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# Statistical Assessment of Automotive PLC Multipath Channel Models

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***Abstract*—This paper addresses the modeling of in-vehicle power line communication channels via multipath parametric representations. The study is based on a set of frequency-domain measurements carried out on a commercial automobile. The proposed procedure for the computation of model parameters from real measured data is briefly summarized and a systematic assessment aimed at collecting some useful statistical information on both the estimated models and the channel features is thoroughly discussed. Specific emphasis is given to the definition of the range of the key parameters that allow characterizing real automotive PLC channels.**

## I. Introduction

In the past few years, the power line communication (PLC) technology has been established as a cost effective alternative to dedicated data communication channels in a large variety of applications [1], [2], [3], [4], [5]. Cables or wires needed for supplying energy to buildings, vehicles or even electrical industrial equipment have been considered as a potential budget saving alternative medium for enabling the communication among the different interconnected apparatus. Standard solutions for PLC modems and communication protocols can be effectively employed in this field for allowing the exchange of information among the safety and comfort electronic equipments in cars, boats or airplanes.

Within this context, the assessment of the performance of different design scenarios implementing the PLC technology requires the availability of numerical models of the power line channel. In order to include the large variability of PLC channel responses in a single model with the aim of collecting statistical information on the system performance, a number of alternative approaches have been developed. It is important to notice that most of the state-of-the-art approaches provide a general modeling framework but are mainly focused on in-home PLC channels (e.g., see [6] and references therein), being their extension to other applications partially addressed in the literature.

This paper concentrates on the modeling of automotive power line channels via parametrized black-box relations accounting for the inherent multi-path nature of power distribution networks. It provides an extension to [7] and [8], where the same mathematical representation is used for the deterministic modeling of automotive PLC channels. The novel contribution of the present paper is a statistical assessment carried out on the available frequency-domain data and estimated models. Specific attention is payed on the number of delays used to represent the rich frequency-domain response of the channel, on model accuracy and complexity and on the position of the maximum delay included in the model. The above assessment allows to define the range of parameters leading to synthetic models emulating the behavior of real automotive PLC structures. Furthermore, this contribution aims at supplementing the available channel statistics that researchers have obtained through measurements on different car models of different brands [5], [9], [10], [11], [12].

## II. Measurement data set

This study relies on a set of measurements carried out by the authors on a popular economy car manufactured by General Motors which has the dimensions and electronic features typical of many compact cars produced by any auto-maker. Two-port frequency-domain scattering measurements have been carried out by means of a vector network analyzer between different pairs of probing points of the in-vehicle power distribution system. The frequency range [500 Hz ÷ 100 MHz] was selected with the aim of covering the features of present [13] and future [14] in home PLC modems. Different static operating states of the car have been considered (key inserted, console on and engine off, engine on). The probing points are the dashboard light and car-radio connectors, on the front side of the console, the trunk and license plate lights and the front and rear lights (indicators, fog lights, reversing lights, dipped headlights, high-beam and parking-light points are considered).

As an example, Fig. 1 shows the magnitude of the $S_{21}$ scattering parameter associated with all the 106 measured links and/or operating states considered. In particular, the black curves of Fig. 1 are the responses associated with the link between the front left headlight and the power-supply connector of the car-radio, recorded during two different operating states of the car.

## III. Modeling via multipath representations

This section briefly introduces the model representation assumed to describe the behavior of a link of an in-vehicle PLC channel.

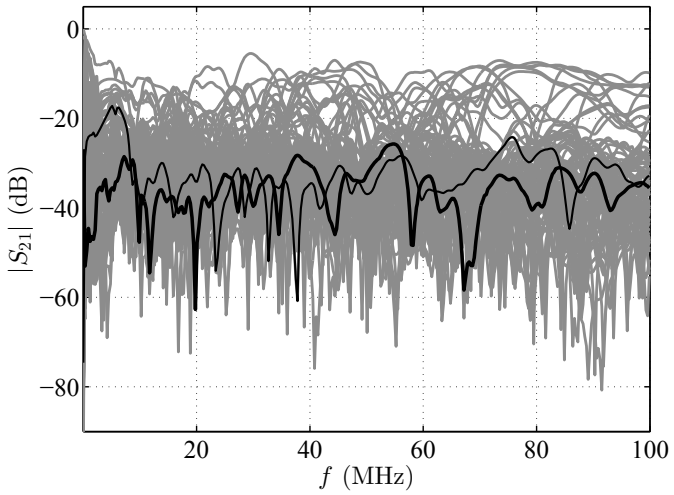


Fig. 1. Magnitude of the scattering parameter $S_{21}$ of the power line channel of the test vehicle. The frequency range is [500 Hz ÷ 100 MHz]. The gray curves belong to the complete set of 106 measurements corresponding to different links and/or possible operating states of the car. The black thick lines are two example measurements in the set.

The proposed model in the frequency-domain is expressed as:

$$H(j\omega) \approx \sum_{k=1}^{m} g_k \exp(-j\omega\tau_k) \tag{1}$$

where $H$ is the frequency-domain transfer function of interest (e.g., the $S_{21}$ parameter of Fig. 1 defining the ratio between the received and the transmitted signals), $\omega = 2\pi f$ is the angular frequency, $g_k$ and $\tau_k$ are the complex weighting coefficients accounting for the attenuation and phase distortion of the transmitted signal and the propagation delays, respectively for $k = 1, 2, \ldots, m$. The value of $m$ will be thoroughly investigated in the next sections. An approximation error is introduced and defined as follows:

$$E = \frac{||\boldsymbol{H} - \boldsymbol{D}\boldsymbol{g}||^2}{||\boldsymbol{H}||^2} \tag{2}$$

where $\boldsymbol{H}$ is the $n$-dimensional vector sampling $H$ at $n$ discrete frequency points $\omega_1, \omega_2, \ldots, \omega_n$, $\boldsymbol{D}$ is the $n \times m$ dimensional delay matrix ($D_{ik} = \exp(-j\omega_i\tau_k)$, $i = 1, 2, \ldots, n$, $k = 1, 2, \ldots, m$), $\boldsymbol{g}$ is the $m$-dimensional column vector of the coefficients $g_k$ and $||(\cdot)||$ is the norm assumed in the Euclidean space of complex variables (i.e., $||(\cdot)||^2 = (\cdot)^H(\cdot)$ where $(\cdot)^H$ denotes the Hermitian transpose conjugate operator). Hence, $E$ represents the relative mean square error computed from the difference between the reference frequency-domain channel measurements and the predicted responses.

In [7], the multipath representation (1) has been preliminary verified on a set of measurements that have been performed on a Pontiac Solstice by the British Columbia University of Canada and have been made available to the research community [9]. A deeper justification of the multipath model in the automotive context is reported in [8], which also reduces the error $E$ obtained in [7] using an orthogonal least squares estimation algorithm [15] to optimize the selection of the subset of delays $\tau_k$. It is relevant to remark that the direct use of frequency-domain measurements is always a possibility. However, the availability of a compact mathematical description as (1) facilitates its implementation in a possible software or hardware channel emulator. Moreover, through statistical inference (which is a second step that could follow the work presented in this paper), it could allow a designer to potentially explore a number of channel realizations greater than the one available from measurement only.

## IV. Statistical assessment

This section collects the results of the application of the proposed modeling technique [8] to all the available measurements and derives some useful statistical information on the model complexity and features.

Tab. I summarizes the results of a first test, where the information on the percentile of the number of model delays $m$ included in the models is given (e.g., see equation (1) and the terms $e^{-j\omega\tau_k}$, $k = 1, \ldots, m$).

TABLE I
Statistics of the number of delays obtained by applying the proposed technique to the 106 measurements of Fig. 1.

| | $m$ ($E \leq 0.001$) | $m$ ($E \leq 0.01$) | $m$ ($E \leq 0.05$) |
|---|---|---|---|
| Average | 175 | 85 | 40 |
| 1–st quartile (25%) | 114 | 49 | 24 |
| Median (50%) | 157 | 75 | 35 |
| 3–rd quartile (75%) | 207 | 96 | 50 |
| 90–th percentile (90%) | 327 | 129 | 69 |

In this assessment, the complexity of the obtained models is quantified as the number of delay terms needed to obtain a desired model accuracy $E$ (note that the $\leq$ sign in Tab. I refers to the stopping condition of the algorithm [8]). As an example, the forth row of Tab. I highlights that 75% of the links can be approximated by models with a number of terms lower than 50 for $E = 0.05$, 96 for $E = 0.01$ or 207 for $E = 0.001$.

As an example, Fig. 2 compares one example measurement with the prediction obtained by means of (1) for $E = 0.01$, thus highlighting the good accuracy of the model. Lower values of the error threshold, as $E = 0.001$, lead to even better results, with the model response overlapping the reference measurements in all the frequency band of interest and with an unavoidable increase of the total number of terms (see Tab. I).

An additional and useful information arising from the above test is that the maximum delay $\tau_m$ included in the model is in general large even for those models with a limited number of terms. As an example, for the case $E = 0.05$, the position of the maximum delay is 578 (the position is defined as the ratio between $\tau_m$ and the sampling period $T = 1/(2 \times 100$ MHz). In other words, this test highlights that compact models with some tens of terms still have the delays spanning a

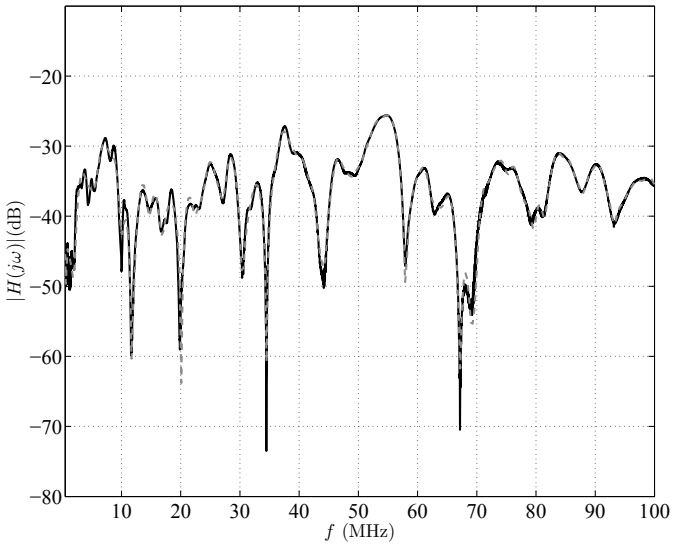


Fig. 2. Magnitude of a selected $H(j\omega)$ network response. Solid black: measurement; dashed gray: model response obtained for $E = 0.01$.

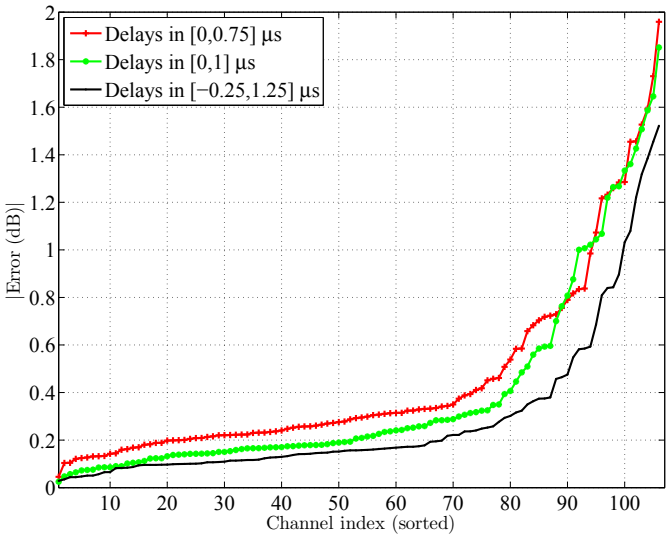


Fig. 3. Mean absolute error per HomePlug AV2 subcarrier ($E = 0.001$) and three different intervals for the constrained model estimation.

wide range, thus impacting on a large amount of resources allocated by a possible hardware emulator implementing the model equations. In this case many null coefficients need to be associated to those delays that are not included in the model but that are within the range. This observation suggests applying the estimation procedure of [8] subject to a constraint in order to force the delays in a specific interval. Moreover, for this second test and in the rest of the paper, we will focus our attention on the $[1.8, 86]$ MHz frequency band. This frequency range has been selected by the HomePlug Alliance for the next generation in home power line technology, namely HomePlug AV2 [14]. The interest reader can find an overview of HomePlug AV2 in [16].

Fig. 3 collects the mean absolute error in dB obtained on the HomePlug AV2 subcarriers (i.e., 3455 subcarriers in the $[1.8, 86]$ MHz frequency range) arising from the models estimated via the aforementioned constrained procedure. In practice, for each measured channel, the absolute error between the measured channel (in dB) and the estimated delay-constrained multipath model (in dB) is computed for each carrier and averaged ($|\text{Error(dB)}| =< ||H(j\omega)(\text{dB})|(\text{meas}) - |H(j\omega)(\text{dB})|(\text{model})| >_\omega$ where $< \cdot >_\omega$ denotes the mean operation). Channel index is sorted in Fig. 3 for better visualization. The error threshold $E = 0.001$ and three alternative constrained ranges of delays ($[0, 0.75]\,\mu s, [0, 1]\,\mu s, [-0.25, 1.25]\,\mu s$) are considered in this comparison. The value of $E = 0.001$ has been selected to obtain an high per carrier precision. First, it is important to note that the mean error (not the absolute one) for all the three cases reported in Fig. 3 is nearly 0 dB for all the considered paths. This implies that the error depicted in Fig. 3 does not imply a biased model. Second, the range $[-0.25, 1.25]\,\mu s$, that includes also some precursor taps, is preferable for all the considered paths. In particular, it allows obtaining average absolute errors per carrier lower than 0.2 dB for the 65% of the measured channels. Tab. II reports the same statistics

TABLE II
STATISTICS OF THE NUMBER OF DELAYS OBTAINED BY APPLYING THE PROPOSED TECHNIQUE TO THE 106 MEASUREMENTS OF FIG. 1 WITH DELAYS CONSTRAINED IN THE RANGE $[-0.25, 1.25]\,\mu s$.

| | $m$ ($E \leq 0.001$) |
|---|---|
| Average | 187 |
| 1–st quartile (25%) | 146 |
| Median (50%) | 209 |
| 3–rd quartile (75%) | 244 |
| 90–th percentile (90%) | 265 |

of Tab. I, for the case of $E = 0.001$, but with the delays constrained in the $[-0.25, 1.25]\,\mu s$ range. The values of Tab. II are greater than the ones of Tab. I, but with the advantage that the number of taps to be implemented in a possible hardware emulator is significantly reduced to 300 (obtained sampling the $[-0.25, 1.25]\,\mu s$ interval at a frequency of 200 MHz). Since this number of taps appears physically feasible in an emulator, there is no need to consider the reduced tap ranges considered in Fig. 3: moreover, we also note that the presence of some precursors (the range $[-0.25, 0]\,\mu s$) would not be a problem in a channel emulator where they could be implemented causally. In what follows we will strengthen the affirmation that a multipath model with delays constrained in the range $[-0.25, 1.25]\,\mu s$ is suitable for modeling the automotive power line channel. We use all the 300 available taps to demonstrate that some characteristic channel parameters do not change for all the considered channels. In particular, for each measured channel we have computed the maximum ($\max_\omega$), the mean ($< \cdot >_\omega$) and the standard deviation ($\sigma(\cdot)$) of the magnitude of $\boldsymbol{H}$ over the HomePlug AV2 frequency range with or without the 300 taps constraint. In Fig. 4, the cumulative distribution

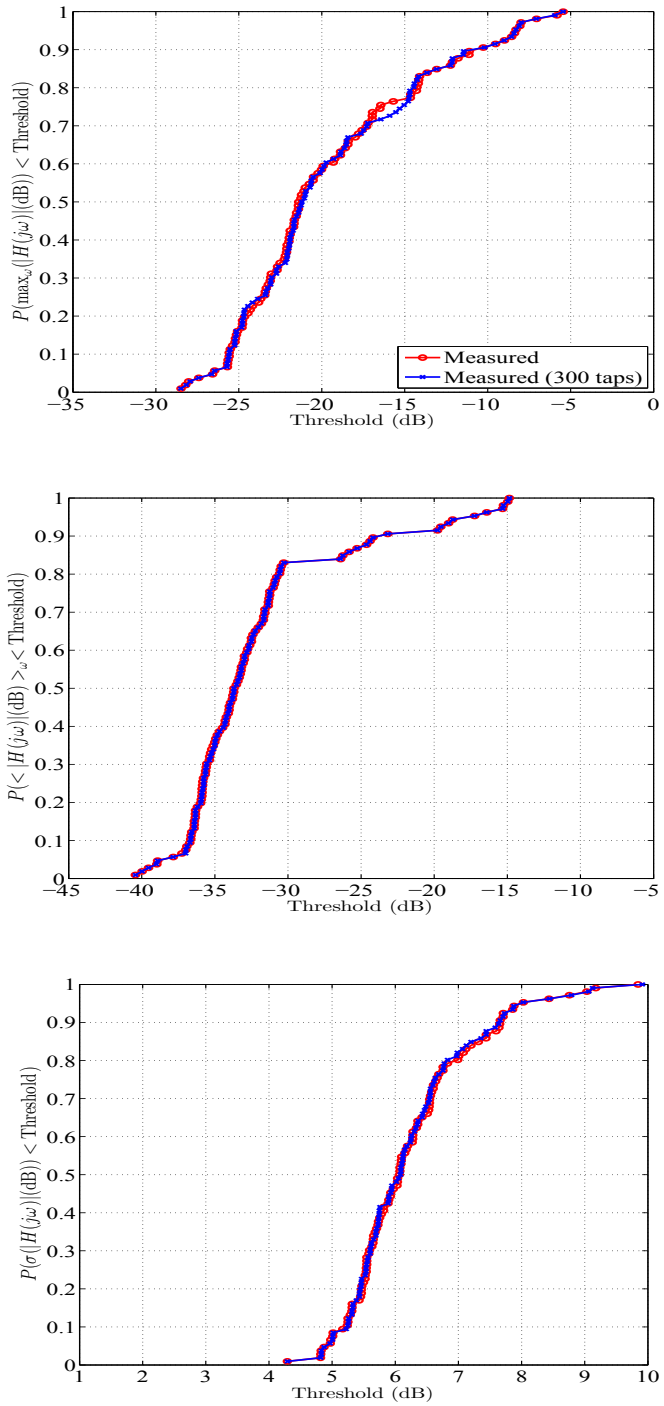


Fig. 4. Cumulative distribution function of the maximum, mean and standard deviation of the magnitude of $\boldsymbol{H}$ computed from both the raw and the truncated measured responses (see text for details). The frequency band considered in this comparison is $[1.8, 86]$ MHz. Top panel: maximum; central panel: mean; bottom panel: standard deviation.

function is reported, showing that the statistics do not change noticeably.

Considering again the HomePlug AV2 frequency band, a similar superposition of curves is obtained by analyzing another important channel parameter, i.e. the coherence band-

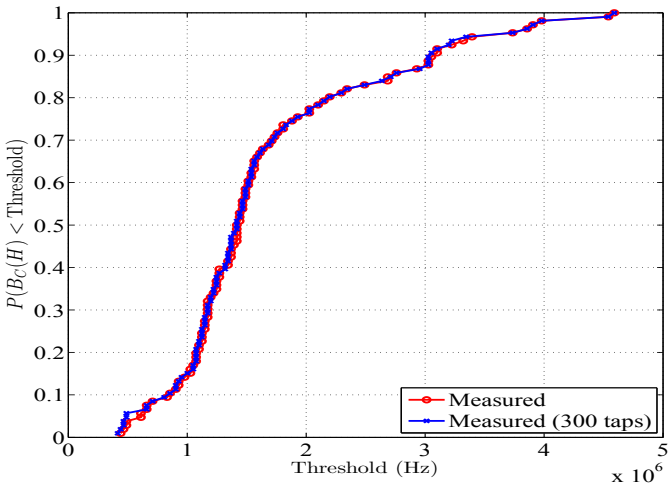


Fig. 5. Cumulative distribution function of the coherence bandwidth computed from both the raw and the truncated measured responses (see text for details). The frequency band considered in this comparison is $[1.8, 86]$ MHz.

width (at 90%), which is depicted in Fig. 5. The statistics shown in Figs. 4 and 5, besides proving that limiting the delays in the $[-0.25, 1.25]\,\mu s$ is a suitable choice for an automotive channel multipath model, contribute to the automotive channel characterization effort that researchers are doing on different car models. For instance, it is interesting to note that the central panel of Fig. 4 shows that the measured channels have a mean value of the magnitude of $\boldsymbol{H}$ lower than $-14.8$ dB and greater than $-40.5$ dB. This result appears similar to [5] where values between $-20$ dB and $-40$ dB are reported for the same parameter (the upper frequency considered in [5] is 70 MHz). We also observe that our results in terms of mean of the magnitude of $\boldsymbol{H}$ can be compared with the ones presented in [11] (for the $[0, 100]$ MHz range) with a good agreement. For this latest comparison, we only advert the reader that in [11] results are presented in terms of voltage transfer function (the channel attenuation): hence, in order to obtain a proper comparison, our results shall be scaled down by 6 dB (see [9] for the relation among S-parameters and voltage transfer function to be used). In particular, in [11], values lower than $-13$ dB and greater than $-43$, $-46$, $-52$ dB (these 3 values are related to different engine states [11]) are shown.

As per the coherence bandwidth, we have found that it is always greater than 439 kHz: this result is comparable with the minimum value of 400 kHz reported in [5]. Instead, a minumum value of approximately 200 kHz has been reported in [11] where, in general, channels that are less coherent have been found. Note that differences are expected when considering different car brands and models: this is reflected for instance in [12] where 4 different cars are analyzed showing a coherence bandwidth between 412 kHz and 4.1 MHz (in [12] the considered upper frequency is 30 MHz). Based upon these data, the carrier spacing of HomePlug AV2, which is the same of HomePlug AV (approximately 25 kHz) is probably over-margined for automotive applications.

In Tab. III, for the sake of completeness, average values

($< \cdot >_{\boldsymbol{H}}$) of the parameters considered in Fig. 4 and Fig. 5 are computed at the 99.9 % confidence interval: we observe that a better resolution of the value at the same confidence level could be only obtained by increasing the number of measurements.

TABLE III
AVERAGE VALUES OVER THE 106 MEASUREMENTS OF FIG. 1 OF THE PARAMETERS SHOWN IN FIG. 4 AND FIG. 5.

| Parameter | Confidence interval (99.9 %) |
|---|---|
| $< \max_\omega(\lvert H(j\omega)\rvert) >_{\boldsymbol{H}}$ | $[-21.33, -17.62]$ dB |
| $< \lvert H(j\omega)\rvert >_{\omega,\boldsymbol{H}}$ | $[-33.92, -30.07]$ dB |
| $< \sigma(\lvert H(j\omega)\rvert) >_{\boldsymbol{H}}$ | $[5.91, 6.58]$ dB |
| $< B_C(H) >_{\boldsymbol{H}}$ | $[1.39, 1.98]$ MHz |

The values in Tab. III are in agreement with the previous literature, in the limits of the expected differences that characterize different car models. For instance, one can scale down by 6 dB the values given for $< \lvert H(j\omega)\rvert >_{\omega,\boldsymbol{H}}$ and compare them with the $-38$ (or $-39$) dB values reported by [11].

## V. CONCLUSIONS

In this paper a statistical assessment of the automotive power line channel has been performed. It has been proven that a multipath model with taps in the range $[-0.25, 1.25]\,\mu s$ is suitable to model the channel. The delay range, initially derived by constraining a literature method, has been proven to be sufficient to preserve characterizing parameters of the power line channel and appears to be suitable for a possible hardware channel emulator (300 taps at 200 MHz frequency). The derived statistics also have been compared with previous finding in the literature, showing good agreement within the limits of the different car brand and models considered. The next steps of this work could be to derive a stochastic mathematical model, able to generate random multipath automotive channels, and to design a hardware channel emulator.

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