On PLC Channel Models: an OFDM-based Comparison

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***Abstract*—In this paper, some indoor PLC channel models are compared from an OFDM communication system perspective. Firstly, three representative models have been selected to generate channels in a statistical way, which are later included in an OFDM system simulator designed according to Homeplug-AV parameters. Secondly, the system performance is analyzed for the three cases of channel models and is compared to the one obtained for a set of almost 200 measured channels. An additional study about the Gaussian nature of the linear distortion in the OFDM system caused by the channels (modeled and measured) is presented.**

I. INTRODUCTION

Power Line Communications (PLC) has become a mature technology that can be useful in different scenarios like: outdoor access networks, indoor local area networks (LANs), in-vehicle networks, smart-grids solutions, etc [1]. These systems have reached a remarkable commercial success, at least for indoor LANs that gives support to internet and digital video distribution inside the home. Two recent international standards for this application have been released: ITU G.hn [2] and IEEE 1901 [3]. In the smart-grids field, a promising future for PLC is also perceived and new standards like ITU 6.9955 (ex G.hnem) and IEEE 1901.2, for narrow-band systems, are already available.

This paper is focused on broadband indoor PLC. In the last years, many channel models have been proposed for this scenario that could be classified in two groups. Some of them are based on the physical structure of the power network, which can be represented by a set of interconnected transmission lines terminated in open circuit or in loads of diverse nature. This modeling approach is usually referred to as bottom-up. Alternatively, other models characterize the channel following a behavioral approach, that is, representing its impulse response as a set of delayed echoes with different amplitudes (according to the multipath nature of the PLC channels). This kind of models are usually denoted as top-down.

The purpose of this work is to evaluate the adequacy of several PLC channel models to the expected in actual networks, but from a communication system point of view. Perhaps the most important parameter of a communication system is the achievable bit-rate. Hence for a modem developer is crucial to reach reliable bit-rate estimations when simulating the system on a channel model. Some of the channel models included in this study were already compared in depth in [4], but considering only behavioral parameters of the modeled and measured channels, like the attenuation of the frequency response or the delay spread of the impulse response. Here that analysis is extended by assessing their performance in a multi-carrier modulation system, which has been proven to be the best transmission technique for PLC. To this end, an OFDM system like Homeplug AV (HPAV) [5] has been chosen. The performance obtained with the modeled channels is benchmarked with the result on measured channels. Since the bit-rate is closely related to the signal to noise and distortion available at the receiver, this paper also investigates the Gaussian nature of that distortion: the Inter-Carrier Interference (ICI) and Inter-Symbol Interference (ISI) experienced by a multi-carrier system on indoor PLC channels, a result not reported yet to the authors best knowledge.

The contents can be summarized as follows. In the next section, the different channel models employed in the work are concisely reviewed. In the third section, the results obtained by simulating HPAV-like transmission systems over modeled channels are described and, in the fourth one, the Gaussian nature of the distortion in a multi-carrier system is addressed. Finally, some conclusions are given in the last section.

II. CHANNEL MODELS

Among the available indoor PLC channel models in the literature, three of them are selected (which are frequently cited by the community). They will be referred to as: *Simplified bottom-up* [6], *L-taps* [7] and *Multipath* [8]. All of them describe of provide procedures to generate parameters, according to certain probability distributions, that permits to obtain statistical ensembles of channels. A LTI (Linear Time Invariant) behavior is assumed for the channels. Although

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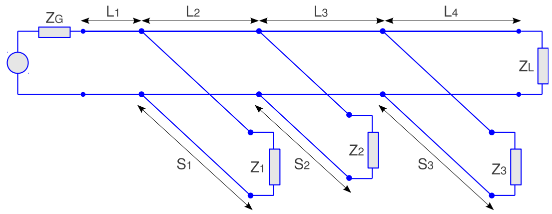

Figure 1: Diagram of the simplified topology used in the model by Cañete et al.

PLC channels may exhibit periodical time-variations (see [9]), this is out of the scope of this work. An ensemble of 1000 channels has been generated for each channel model, whereas the measured channels have been taken from a set of almost 200 links registered at many homes in Spain.

A. Simplified bottom-up model

The first model was proposed by Cañete et al. in [6]. It is shown in Fig. 1 and is based on a particularly simple topology of a PLC network with few transmission lines and loads.

The parameters of this topology are selected according to physical considerations. A channel generator constructed from the model is available for download in [10]. Although the line lengths or the loads impedance are generated from independent statistical distributions, the topology gives a natural correlation to the behavioral parameters of the channel response (derived by means of transmission line theory), like the attenuation and the RMS-DS (root mean squared-delay spread). The generated channels behavior have been compared with measured channels to assess its validity in [6].

B. L-taps model

The second model included in this study was proposed by Galli firstly in [11] and lately extended in [7] with more flexible parameters (and applied not only to PLC but also to other wireline channels like coaxial or phone-line). It is based on a model for the channel impulse response with L taps, where their amplitudes and delays (what defines the multipath character) are selected according to statistical distributions, but imposing a correlation between the channel attenuation and the RMS-DS. The correlation is extracted from measured channels. In our study, two cases are considered for this channel model: L=2, with taps of equal amplitude, and L=1000, with tap amplitudes selected according to a Gaussian-shaped power-delay profile (as indicated in [7]). Therefore, two representative cases are covered: the most simple model and a quite complicated one.

C. Multipath model

The third model under consideration here was initially proposed by Zimmermann et al. in [12] for the outdoor scenario. It also consists in a multipath model for the channel frequency response with a limited number of paths[1]. Lately, it was extended by Tonello in [8], adapting it to indoor PLC channels by defining statistical distributions for its parameters values. There is a generator based on this model, available in [13], which has been employed here. However, as explained in [4], this model lacks of realistic attenuation values. Hence, for this study, the channel responses of the generated ensemble have been scaled so that their mean attenuation matches with the measured channels [2].

D. Characteristics of the channels

In order to give an idea of the channels features, in Fig. 2 a scatter plot with the mean amplitude of the channels frequency response vs the impulse response RMS-DS is presented. The objective is to highlight whether the models offer a good fit with the correlation, and level of dispersion, observed in measured channels between both parameters. It is remarkable that measured channels exhibit an important correlation, i.e. it is unlikely to face a channel with high attenuation and low delay spread. However, this correlation is over-estimated by the *L-taps* model (the points are very tight to the regression lines), while the *Multipath* model under-estimates this correlation, the *Bottom-up* model exhibits a grade of correlation closer to the measurements [3]. It is also shown that both the *Bottom-up* and *L-taps* models offer a reasonable fit with the measured values in terms of amplitude range, but the *Multipath* model provides results with less dispersion.

III. Performance of an OFDM HPAV-like Transmission System

In this section, results for simulations carried out for a HPAV-like transmission system are discussed. The three channel models are compared by analyzing the bit-rate attained in each case and the one obtained with the measured channels is used as a benchmark.

A. Simulation description

The analysis has been carried out for a frequency band from 2 to 28.5 MHz, which is the one employed

[1]Although the three models capture the multipath character of PLC channels responses, the term multipath has been reserved for this one because it was published earlier with that name.

[2]in [13], a second version of generator has been released. The measured channels taken as reference are organized in nine classes, according to their behavior, but the generator only provides parameters for three of the classes. Hence, there is no way of creating an ensemble of channels whose characteristics cover the whole range found in actual scenarios.

[3]The regression line slope is not very significant in the generated channels, since it changes for different realizations of ensembles, due to the out-layers

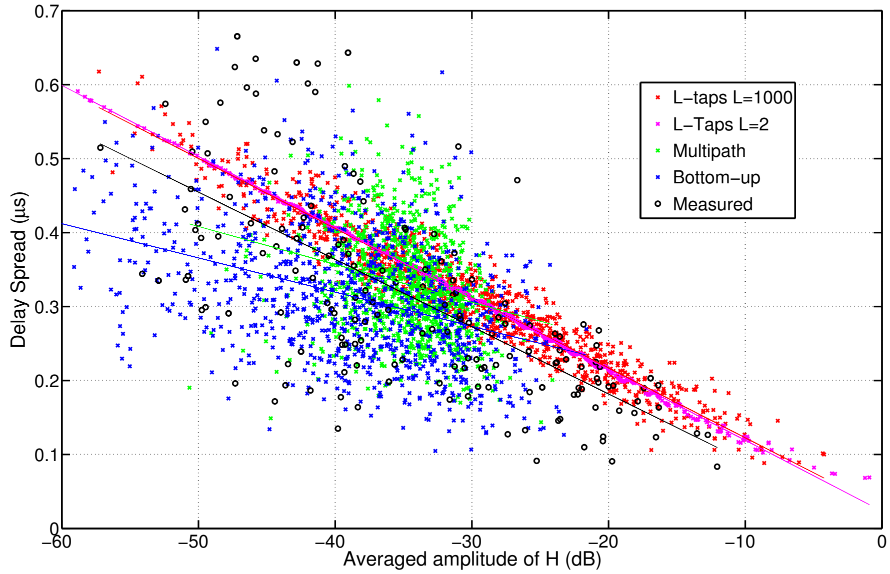

Figure 2: Scatter plot of the channels frequency response mean amplitude vs impulse response RMS-DS. Regression line is also included for each of the channel subsets with the solid lines.

in HPAV. The system parameters are summarized in Table I (the values are obtained assuming a sampling frequency of 75 MHz). It is worth mentioning that many of these parameters are similar to those of systems compliant with ITU G.hn standard as well (although a larger bandwidth and denser constellations are allowed [2]).

The functions used for the pulse-shaping and windowing have been derived from [14], while the length of the pulse-shaping has been taken from [15] and the one of the windowing and the cyclic prefix from [14] and [5]. Cyclic prefix length in Table I does not include the windowing samples (both give a guard interval of 5.56 μs). As well, the code-gain has been estimated following the considerations in [15], while the code-rate has been taken from [16].

In the simulations, only additive white Gaussian noise (AWGN) has been included, with a power spectral density (PSD) of -90 dBm/kHz, which is a simple but reasonable estimation of the expected level of background noise. Impulsive noise has been avoided so that the system performance was essentially determined by the effect of the channel response. Finally, the mask for the transmitted PSD is compliant with regulations and permits to enable 917 carriers for transmission (out of 1536).

Regarding the bit-loading, two strategies has been considered: to assign a given constellation to each carrier independently (denoted as TG=1); and to assign the same constellation to ten adjacent carriers, which is usually known as tone-grouping (denoted as TG=10).

Table I: OFDM system Parameters

Parameter	Value
Number of carriers (N)	1536
Cyclic prefix (samples/μs)	327/4.36
Pulse-shaping (samples/μs)	372/4.96
Windowing (samples/μs)	90/1.2
Transmission PSD (dBm/kHz)	-20
Constellation (bits/symbol)	1,2,3,4,6,8,10
System margin (dB)	3
BER target	10^{-5}
Code-rate	16/21
Code-gain (dB)	12

B. *Simulation results*

In Fig. 3, the system bit-rate estimated from the simulations both on the measured and modeled channels is presented. The plot represents the cumulative distribution function (CDF) for the different models and the two tone-grouping options. The maximum achievable bit-rate in all cases is 135.89 Mb/s and the best performance in the actual channels is obtained with the TG=1, as could be expected.

Results with the *Bottom-up* model are, by far, the closest to the measurements for both options. The *L-taps* model provides higher bit-rates than the estimated from measurements for both L=2 and L=1000. Al-

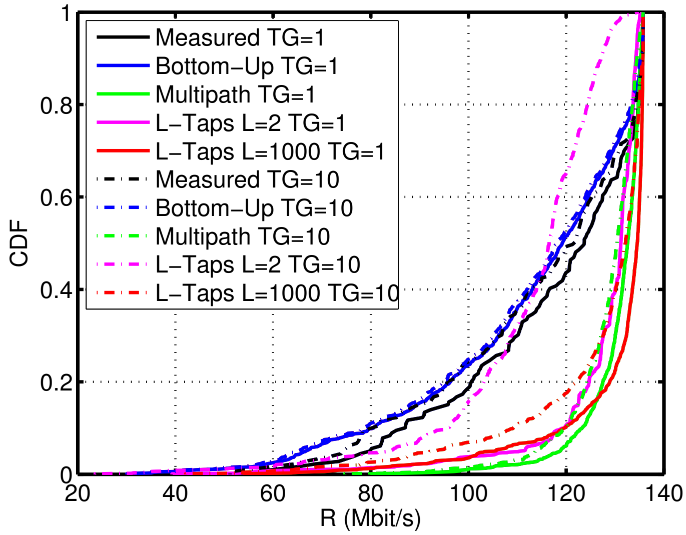

Figure 3: CDF of the achieved bit-rate for the measured channels and the ones generated according to the models

though for L=2 and TG=10 shows an erratic behavior, because it under-estimates the bit-rate for the better channels (what must be due to its lack of frequency selectivity). In such cases, the mean attenuation is low and quite realistic, but the channel response with only two-taps is very 'artificial': periodical in frequency, alternating notches and very low-attenuated carriers. The *Multipath* model, despite the compensation of the mean attenuation applied, does not provide realistic values and over-estimates the bit-rate as well. It exhibits not only a problem of the attenuation values but also of the distribution they have. In fact, there are many channels in which it is the maximum bit-loading level that limits the system performance.

IV. Study of the Gaussian nature of the distortion in a multi-carrier PLC system

The objective of this section is twofold. On one hand, to give a response to the question of whether the distortion in a multi-carrier transmission system caused by the PLC channel frequency selectivity can be considered with Gaussian or normal distribution. On the other hand, this fact has been tested by simulating transmissions through both the measured channels and channels generated with the models. Hence, this trial constitutes an additional evaluation of the models adequacy to the actual conditions.

The simulations have been performed on a generic OFDM system, some of whose parameters have been changed to see their sensitivity on the results. Approximately two hundred channels have been used in the tests for each model.

A. Statement of the problem

In an OFDM system, the $i-th$ symbol received at carrier k can be expressed as,

$$Y_k^i = \widetilde{H}_k X_k^i + \sum_j \sum_{p \neq k} ICI_p^j X_p^j + \sum_{j \neq i} ISI_k^j X_k^j, \quad (1)$$

where X_k^i is the $i-th$ symbol transmitted at carrier k; $\widetilde{H}_k$ denotes essentially the equivalent low-pass frequency response at this carrier; ICI_p^j stands for the Inter-Carrier Interference term due to symbol j in carrier p and ISI_k^j stands for the Inter-Symbol Interference term due to symbol j in carrier k. The criterion used in (1) is that the distortion due to symbols transmitted in other carriers, either in the preceding, current or succeeding symbols, is considered ICI. Strictly speaking, $\widetilde{H}_k$ is not exactly the frequency response because when the CP is shorter than the impulse response it includes a residual self-distortion term caused by the symbol X_k^i (i.e. it is neither ISI nor ICI). More details about this distortion analysis can be found in [17].

Since the number of carriers usually employed in PLC systems is quite large, it may be expected that the distortion in the form of ISI and ICI was normally distributed (following the central limit theorem). However, three conditions may affect this intuitive reasoning: X_k^i takes only a discrete set of values (according to quadrature amplitude modulation -QAM- constellations); the distortion terms from adjacent carriers can be correlated (unless the channel coherence bandwidth is of the order of the carriers separation); and there may be some carrier with a dominant distortion in the sum. These characteristics may make the convergence towards a Gaussian distribution slower and then the

Table II: Mean and standard deviation values of percentage of carriers with Gaussian distortion.

Channel set and cp length	$\mathbf{N = 2^9}$	$\mathbf{N = 2^{10}}$	$\mathbf{N = 2^{11}}$	$\mathbf{N = 2^{12}}$
Measured cp=20	94.69 / 3.79	94.61 / 3.48	94.32 / 4.10	94.93 / 3.33
Measured cp=100	94.82 / 2.93	93.61 / 4.73	95.16 / 3.66	94.85 / 3.52
Measured cp=160	94.72 / 2.95	95.20 / 2.91	94.54 / 2.96	95.73 / 3.08
Bottom-up cp=40	95.83 / 4.28	93.52 / 7.2	94.55 / 6.25	95.43 / 5.05
Bottom-up cp=100	94.15 / 7.11	94.71 / 6.55	95.00 / 5.66	95.80 / 5.43
Bottom-up cp=160	90.07 / 11.81	94.52 / 6.87	94.30 / 8.27	95.89 / 5.93
Multipath cp=40	94.77 / 4.71	94.37 / 3.33	94.02 / 3.44	94.85 / 3.71
Multipath cp=100	94.34 / 5.72	94.28 / 4.73	95.24 / 3.93	92.40 / 5.87
Multipath cp=160	82.37 / 16.17	92.97 / 3.91	94.80 / 2.87	95.10 / 2.00
L-taps L=2 cp=40	95.05 / 3.80	91.92 / 7.85	94.67 / 3.48	96.67 / 3.52
L-taps L=2 cp=100	92.94 / 8.65	96.61 / 4.89	96.86 / 6.97	93.81 / 7.01
L-taps L=2 cp=160	94.38 / 5.51	96.11 / 5.00	95.43 / 7.89	93.40 / 5.65
L-taps L=1000 cp=40	94.49 / 2.98	93.92 / 3.00	93.58 / 2.98	94.76 / 2.89
L-taps L=1000 cp=100	89.41 / 9.98	96.10 / 4.89	97.13 / 4.04	93.18 / 6.18
L-taps L=1000 cp=160	93.56 / 7.96	95.58 / 5.81	95.05 / 7.38	93.06 / 6.62

percentage of carriers whose distortion is Gaussian would be low.

B. Results analysis

The distortion terms in (1) have been estimated for the simulated OFDM transmissions over the different channels. Afterwards, normality tests have been applied to their real and imaginary parts. The number of carriers in the system have been selected in the set $\{512,1024,2046,4096\}$, which are usual values in indoor PLC modems for broadband systems. Also, different distortion levels have been evaluated to see whether the magnitude of the distortion influences its normality or not. For this purpose, the cyclic prefix length has been taken in the set $\{40,100,160\}$, which correspond to $\{0.54,1.34,2.14\}\mu$s, respectively. In the study, the constellation used has been restricted to 4-QAM, what would be close to the worst case for the normality tests. For larger constellations the convergence towards normality should be higher.

Different normality tests have been used [4]. However, since all of them give similar results, only the ones from the Anderson-Darling test [18] are shown. The procedure consists in passing the test to the distortion at each carrier and then calculating, for each channel, the percentage of carriers in which the hypothesis is satisfied. Table II summarizes the mean value and the standard deviation of this percentage of carriers for the sets of measured and modeled channels.

As seen, in approximately 95% of the carriers the distortion can be considered Gaussian for the measured channels. The low values of the standard deviation make the result quite reliable. Regarding the generated channels, results are also consistent and similar for all models, although the *Bottom-up* model provide the closest to the ones obtained in the measurements. Moreover, the cyclic prefix length (i.e. the distortion level) does not influence remarkably the results, what reinforces the conclusion. In addition, the fraction of carriers in which the distortion can not be considered Gaussian may be not so important because some of them are close to notches of the frequency response (a usual feature of PLC channels) and would convey few information or even none.

V. Conclusion

In this paper, three representative models for indoor PLC channels have been analyzed by means of multi-carrier communication system simulations and benchmarked against measured channels. Firstly, the bit-rate attained by a HPAV-like transmission over the channels has been estimated. Secondly, the linear distortion that channel selectivity introduces in the system has been studied. In both situations, the *Bottom-up* channel model proposed in [6] outperforms the others. Besides, it has been verified that the distortion of a multi-carrier system over PLC channels, in the form of ISI and ICI, can be assumed to be normally distributed.

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