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# Behavioral Modeling of Power Line Communication Channels for Automotive Applications

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**Abstract**—The black-box modeling of a power line communication channel in a car is addressed in this paper. The proposed behavioral approach is based on the so-called multipath model representation, that describes the transmission of a signal on a possibly complex power network by means of a finite number of delayed echoes. Model parameters are estimated from the frequency-domain response of the channel via a well-defined modeling procedure. A first assessment on the inclusion in the model equation of the variability of the response of the channel is carried out. The effectiveness of the approach has been demonstrated on a set of real measurements carried out on a commercial automobile.

## I. INTRODUCTION

Nowadays, the design of modern automobiles requires the installation of a large number of in-vehicle electronic equipments. Devices and systems for both safety and comfort are spread all over the car. Well known examples are control circuits for the airbags, anti-blocking systems as well as audio and visual equipments, that require a large number of wires for power and data transfer. All these circuits and connections unavoidably raise the weight of the car and building costs.

In this framework, a promising solution is represented by the power line communication (PLC) technology, that has already been successfully used for buildings applications. PLC modems can be effectively used for the data exchange between two points in the car via the power distribution network, without placing additional dedicated wires. This solution, that relies on standard circuits and communication schemes, helps in reducing the number of connections and preserving the budget.

Numerical models of the power line channel are therefore required for assessing the performance of application designs implementing this technology. The recent literature proposed a large number of methodologies based on different approaches, including multiconductor transmission line theory, digital filters and simplified formulas from digital signal processing [1], [2], [3], [4]. The above approaches, however, require detailed information on the topology of the interconnected structure (that is hardly available for the PLC designer) or assume an oversimplification of the real channel. As an alternative, when the power network is considered as a black-box, a purely behavioral approach can be used instead [5]. This approach, which is based on model representations that are suitable to describe the point-to-point behavior of a PLC channel, has several strengths. Mainly, the model structure is defined by a limited number of parameters that can be

effectively determined from real measured data, via a well-defined procedure. Also, the model accuracy and complexity can be easily tuned by setting an appropriate threshold during the model generation.

The aim of this paper is twofold, (i) extend the application of the behavioral approach to the case of in-vehicle of PLC channels, and (ii) carry out a preliminary assessment for including in the model equation the variability of the response of the channel due to possible different operating states of the car and of the electronic equipments connected to the power distribution network. The detailed procedure for the estimation of model parameters from real measurements is thoroughly discussed with specific emphasis on the effects of data processing in the different modeling steps.

## II. MEASURED DATA

The results collected in this paper are based on a set of measurements available from the official website of the “In-Vehicle Power Line Communication” project at the UBC, University of British Columbia [3]. The available data consists of a number of real measurements of the power line channel scattering parameters data carried out on a small sports car from the Pontiac division of GM, General Motors. The test vehicle has the dimensions and the electronic features typical of many modern compact cars.

A vector network analyzer is used to collect a systematic set of two-port frequency domain scattering measurements between different probing points of the in-vehicle power distribution system. The frequency range is [500 kHz, 100 MHz] and the probing points are the body control module, the cigarette lighter, the air conditioning fan button, the outside view mirror controller and the front and rear lights.

As an example, Fig. 1 shows the magnitude of the  $S_{21}$  scattering parameter associated to the link between the front right and the rear left lights. The different curves in the figure correspond to different possible operating states of the car (e.g., engine turned on or off, ...).

## III. MODEL STRUCTURE

The car power distribution system consists of a possibly complex interconnected structure that can be effectively represented by means of a network of multiconductor transmission lines. The complexity of the structure as well as the uncertainty on its physical parameters suggest to describe the behavior of the PLC channel, i.e., the transmission of the information

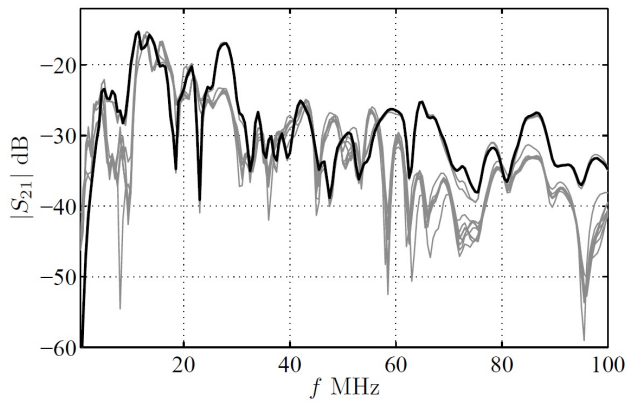


Fig. 1. Magnitude of the  $S_{21}$  scattering parameter of a channel between the front right and the rear left lights. The frequency range is [500 kHz, 100 MHz]. The different curves in the plot correspond to thirteen possible operating states of the car (e.g., lights turned on or off, ...). The black thick line is the measured curve in the set that has been selected for the application of the proposed technique.

between two points of the power network, via the so-called multipath model representation. The multipath model is a black-box parametric representation aimed at describing the signal at the receiver side as a sum different delayed echoes of the transmitted signal. [5], [6], [7]. The proposed model, that accounts for the effects of the multiple reflections of signals on the power line, writes:

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

where  $H$  is the frequency domain transfer function of interest (e.g., the  $S_{21}$  parameter of Fig. 1),  $g_k$  are complex weighting coefficients accounting for the attenuation and phase distortion of the transmitted signal and the  $k$ -th exponential term corresponds to the delay  $\tau_k$ . It is worth noticing that model (1) can be suitably extended by including frequency-dependent weighting coefficients accounting for the cable losses. However, for the specific application at hand and for the frequency range of interest, this simple lossless relation has been proven to provide accurate results.

The estimation of model (1) amounts to determining the number of echoes, the delays and the linear coefficients.

#### IV. MODELING PROCESS AND RESULTS

This Section summarizes the step-by-step procedure for the estimation of model parameters and collects the results on its application to the real measurements of Fig. 1.

**STEP 1. Compute the impulse response of the channel** via the inverse FFT (iFFT) of the original frequency-domain data. If the approximation defined by (1) holds, the impulse response turns out to be defined by a number of delayed pulses arising from the exponential terms in the model equation.

As an example, Fig. 2 shows the impulse response arising from the processing of the selected  $S_{21}$  scattering parameter of Fig. 1. The black curve in the Figure has been obtained by means of the Matlab<sup>®</sup> function `ifft.m`.

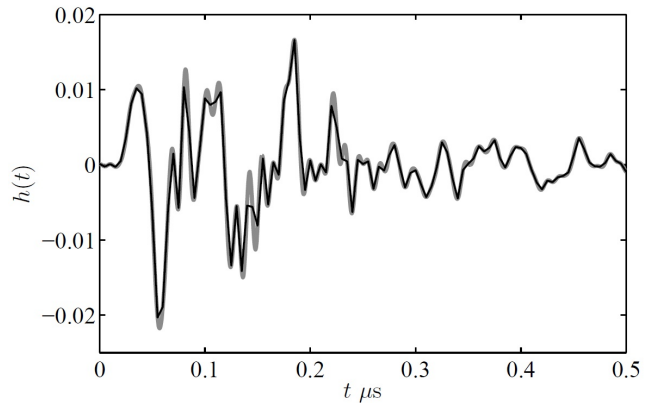


Fig. 2. Impulse response obtained via the inverse FFT of the measured  $S_{21}$  parameter. Black curve: direct application of the `ifft` Matlab function; Gray curve: response with increased time-resolution obtained by zero-padding the original frequency domain response up to 1 GHz.

It is relevant to remark that the typical bandwidth of the measurements, for this class of applications, leads to impulse responses with a low spatial resolution that hardly allows the estimation of the position of peaks. Owing to this, the resolution of the impulse response needs to be improved via standard techniques like zero-padding, that amounts to appending zeros to the frequency-domain response up to a larger frequency. The effect of zero-padding can be appreciated from the gray curve of Fig. 2 that represents the same impulse response generated by filling in the selected frequency domain response with zeros up to a maximum frequency of 1 GHz. Clearly, zero-padding does not introduce additional information. However, it allows to easily locate the pulses composing the impulse response and therefore the set of delays that will be possibly included in model (1).

**STEP 2. Determine the number of delays  $n$  and the values  $\{\tau_k\}; k = 1 \dots, n$**  from the impulse response of Fig. 2. Roughly speaking, this is done by selecting the subset of delays corresponding to the peaks of the impulse response leading to the largest reduction of the error between the measured and the predicted responses.

Specifically, this is achieved by considering all the possible  $M$  peaks of the impulse response as tentative delays and by recasting the scalar frequency domain equation (1) in terms of the following linear least squares problem:

$$\mathbf{H} \approx \mathbf{D}\mathbf{g}. \quad (2)$$

where vector  $\mathbf{H} = [H(j\omega_1), H(j\omega_2), \dots, H(j\omega_N)]^T$  collects the available tabulated frequency samples known at the  $N$  frequencies  $\{\omega_1, \dots, \omega_N\}$ , matrix  $\mathbf{D}$  writes

$$\mathbf{D} = \begin{bmatrix} e^{-j\omega_1\tau_1} & \dots & e^{-j\omega_1\tau_M} \\ e^{-j\omega_2\tau_1} & \dots & e^{-j\omega_2\tau_M} \\ \vdots & \vdots & \vdots \\ e^{-j\omega_N\tau_1} & \dots & e^{-j\omega_N\tau_M} \end{bmatrix} \quad (3)$$

and vector  $\mathbf{g}$  collects the unknown weighting coefficients  $\{g_1, g_2, \dots, g_M\}$ .

In order to select the subset of delays leading to the largest reduction of the approximation error, matrix  $\mathbf{D}$  is decomposed into the product of an orthonormal matrix  $\mathbf{Q}$  and of an upper triangular matrix  $\mathbf{R}$ . This is achieved by means of the standard  $QR$  factorization (e.g., the Matlab<sup>®</sup> function `qr.m` is readily available and can be effectively used). In turn, equation (2) becomes:

$$\mathbf{H} \approx \mathbf{D}\mathbf{g} = \mathbf{Q}\mathbf{R}\mathbf{g} = \mathbf{Q}\bar{\mathbf{g}}. \quad (4)$$

From the above equation, the approximation error is defined by  $\|\mathbf{H} - \mathbf{Q}\bar{\mathbf{g}}\|^2$  where  $\|(\cdot)\|^2$  is the norm assumed in the euclidean space of complex variables (i.e.,  $\|(\cdot)\|^2 = \langle (\cdot), (\cdot) \rangle = (\cdot)^*(\cdot)$ ). With few mathematical steps, it can be also verified that:

$$\|\mathbf{H} - \mathbf{Q}\bar{\mathbf{g}}\|^2 = \mathbf{H}^*\mathbf{H} - \bar{\mathbf{g}}^*\mathbf{Q}^*\mathbf{Q}\bar{\mathbf{g}} = \mathbf{H}^*\mathbf{H} - \bar{\mathbf{g}}^*\bar{\mathbf{g}}. \quad (5)$$

Equation (5) suggests to select the  $n$  coefficients of vector  $\bar{\mathbf{g}}$  that largely contributes to the second term, i.e.,

$$\bar{\mathbf{g}}^*\bar{\mathbf{g}} = \sum_{k=1}^M |\bar{g}_k|^2 \quad (6)$$

In this example, only the  $k$ -th terms that are greater than a certain threshold are selected. It is relevant to remark that better results are achieved via the solution of a weighted least squares problem obtained by multiplying the left and the right hand sides of equation (2) with a weight matrix  $\mathbf{W} = \text{diag}(1/|H(j\omega_1)|, 1/|H(j\omega_2)|, \dots)$ . For the example at hand, the circles in Fig. 3 corresponds to the peaks of the impulse response that are above the  $2 \cdot 10^{-3}$  relative threshold. The total number of selected delays is  $n = 60$ .

At the end of the process, if needed, the model quality can be improved by lowering the threshold and re-iterating the modeling process.

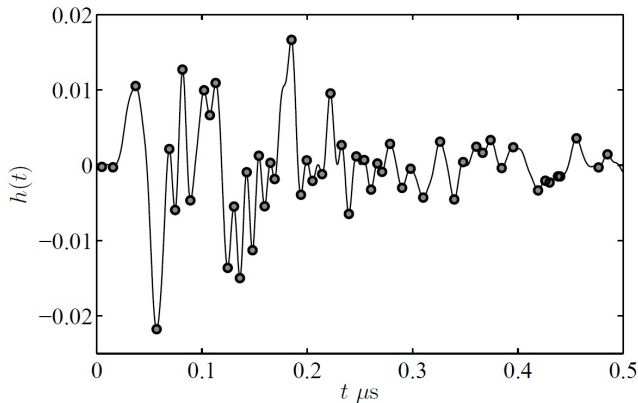


Fig. 3. Peaks of the impulse response of Fig. 2 that has been automatically selected by the proposed procedure (see the circles superimposed to the impulse response). The abscissas of the selected peaks correspond to the delay parameters of model (1).

**STEP 3. Estimate the subset of the linear coefficients**  $g_k$  of (1) that are associated to the selected delays. The computation is done from the frequency domain data via the solution of the reduced linear least squares problem (2). In this step, only the columns of the matrix corresponding to the  $n$  selected delays are considered.

Figure 4 compares the measured frequency domain transfer function to the prediction obtained by means of equation (1), thus highlighting that a relatively limited number of terms leads to a compact and accurate model that can be effectively used to reproduce the behavior of the PLC channel. Similar results can be obtained for different links.

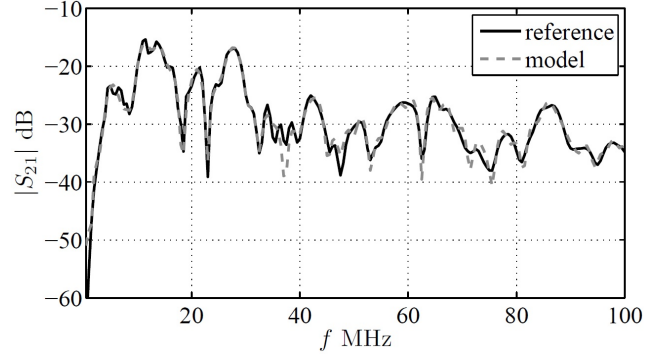


Fig. 4. Magnitude of the  $S_{21}$  selected scattering parameter. Solid black: measurement; dashed gray: model response.

In order to highlight the role of the different echoes in the multipath model equation (1), Fig. 5 shows the magnitude of the reference measured response along with the magnitude of the predicted responses obtained with a model consisting of one, two and five terms. Clearly, one term leads to a model response that has a constant magnitude and two terms provide a response with a simple periodic behavior along the frequency axis. With a larger number of terms (as five in the third gray curve considered in the plot), the response of the multipath model become richer and closer to the real measurement. Of course, a good accuracy is achieved by increasing the number of terms.

**STEP 4. Include in the model equation the variability of the response of the PLC channel** due to possible different conditions of the active terminations of the power distribution network, i.e., of the operating states of the car and of the electronic equipments connected to the power distribution.

The number and values of the delays are assumed to be constant since the physical lengths of the wires and the network topology do not change, and the variability is included in the weighting coefficients  $g_k$  of (1) instead. In this study, a set of deterministic linear coefficients has been computed from the different available measurements of Fig. 1 via the solution of the same reduced least squares problem (2). As an example, Fig. 6 shows the same comparison of Fig. 4 for two different operating states. The two plots correspond to a selection of two gray curves of Fig. 1. This comparison further confirms the

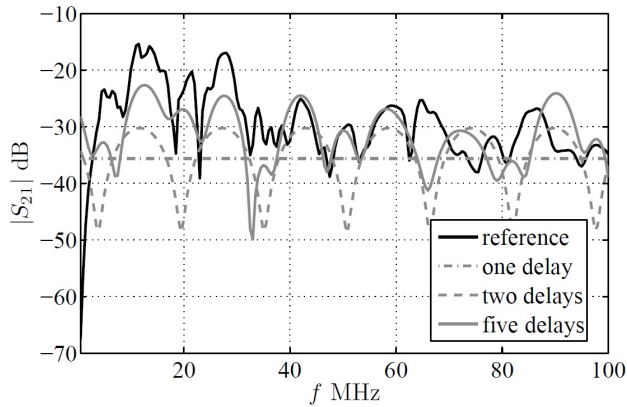


Fig. 5. Magnitude of the  $S_{21}$  reference scattering parameter. Solid black: measurement; dashed gray curves: responses of models with an increasing number of delay terms.

accuracy of the proposed model and of the presented modeling procedure.

In order to gain an insight into the variability of model parameters, Figure 7 shows the magnitude and phase of the linear weighting coefficients  $g_k$  associated to the selected delays of Fig. 3. For each delay in the abscissa, the different symbols represent the  $k$ -th coefficient computed from four responses of the same link that exhibit a pretty different frequency-domain behavior. The plot of Fig. 7 highlights a correlation between a specific response and the position of both the magnitude and phase of the  $k$ -th coefficient, thus suggesting to exploit this information in the development of a statistical model of the PLC channel.

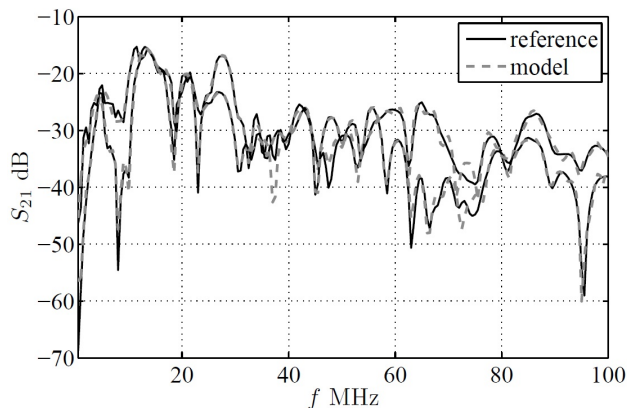


Fig. 6. Magnitude of the  $S_{21}$  scattering parameters of a selection of two alternative measurements. Solid black: measurements; dashed gray: model responses.

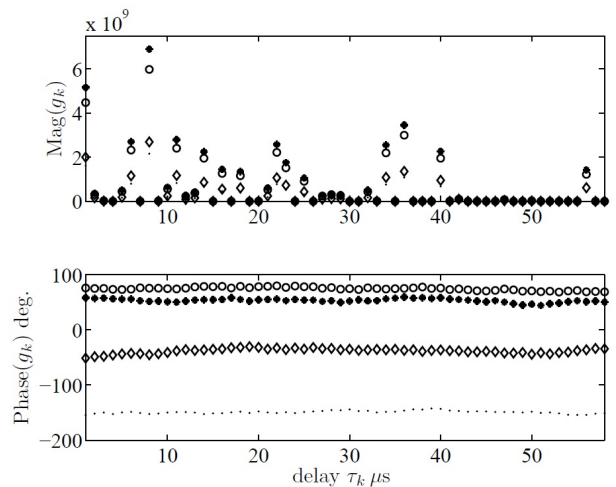


Fig. 7. Linear coefficients  $g_k$  of (1) for four different operating states of the car.

## V. CONCLUSION

In this paper, a purely black-box behavioral approach is applied to the behavioral modeling of the in-vehicle power line channels. The proposed technique allows to generate accurate models of a point-to-point link of the power distribution network, from frequency-domain measurements. The model structure consists of the so-called multipath representation, that allows to describe the transmission of a signal on a complex transmission line structure by means of a number of delayed echoes. The step-by-step modeling procedure is thoroughly described and the strengths of the approach has been demonstrated by means of its application to a set of frequency domain scattering measurements carried out on a commercial automobile.

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