting it to a fixed value, which entails some kind of inertia. However, the impulsive noise occurrence denotes that it is dominated by a factor of randomness. The impulses' power can vary from powerful to weak ones, whereas their occurrence level can fluctuate from high to low ones. Our model depicts these features in a very effective way by taking into account all of the parameters describing the noise present at a power-line channel as discussed in the previous section.

VI. CONCLUSIONS

In this paper we proposed a noise model that would be easily implemented on computer simulations and that best describes the noise affecting a communications system using the OFDM technique on a power-line channel. The suggested model takes into account all the noise components, which describe the PLC channel's noise. The parameters describing each component were studied as well as their statistical properties. All of these properties were taken under consideration in order to comprise our noise model, which makes it as realistic as possible under the conditions of a power-line channel. The model has been constructed so as to depict the features of the impulsive and background noise in the most accurate way, taking care so as to remain simple enough for an easier implementation.

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