On the Statistical Properties of Indoor Power Line Channels: Measurements and Models

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***Abstract*—In the last years, numerous works have analyzed the statistical distribution of indoor power line channels response. A set of models based on two main approaches, bottom-up and top-down, have been proposed. This work analyzes the statistical distribution of the attenuation and the delay spread of indoor power line channels. First, results obtained from a set of more than 200 channel responses measured in 25 different premises are presented. Then, the suitability of various channel models proposed in the literature is evaluated by comparing their statistical distributions with the one of the measured channels.**

I. Introduction

The main characteristics of broadband indoor power line channels response were firstly reported more than one decade ago [1]. Since then, several works have presented statistical analyses of their main parameters. An estimate of the cumulative distribution function of the delay spread was presented in [2], and lately in [3]. The statistical distribution of the number of peaks and notches, their width and height was studied in [4]. Recently, it has been pointed out that the average channel gain and the delay spread are correlated lognormal variables [3]. This conclusion has been drawn from the analysis of a large number of measurements taken in the US and poses a difference with other environments, like the wireless one, in which the correlation between both magnitudes is generally disregarded.

Simultaneously to the channel characterization efforts, numerous channel models have been proposed. Some of them are based on the physical nature of the problem. Indoor power line networks are modeled as a set of interconnected transmission lines terminated in open circuits or in loads of diverse nature [5–7]. Because of this, the modeling approach is usually referred to as bottom-up. One of the advantages of these models is that they can easily incorporate the time variation of the channel. However, they require the definition of realistic network topologies. It has been recently shown that a quite simple network topology with a limited number of loads is able to capture the essential features of these channels [8]. An alternative modeling approach, usually referred to as top-down or statistical, consists in representing the channel response as a set of delayed echoes with different amplitudes. The model parameters are selected to fit the observed responses. An example of this kind of models results from selecting the parameters of the proposal in [9] according to the random distributions given in [10]. Others are the one developed in the Opera (Open PLC European Research Alliance) project [11] and the two-tap model proposed in [3], [12].

In this paper, the statistical distribution of the average channel gain and the delay spread of indoor power line channels is explored. Presented results are based on more than 200 actual channels measured 25 different premises in several Spanish cities in the frequency band up to 30 MHz. One of the objectives of the presented analysis is to assess if the lognormal behavior reported for the US channels in [3] also applies to these channels. This is an important issue for the development of universally valid statistical channel models. The second objective of this work is to use the statistics of the measured channels to assess the suitability of some of the most representative channel models.

II. Statistical Analysis

This section evaluates whether the average channel gain and the delay spread of the measured channels can be modeled as correlated lognormal random variables.

A. Average channel gain

Denoting by H_k the N-point sampled version of the channel frequency response at $f_k = kf_s/(2N)$, where the sampling frequency is $f_s = 60$ MHz, the average channel gain can be computed as

$$\overline{H}_{\text{dB}} = 10\log_{10}\left(\frac{1}{N-k_1}\sum_{k=k_1}^{N-1}|H_k|^2\right), \qquad (1)$$

where k_1 is the index corresponding to 2 MHz, as in [3].

Fig. 1 depicts the quantile-quantile (QQ) plot of the average channel gain vs a standard normal random variable (RV). As seen, the distribution is not symmetrical with respect to the median value, and the probability of high average channel gain values (between -20 dB and -10 dB) is smaller than in a normally distributed variable. This agrees with the slightly platykurtic behavior (kurtosis=2.76) of the distribution.

Comparing these results with the ones in [12], it can be noticed that both exhibit approximately the same minimum values of $\overline{H}_{\text{dB}}$ (around -70 dB). On the other hand, the median of $\overline{H}_{\text{dB}}$ is lower in the channels measured in US (19.4 dB lower for the suburban channels and 14.4 dB for the urban ones) and so does the maximum value.

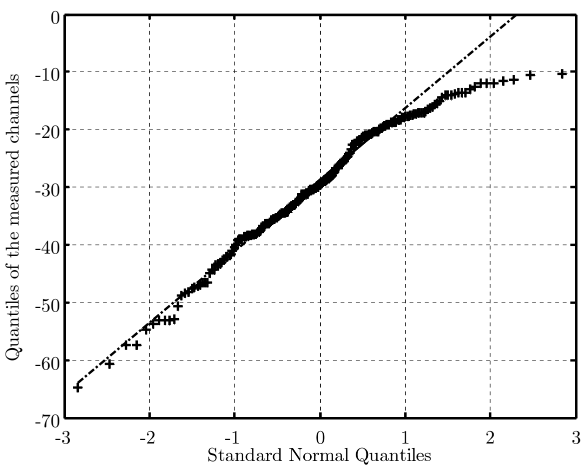

Fig. 1. QQ plot of the average channel gain of the measured channels (dB) vs a standard normal RV.

In order to assess the lognormality of $\overline{H}$, a set of normality tests have been performed on $\overline{H}_{\text{dB}}$ at the 5% significance level. Results are shown in Table I. As seen, the hypothesis (H) that the set of data comes from a lognormal distribution is always rejected (R). Moreover, the small magnitude of the p-value given by all the methods indicate that the probability of error in the decision is very low.

Table I
RESULTS OF THE NORMALITY TESTS ON $\overline{H}_{\text{dB}}$

Test Type	H	p-value
Lilliefors	R	10^{-3}
Jarque-Bera	R	$18.15 \cdot 10^{-3}$
Chi-Square	R	$102.21 \cdot 10^{-6}$
Anderson-Darling	R	$533.02 \cdot 10^{-6}$
Shapiro-Francia	R	$151.62 \cdot 10^{-6}$

Up to this point, the average channel gain has been computed using (1) to allow the comparison with the measurements in [3]. However, averaging the values of $|H_k|$ in linear scale does not seem to be appropriate for power line channels because of two reasons. The first is that the averaging will be severely biased towards the maximum values of $|H_k|$. This is due to the frequency selective behavior the channel response, in which differences of up to 30 dB are quite common. The second is that the channel capacity is a function of the logarithmic values of $|H_k|$. Because of this twofold reason, from now on the average channel gain will be computed as,

$$G(\text{dB}) = \frac{1}{N-k_1}\sum_{k=k_1}^{N-1} G_k = \frac{1}{N-k_1}\sum_{k=k_1}^{N-1} 20\log_{10}|H_k|. \quad (2)$$

B. Delay spread

Fig. 2 shows the QQ plot of the logarithm of the measured delay spread values vs a standard normal RV. It can be observed that the quantiles of the measured data fit the straight line quite well. This behavior is confirmed by the normality tests performed at a 5% significance level, shown in Table II.

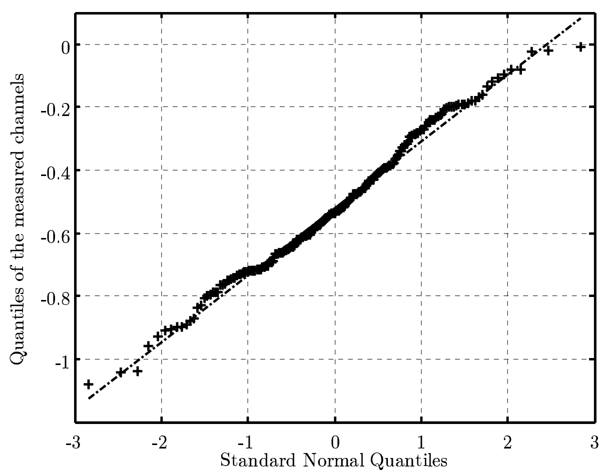

Fig. 2. QQ plot of the logarithm of the delay spread (μs) of the measured channels (dB) vs a standard normal RV.

Table II
RESULTS OF THE NORMALITY TESTS ON THE LOGARITHM OF THE DELAY SPREAD (μs)

Test Type	H	p-value
Lilliefors	A	0.348
Jarque-Bera	A	0.362
Chi-Square	A	0.076
Anderson-Darling	A	0.053
Shapiro-Francia	A	0.127

C. Relation between the delay spread and the average channel gain

As seen in the scattered plot of both magnitudes shown in Fig. 3, they are correlated. Channels with high attenuation values exhibit high delay spread values. The reason is that the more branched the network, the higher number of reflections the signal will found in its way from the transmitter to the receiver, and the stronger time dispersion and attenuation it will suffer. It is also interesting to note that the delay spread exhibits significant dispersion from the regression line when the average attenuation is high. The reason is that channels with short main paths use to be not very branched. Hence, the signal that reaches the receiver through the direct path is much powerful than the echoes coming from the branches, leading to low attenuation and low delay spread values. On the other hand, when the direct path is very long the number of branches tend to be high and the attenuation increases because of both reasons. However, the delay spread will be low when the branches are short and high when the branches are long.

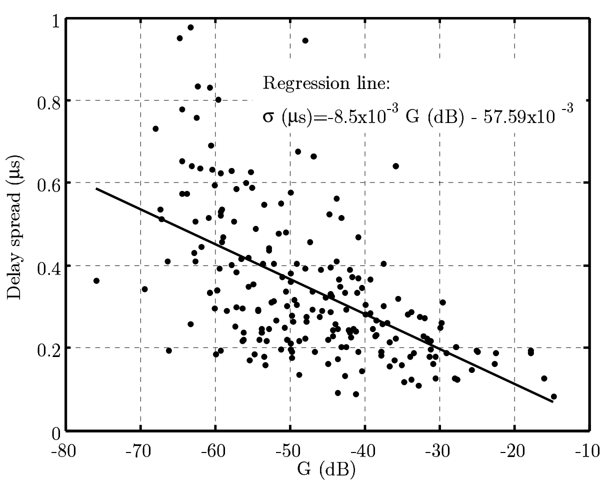

Fig. 3. Scatter plot of the delay spread vs the average channel gain of the measured channels.

III. Channel Models

This section provides a brief description of the channel models to be compared afterwards. They have been selected either because they can be easily implemented or because a channel simulator is freely available. For the sake of brevity, the basics of the models will be provided by means of references, and only the values that have been given to their parameters (if required) will be described.

A. Simplified bottom-up model

This model is proposed in [8] and is a simplified version of the classical bottom-up modeling approach [6]. The simplification is twofold. Firstly, a simplified network topology with only seven line sections is employed. Secondly, loads are modeled using a reduced set of impedance functions. A channel generator according to this model is available for download in [13]. It allows generating both time-invariant and periodically time-varying channels. The topology and the impedances can be manually fixed to give rise, for instance, to reference channels with best, medium and worst conditions. Alternatively, they can be generated at random to create representative channels in a statistical sense. The latter option, using the default values given in the generator for the time-invariant channels, has been employed in this work.

B. Top-down model

In this model, the channel response is represented using a set of echoes whose parameters are computed from statistics derived from measurements. It was firstly proposed in [9] for the outdoor power grid. However, it was lately used in [10] to generate indoor power line channels by selecting the values of its parameters according to certain statistical distributions. A channel generator according to this model is available for download in [14] and is the one employed in this work.

C. Opera model

This model was developed in the Opera research project [11]. The channel impulse response is modeled using a simple echo model without low-pass attenuation due to cable losses. Channels are categorized within four reference types according to the number of paths and time delay among them. In all cases the amplitudes of the echoes follow an exponentially decaying profile. The delays are randomly distributed using a given algorithm. The set of channels generated in this work according to this model is composed of an equal number of channels of each type.

D. Two-tap model

This model is proposed in [12]. It is based on the assumptions that the average channel gain, computed as in (1), and the delay spread are lognormally distributed and negatively correlated. The channel response is modeled as a two-path, equi-amplitude and τ-spaced channel. The amplitudes are easily expressed in terms of the average channel gain, $\overline{H}_{\mathrm{dB}}$, which is generated using a Gaussian distribution whose parameters are derived from measurements. The spacing, τ, is fixed to twice the delay spread, which is computed according to the following procedure. If the kurtosis of the delay spread statistics is low or if the value of $\overline{H}_{\mathrm{dB}}$ that has been computed is low, the delay spread is obtained from the regression line derived from measurements. On the other hand, if the kurtosis is high and $\overline{H}_{\mathrm{dB}}$ is also high, the delay spread is extracted from a lognormal distribution whose parameters are obtained from measurements. In this work, the kurtosis of the measured delay spread values is 4.12, which has been interpreted as low, and the value of $\overline{H}_{\mathrm{dB}}$ has been considered high if it is larger than the median of the measured channels (-29.58 dB).

IV. Models Comparison

In this section, the distribution of the average channel gain and the delay spread of the measured channels is compared to the one resulting from ensembles of 1000 channels generated according to each model.

A. Average channel gain

Fig. 4 depicts the QQ plots of the average channel gain, $G(\text{dB})$, of the generated channels vs the measured ones. The line that would result from the comparison of two identical distributions ($y = x$) is drawn in black as a reference. Its minimum and maximum values correspond to the maximum and minimum values of $G(\text{dB})$ in the measured channels. As seen, the distribution resulting from the simplified bottom-up model is the most similar to the one of the measured channels. The slope of its dashed line (approximately 0.5) reveals that the standard deviation of the generated channels is about one half of the measured ones, i.e., the dispersion of the generated channels is smaller than the measured ones. In fact, the difference between the maximum and the minimum value of $G(\text{dB})$ for the generated channels is about 30 dB. Finally, it can be noticed that its QQ plot is below the dashed line when the average attenuation is very low. This indicates that channels with much smaller gain than the median are more likely in the set of generated channels than in the set of actual ones. This is a feature common to all the models. In fact, this phenomenon is greater in the remaining models.

Concerning the top-down model, the distribution of $G(\text{dB})$ is also less dispersed than in actual channels. This can be noticed both in the slope of the dashed line of its QQ plot, which is about $1/4$, and also in the difference between the maximum and the minimum value of $G(\text{dB})$, which is about 22 dB. Another flaw of the top-down model is that the values of $G(\text{dB})$ are not realistic at all. This drawback can be overcome just by adding a constant gain term to all the generated channels. According to the results obtained in this work, a suitable value is -36.27 dB, which is the difference between the median values of $G(\text{dB})$ in the set of measured channels and in the set of channels generated using the current implementation of the model.

Regarding the Opera model, the average channel gain of the resulting channels is strongly dependent on the reference category that has been employed for their generation. The staircase behavior denotes that the values of $G(\text{dB})$ are quantized, and that all the channels generated according to a given category have nearly the same average channel gain. Moreover, the model is not able to generate channels with average gains in the following ranges: $[-59, -49]$ dB, $[-46, -40]$ dB and $[-36, -28]$ dB.

The two-tap model leads to a distribution with a quite similar variance to the measured one. However, the median of the values of $G(\text{dB})$ is about 15.28 dB higher than in actual channels. This overestimation of the median is a consequence of the aforementioned bias of $\overline{H}_{\text{dB}}$ towards the maximum values of $|H_k|$. This model is able to generate channels with a wide range of average channel gains. Thus, the difference between the maximum and the minimum values of $G(\text{dB})$ is 68.87 dB. On the other hand, some of the generated channels have positive average channel gains, i.e., it produces channels that amplify the transmitted signal, instead of attenuating it.

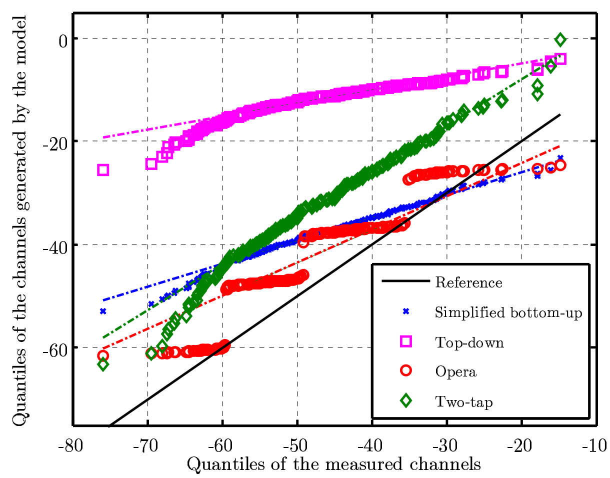

Fig. 4. QQ plots of the average channel gain, $G(\text{dB})$, of the generated channels vs the measured ones.

In order to assess the similarity between the distributions of the generated and measured channels, the Kolmogorov-Smirnov test at a 5% significance level has been applied. Results are shown in Table III. As seen, the hypothesis (H) is accepted only for the channels generated by the simplified bottom-up model and by the two-tap model. Unsurprisingly, the resulting p-value for the Opera model is extremely small. On the other hand, the confidence level of the results concerning the simplified bottom-up and the two-tap models is quite high.

Table III
Results of the Kolmogorov-Smirnov test on $G(\text{dB})$

Channel model	**H**	**p-value**
Simplified bottom-up	A	0.807
Top-Down	R	0.018
Opera	R	$83.18 \cdot 10^{-6}$
Two-tap	A	0.623

B. Delay spread

Fig. 5 depicts the QQ plots of the delay spread of the generated channels vs the measured ones. A zoomed area has been included to appreciate the details. In addition, the line $y = x$ is drawn as a reference. Its minimum and maximum values correspond to the maximum and minimum delay spread values that have been measured. For the sake of clarity, the Opera model has not been included. The reason is that the delay spread of the generated channels is severely quantized. In fact, there are no channels with delay spread values in the ranges $[0.13, 0.21]$ μs and $[0.32, 0.45]$ μs.

As seen, curves corresponding to the simplified bottom-up and the top-down models have an upside-down U shape. This indicates that the distributions of the generated channels are skewed to the left, i.e., the probability of generating channels with small delay spread values is higher than it should be (according to the distribution of the measured channels). Conversely, the probability of generating channels with high delay spread values is smaller than it should be. In fact, these models do not generate channels with delay spread values larger than 0.65 μs. This effect does not occur in the channels generated by the two-tap model, in which the probability of channels with very high delay spread values is much higher than it should be. Actually, it may lead to channels with delay spread values as high as 1.43 μs. Although not extractable from the figure, the median of the measured channels is 0.29 μs, while the median values of the simplified bottom-up, the top-down and the two-tap are and 0.31, 0.32 and 0.27 μs, respectively.

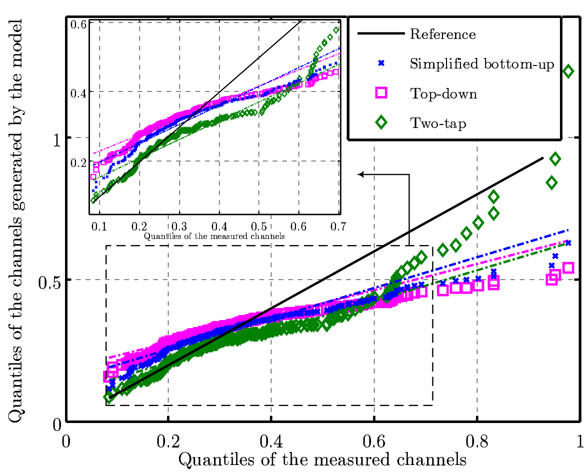

Fig. 5. QQ plots of the delay spread (μs) of the channels generated by the models vs the measured ones.

In order to assess the resemblance between the distributions of the generated and measured channels, the Kolmogorov-Smirnov test at a 5% significance level has been applied. Table IV shows the results. As seen, the hypothesis is accepted only for the channels generated with the simplified bottom-up model. Nevertheless, the resulting p-value indicates that the hypothesis is nearly on the limit of being rejected. In fact, when the test is applied to 100 ensembles of 1000 channels generated with this model, the acceptance ratio is 26%. Repeating the process for the remaining models, the acceptance ratio is 4% for the top-down model and 8% for the tow-tap one. It is always rejected for the Opera channels.

Table IV
RESULTS OF THE KOLMOGOROV-SMIRNOV TEST ON THE DELAY SPREAD

Channel model	**H**	**p-value**
Simplified bottom-up	A	0.051
Top-Down	R	0.035
Opera	R	$264 \cdot 10^{-12}$
Two-tap	R	$4.854 \cdot 10^{-3}$

C. Relation between the delay spread and the average channel gain

Fig. 6 depicts the scatter plot of the delay spread vs the average channel gain of the generated and the measured channels. The correlation coefficient between both magnitudes is shown in the legend.

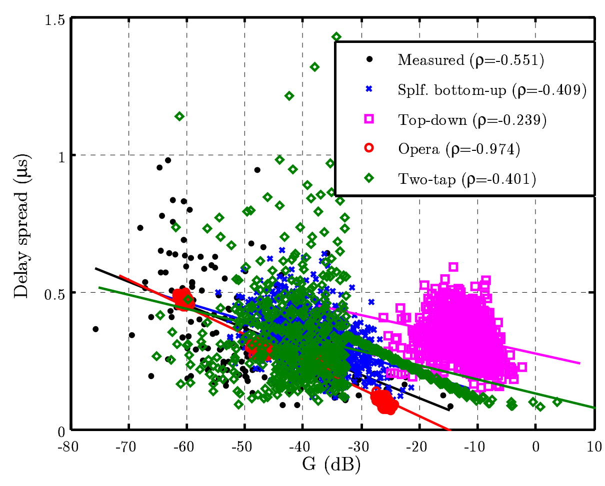

Fig. 6. Scatter plot of the delay spread vs the average channel gain of the measured and generated channels.

The severe quantization of the delay spread and the average channel gain in the Opera channels is clearly observable. Regarding the top-down model, in addition to the aforementioned *offset* of the average channel gain values, it can be noticed that the correlation is lower than in actual channels. It is worth noting the behavior of the two-tap model. The correlation is artificially high when G(dB) is high. On the other hand, they are absolutely uncorrelated when G(dB) is low. Obviously, this is due to the decision adopted in the channel generation procedure. However, it reflects a limitation of the model: either both magnitudes are perfectly correlated or absolutely uncorrelated.

V. Conclusion

This work has presented a statistical analysis of the average channel gain and the delay spread of a set of more than 200 actual channels in the frequency band up to 30 MHz. Obtained results confirm that both magnitudes are negatively correlated and that, while the delay spread seems to be lognormally distributed, it is not the case of the average channel gain.

Statistics derived from measurements have been also used to compare the suitability of four channel models: the simplified bottom-up model proposed in [8], the top-down model proposed in [9, 10], the Opera model [11] and the two-tap model proposed in [12]. Results indicate that statistics of the channels generated with the simplified bottom-up model are the closest to the measured ones. The top-down model generates channels with unrealistic gains. Although this can be easily overcome by adding a constant gain term proposed in this work, still the statistics of the average gain and the delay spread and the correlation between them are worse. The characteristics of the channels generated with the Opera model are severely quantized. The two-tap model generates channels with realistic average attenuation values, but it is unable to reflect the limited degree of correlation observed in actual channels between the average attenuation and the delay spread.

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