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Power Line Communication Channel Modeling for In-Vehicle Applications

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Abstract—This paper addresses the problem of generating an accurate power line communication channel model for in-vehicle applications. The proposed modeling methodology is based on a state-of-the-art behavioral representation based on the multipath propagation of signals in a possibly complicated interconnected power structure. The procedure for the computation of model parameters is thoroughly discussed. The effectiveness of the approach has been demonstrated on a set of real measurements carried out on a commercial automobile.

I. INTRODUCTION

In the past few years, the number of in-vehicle electronic equipments used in modern automobiles has grown rapidly. Devices for both safety and comfort, including control circuits for the electronic stability, anti-blocking systems as well as audio and video equipments require a large number of wires for power and data transfer that unavoidably raise the weight of the car and building costs.

In this framework, a promising solution that helps in reducing the number of connections and thus preserving the budget is represented by the power line communication (PLC) technology, that has already been successfully implemented in a number of applications [1]. PLC modems can be used to communicate between two points in the car via the power distribution network, without placing additional dedicated wires for data exchange. This solution relies on standard circuits and communication schemes, thus making this choice an effective alternative for this class of applications.

Numerical models of the PLC channel are thus required for assessing strengths and limitations of application designs implementing this technology. The recent literature proposed a number of alternative modeling methodologies. Without loss of generality, we limit ourselves to the results on the physical-based modeling of the power delivery network via the cascade connection of multiconductor transmission lines or digital filters [2], [3]. The above class of approaches, providing accurate results in reproducing the behavior of real power networks, requires detailed knowledge of the possibly complex interconnected structure (that is hardly available for the PLC designer). The lengths and crossection of wires as well as the information on materials need to be known. As an alternative, simplified formulas from digital signal processing theory can be used [4]. This method, however, represents an oversimplification of the real channel, with the aim of generating an initial guess for the quantitative computation

of the performance of the PLC channel [5]. When the power network is considered as a black-box, a purely behavioral approach can be used instead [6]. 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, and the model accuracy and complexity can be easily tuned by setting an appropriate threshold during the model estimation.

This paper focuses on the latter behavioral approach with the aim of extending the application of this method, that has already been successfully used in building applications, to the case of in-vehicle PLC channels. The modeling procedure for the computation of model parameters from real measured data is thoroughly discussed with specific emphasis on the effects of data processing in the different modeling steps.

II. MEASUREMENTS

This study relies on a set of freely available measurements that can be downloaded from the official website[1] of the "In-Vehicle Power Line Communication" project at the University of British Columbia [5]. These measurements consist of the power line channel scattering parameters data collected from a Pontiac Solstice 2006. The Solstice is a small sports car from the Pontiac division of General Motors (GM) which has the dimensions and electronic features typical for many compact cars and any auto-maker.

Specifically, a systematic set of two-port frequency domain scattering measurements has been carried out by means of a Vector Network Analyzer (VNA) between different pairs of 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, which is part of the fuse/relay box on the front passenger side of the console, the cigarette lighter, the outside view mirror controller, the heating ventilating air conditioning fan button and the front and rear lights. The lamps had to be removed during the measurements to access the power line.

As an example, Fig. 1 shows the magnitude of the S_{21} scattering parameter associated to the link between the outside rear view mirror controller and the rear left light. The different

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[1]The link is: http://www.ece.ubc.ca/ lampe/VehiclePLC_folder/PLC.htm.

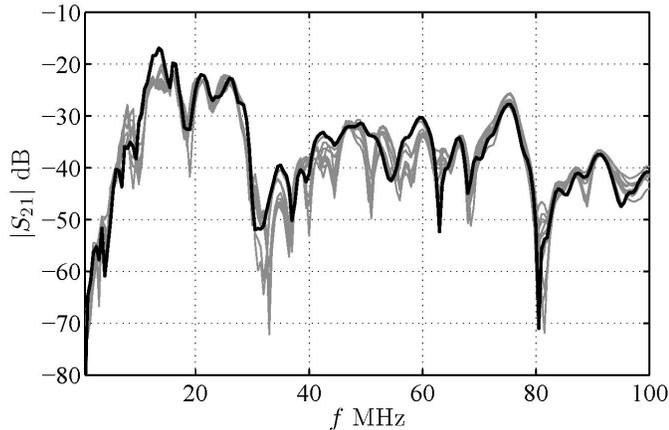curves in the figure correspond to different possible operating states of the car (e.g., engine turned on or off,...).

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

III. MULTIPATH MODEL REPRESENTATION

This Section describes the model representation assumed to mimic the behavior of a PLC channel, i.e., the transmission of the information between two points of the power distribution network of a car.

Due to the physical nature of the typical power distribution system, that consists of a complex interconnected structure of multiconductor power lines, a signal transmitted on the PLC channel will be delayed and corrupted by possible multiple reflections. As a result, the signal at the receiver side turns out to be the sum of different delayed echoes of the transmitted signal. This is the rationale of the so-called multipath model that has been successfully used in the literature for the behavioral modeling of a PLC channel [6], [7], [8]. The proposed model in the frequency domain writes:

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

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 τ_k. The above relation approximates the transfer function of an ideal lossless interconnected structure via the sum of a finite number of delay terms. It is relevant to remark that the above model can be suitably modified by including additional frequency-dependent weights that account for the cable losses. However, for the specific application at hand and for the frequency range of interest, the simplest lossless relation of eq. (1) can be effectively used.

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

IV. MODELING PROCEDURE AND RESULTS

The proposed strategy for the estimation of model parameters from a set of real measured transfer functions like the ones of Fig. 1 can be summarized by the following three steps:

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. The positions of the pulses along the time axis represent the time delays τ_k.
   As an example, the gray curve of Fig. 2 is the impulse response arising from the processing of the selected S_{21} scattering parameter of Fig. 1. The time domain response has been obtained by means of the Matlab® function ifft.m.
   It is worth noticing that the typical bandwidth of the measurements for this class of applications, that is on the order of one hundred MHz, leads to an impulse response with a low timing 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 and also highlights the possible spurious oscillations coming from the iFFT of a signal that has a limited bandwidth. However, it allows to easily locate the sharp pulses composing the impulse response and therefore the set of delays that will be possibly included in model (1). From the curve of Fig. 3, the number of delays n and the values $\{\tau_k\}; k = 1 \dots, n$ are chosen by means of a threshold mechanism. Specifically, only the delays corresponding to the peaks of the impulse response with relative magnitude above a certain threshold, are selected. The circles in Fig. 3 highlight the peaks of the impulse response that are above the 1% relative threshold. At the end of the process, if needed, the model quality can be improved by lowering the threshold and re-iterating the modeling process.
2) Once the delay terms have been determined, the linear coefficients g_k of (1) are estimated from the frequency domain data via the solution of the following linear least squares problem:
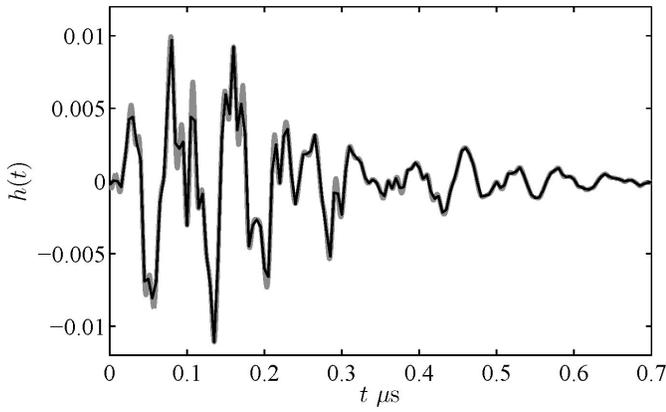
Fig. 2. Impulse response obtained via the inverse FFT of the measured S_{21} parameter. Black curve: direct application of the `ifft` Matlab function; Gray curve: response with increased time-resolution obtained by zero-padding the original frequency domain response up to 1 GHz.
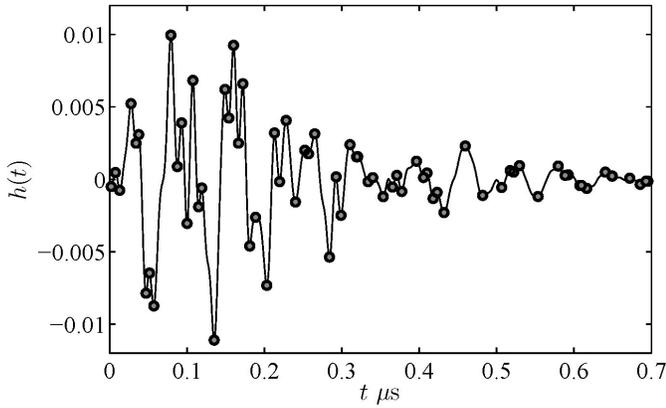

Fig. 3. Automatically selected peaks of the impulse response of Fig. 2 (see the circles superimposed to the impulse response). The abscissas of the selected peaks are the delay parameters of model (1).

Fig. 4. Linear coefficients g_k of (1).

Fig. 5. Magnitude of the S_{21} reference scattering parameter. Solid black: measurement; dashed gray: model response.

$$
\begin{bmatrix} H(j\omega_1) \\ H(j\omega_2) \\ \vdots \\ H(j\omega_N) \end{bmatrix} \approx \begin{bmatrix} e^{-j\omega_1\tau_1} & \dots & e^{-j\omega_1\tau_n} \\ e^{-j\omega_2\tau_1} & \dots & e^{-j\omega_2\tau_n} \\ \vdots & \vdots & \vdots \\ e^{-j\omega_N\tau_1} & \dots & e^{-j\omega_N\tau_n} \end{bmatrix} \begin{bmatrix} g_1 \\ \vdots \\ g_n \end{bmatrix}
$$
(2)

In the above equation, $\{H(j\omega_1),\dots,H(\omega_N)\}$ are the available tabulated frequency samples known at the N frequencies $\{\omega_1,\dots,\omega_N\}$. Figure 4 shows the magnitude and phase of the linear coefficients g_k associated to the selected delays of Fig. 3.

Figure 5 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.

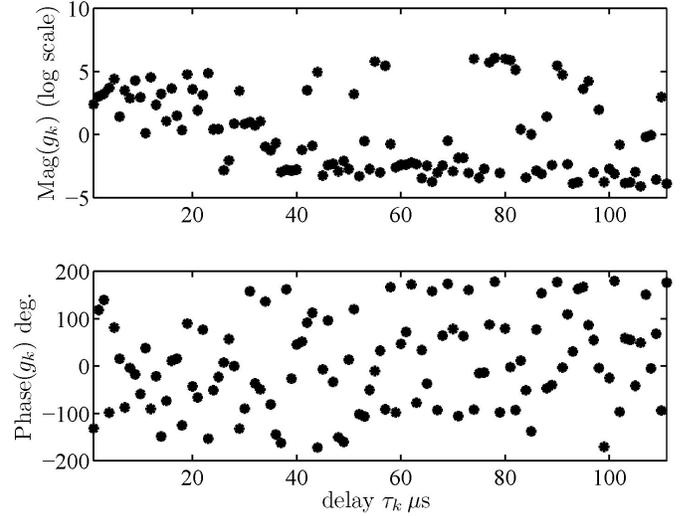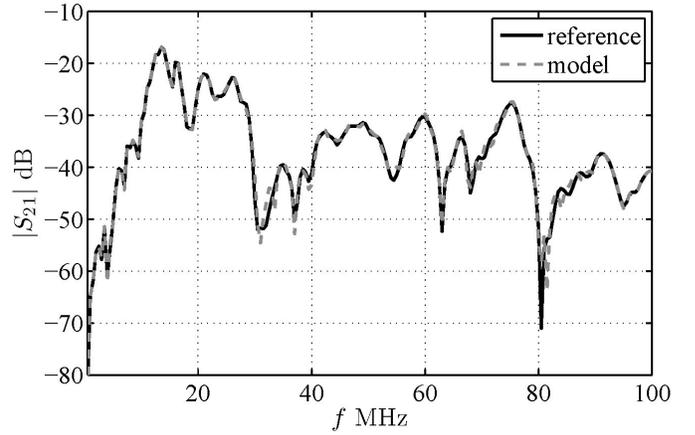Table I shows the figures of model complexity and accuracy for different values of the relative threshold set during the selection of delays (see the previous step). The complexity is quantified by the number of delays included in the model and the accuracy by means of the root mean square error (RMS) computed form the sampled frequency-domain responses of Fig. 5.

3) For a specific data link, the last step of the modeling

TABLE I
FIGURES OF MODEL COMPLEXITY AND ACCURACY FOR DIFFERENT VALUES OF THE RELATIVE THRESHOLD SET DURING THE AUTOMATIC SELECTION OF DELAYS.

Rel. Threshold	n	RMS error
2 %	74	5.1e-3
1.5 %	83	4.0e-3
1 %	111	3.1e-3
0.5 %	189	1.9e-3

process amounts to including 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 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 least squares problem (2). As an example, Fig. 6 shows the same comparison of Fig. 5 for two different operating states. The two plots correspond to a selection of two gray curves of Fig. 1. This comparison further confirms the accuracy of the proposed model and of the presented modeling procedure.
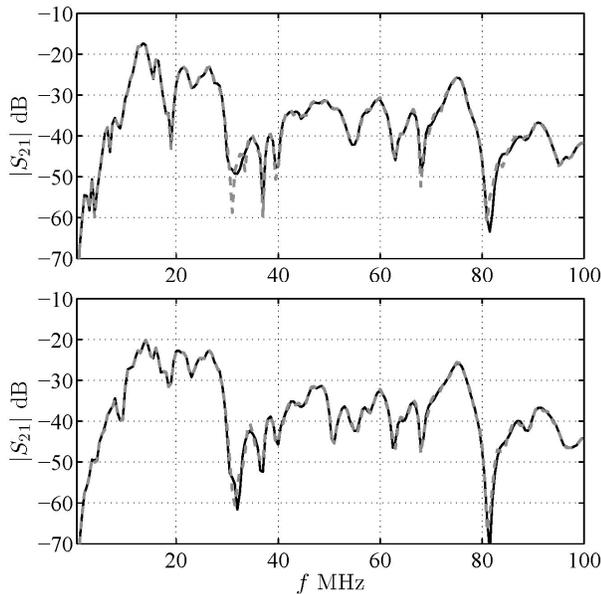

Fig. 6. Magnitude of the S_{21} scattering parameters of a selection of two alternative measurements. Solid black: measurements; dashed gray: model responses.

V. CONCLUSION

This paper addresses the in-vehicle power line channel communication modeling via a black-box behavioral methodology. The proposed approach, based on the so-called multipath parametric model representation, has several strengths and has already been successfully applied to different applications. The model is defined by a set of delays and weighting coefficients that account for the inherent multipath propagation of the signals in a possibly complicated power distribution network. Model parameters can be effectively determined from frequency-domain measurements via a well-defined modeling procedure. 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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