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Broadband PLC Field Trial on a Compact Electric Vehicle

Marco De Piante, Fabio Versolatto, and Andrea M. Tonello
University of Udine, Via delle Scienze 208 - 33100 Udine - Italy
e-mail: {marco.depiante, fabio.versolatto, tonello}@uniud.it

***Abstract*—Power line communication (PLC) is a valuable solution to limit the amount of wiring, reduce the weight and thus increase the performance of electric vehicles. Basically, PLC removes the need of a dedicated wiring infrastructure for the data exchange by signaling over the power delivery cables.**

This work shows the potentialities of such technology reporting the performance of commercially available PLC devices designed for in-home networks and adapted for the in-vehicle scenario. Further, it provides an insight on the channel and noise characteristics and proves the robustness of PLC, a technology that is able to cope with high attenuation, large periodic noise and disruptive impulses. Finally, an application example where a rear camera is connected via PLC to a display placed on the dashboard of the vehicle is described.

I. Introduction

Power line communication (PLC) is one among the most attractive communication technologies in the field of in-vehicle applications because it enables exploiting the in-vehicle wiring for the communication needs. Among the possible applications of PLC, some examples are the x-by wire services, the communications between sensors/actuators and the main unit, or the so-called infotainment [1]. By reducing the amount of dedicated cables for data communications, PLC reduces the weight, improves the performance and, ultimately, increases the efficiency. In this respect, it should be noted that, nowadays, the wires contribute as the third factor, after the engine and the gearbox, to the total weight of the vehicle.

Despite the advantages, the use of PLC for in-vehicle applications has been limited by the hostile conditions of the medium, that are a mix of large channel attenuation, high levels of noise and, further, low values of the line impedance.

The characteristics of the in-vehicle PLC channel were reported in several works in the literature from experimental basis. Namely, [1] points out a channel attenuation always in excess of 25 dB, [2] confirms the previous finding proving that the attenuation settles above 30 dB, and [3] provides a comprehensive analysis in terms of scattering parameters. Furthermore, [3] shows that parasitic wireless propagation effects at high frequencies may enable communications even across open switches. Finally, the study in [4] a) describes an experimental campaign whose results, i.e., the scattering parameters, have been made available online, b) confirms the large attenuation evidenced by other works and c) points out a frequency selective behavior of the channel response.

Beside the experimental evidences, the in-vehicle channel has been also modeled, either according to a top-down approach, fitting the multipath propagation model [5] to the in-vehicle scenario [6], or according to a bottom-up approach, exploiting the transmission line theory. Physically, the channel is given by the conductors that deliver the electrical power throughout the vehicle. Typically, the circuit is given by a dedicated conductor from the battery to the load, as for instance the lights, and by the body of the vehicle for the reverse path. In this case, the conductors are not closely arranged, the propagation is not strictly transverse electromagnetic (TEM) and thus the telegrapher's equations that describe the signal propagation cannot be solved in a closed-form. Therefore, bottom-up approaches are based on numerical solutions of the telegrapher's equations, as described in [7]. Alternatively, [1] proposes a wavelet model of the scattering parameters.

Beside the large attenuation, the in-vehicle PLC channel is characterized by disruptive impulsive noise. A review of the in-vehicle PLC noise was provided in [8]. Noise measurements were discussed in [9], [10], and [11]. In particular, [9] shows that noise peaks of up to 6 V are possible. A noise model that is based on the Markov process is described in [10].

The line impedance is the last important quantity that has an impact on PLC performance. In general, the line impedance exhibits a frequency selective behavior, similar to that of the in-home scenario [12]. Mismatches between the internal impedance of the modem and the line impedance lead to reflection effects that limit the amount of power injected into the network. Thus, the design of the coupling part of the transceiver is a fundamental aspect in PLC [13].

Finally, it has to be noted that PLC may interfere with wireless communications. The power spectral density of the transmitted signal must be kept as low as possible, say, below -60 dBm/Hz [9]. The low admitted power spectral density, together with the horrible channel attenuation, the large noise and the unmatched and frequency selective line impedance render in-vehicle PLC even more challenging.

To show that despite the large impairments, high-speed in-vehicle PLC are possible, in this work, we report the results a field trial of a PLC system. The electric vehicle is a compact car that we described in [14] both in terms of channel characteristics and noise. The PLC technology that we consider herein is broadband, compliant with the HomePlug AV2 standard and capable of 500 Mbps at the physical layer [15]. We customized commercial HomePlug AV2 adapters for the purposes of the field trial and we investigate their performance. We focus on the throughput and the delay, we discuss the disruptive role of the noise, in particular, during the

TABLE I. OVERVIEW OF THE MAIN PLC STANDARDS

Standard	Frequency classification	Datarate at PHY (Mbps)
G3	Narrow band	< 0.24
P1901.2	Narrow band	< 0.5
PRIME	Narrow band	0.128
G.hn	Broadband	> 200
HomePlug AV2	Broadband	500
P1901	Broadband	540

braking phase, and we provide an insight on the characteristics of the channel and the line impedance. Hence, we present a practical application example of PLC. Namely, we connect a camera on the back of an electric vehicle to a monitor placed on the dashboard exploiting the feeding cable of the rear lights.

The remainder of the paper is divided as follows. Section II overviews the PLC technology, the standard that we adopt and the integration performed from commercially-available devices. Section III provides details about the vehicle and its electrical wiring and Section IV reports the experimental results. Hence, Section V provides some details on the proposed application example. Finally, some conclusions follow.

II. PLC TECHNOLOGY OVERVIEW

PLC superposes a high frequency signal to the mains. Table I reviews the most important PLC standards. According to the range of frequencies that it occupies, PLC is divided in narrow band and broadband. Narrow band PLC operates below 500 kHz and it is intended for low-rate robust communications, as metering, home automation or remote command and control services. Narrow band PLC is widely deployed for Smart Grid applications, and the most popular standards are PRIME [16] and G3 [17]. Recently, IEEE P1901.2 [18] has introduced ad-hoc mechanisms for the coexistence between non-compatible narrow band PLC devices.

Broadband PLC operates in the range of frequencies between approximately 2 and 86 MHz and it is intended for high-speed communications as multimedia streaming. Broadband PLC was designed for the domestic scenario, where it can provide a valuable alternative to wireless solutions. In-home PLC standards are HomePlug AV, P1901 and G.hn. The former is the most popular and, in its current version, it enables up to 500 Mbps at the physical layer. A new variant of HomePlug AV is HomePlug Green PHY. Green PHY is the broadband alternative to narrow band PLC for services that require low data rate but also low power consumption and low cost. HomePlug Green PHY is also intended for communications between the vehicle and the infrastructure.

In this work, we aim to address the performance of the current commercial devices, based on a broadband PLC technology intended for the in-home scenario, in the in-vehicle scenario. In fact, we believe that broadband PLC can be a valuable solution both to deliver high-speed multimedia content within the vehicle and to convey signals from sensors and actuators to the central unit without the need of a heavy, dedicated wiring infrastructure. We choose commercial devices based on the HomePlug AV2 standard. Further details about the standard are provided in the next section. We customized the PLC devices in order to fulfill the requirements of the in-vehicle scenario. Details about the customization are provided in Section II-B.

A. HomePlug AV2

HomePlug AV2 is a PLC standard intended for very high speed in-home applications. Such extremely high performance are obtained combining a mixture of state-of-the-art communication solutions. Among these, the most important are the following [15].

- *Frequency Extension*. HomePlug AV2 extends the signaling frequency from 2-30 MHz up to 2-86 MHz, providing more than 80 MHz of communication channel bandwidth. Previous broadband PLC solutions were limited to the frequency range up to 30 MHz for EMC-related issues. Now, HomePlug AV2 adopts ad-hoc power management solutions to reduce the power spectrum of the transmitted signal and ultimately to avoid interfering with existent radio services. Note that the frequency extension leads to a sampling frequency of 200 MHz.
- *Multi Carrier Modulation*. HomePlug AV2 deploys orthogonal frequency division multiplexing (OFDM) with up to 8192 carriers combined with quadrature amplitude modulation with up to 4096 levels. OFDM is a multi carrier communication scheme that is able to cope with the frequency selectivity and thanks to its extremely high performance and low complexity it has been adopted by a number of standards. Among these, long term evolution (LTE) mobile systems, asymmetric digital subscriber lines (ADSLs), and WiFi.
- *High-Rate Turbo Codes*. Channel codes improve the robustness of the communication by adding redundancy. HomePlug AV2 adopts efficient turbo codes that size the redundancy to the characteristics of the channel in order to ensure always the best performance. In numbers, the amount of required redundancy that have to be added can be as low as 11% of the pure information data stream.
- *MIMO*. HomePlug AV2 introduces multiple-input multiple-output (MIMO) transmission schemes. MIMO can be used when more than two conductors are present, to deliver more than one data stream or to exploit the spatial diversity to improve the communication robustness (via beamforming). For the purposes of this work, we do not exploit MIMO.

Besides the former advances, HomePlug AV2 adopts further signal processing solutions, as windowing, efficient notching, and impedance-mismatch compensation and guard-interval adaptation strategies whose details can be found in [15]. Another interesting feature of HomePlug AV2 is that it can operate in direct current (DC) networks, as those within electrical vehicles or between the vehicles and the electrical charging infrastructure. This important feature, in conjunction with the fact that it is one among the most widespread standards makes HomePlug AV2 a good choice for the scopes of this work.

B. PLC Device Integration

We adapted a set of commercial HomePlug AV2 devices that are designed for in-home networking on 230V AC networks. Basically, we modified the power supply circuitry to feed the modems from 12V DC instead of 230 AC. To this aim,

Fig. 1. Estrima Bir, the smallest electrical vehicle in Italy.

we adopt a standard step-down (buck) converter. We apply a low pass filter between the step-down converter and the point of injection of the PLC signal, to limit the switching noise contribution at high frequencies due to the converter. We do not adopt further noise reduction strategies as the modems are intended to be installed on termination nodes without noisy devices.

III. Overview of the On-Trial Vehicle

We aim to study the suitability of broadband PLC for the communication needs in electrical vehicles. To this aim, we perform a field trial on the Estrima - Birò, which is the most popular compact electric vehicle in Italy. Fig. 1 is a picture.

The Estrima - Birò represents a worst case test scenario for PLC because the vehicle is compact, and all the noise sources, as the DC/DC converter, are close to the PLC devices and they contribute to the conducted and coupled noise components. Hence, if the use of PLC is validated in this worst case scenario, we expect such technology to be promising also where the impact of noise may be less disruptive.

A. Description of the Vehicle

The Estrima - Birò is equipped with two brush-less motors, capable of 2 kW each, that are directly connected to the rear wheels. The maximum speed is set to 45 kmh and the vehicle is able to tackle slopes up to 20%. The power is provided by a 48V lithium battery pack controlled by a battery management system. Auxiliary services, as lights, are connected to the 12V electrical circuit of the vehicle which is fed by the DC/DC converter. The return-current path is provided by a dedicated wire that is shared among nearby devices and that is not connected to the vehicle case.

In [14], we presented the results of an experimental characterization of the channel attenuation, noise amplitude, noise spectrum and line impedance in the range of interest for PLC applications. The vehicle in [14] was equipped with lead gel batteries. Basically, the main findings of the campaign in [14] are the following.

- The noise close to the DC/DC converter is very high. Namely, the difference in terms of maximum amplitude between the noise measured near the DC/DC converter (on the 12V side) and the rear lights is about 10 times.
- There is no clear relation between the wiring length and the channel attenuation and there is no substantial difference of the channel characteristics during the different states of the vehicle, e.g., running, stationary, etc..
- Interestingly, the channel from the battery pack to the auxiliary circuit, which crosses the DC/DC converter, shows frequency windows with a relatively low attenuation in the higher frequency range. This result can be due to radiated/coupled effects.

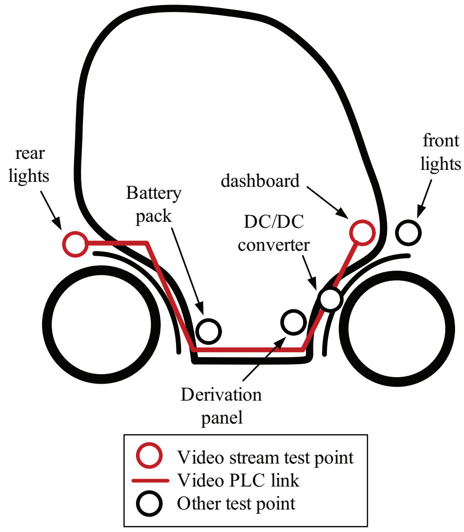

Fig. 2. Schematic view of the wiring of the vehicle.

B. Selection of the Connection Points

Fig. 2 is a schematic view of the wiring of the vehicle. We focus on the 12V auxiliary circuit that feeds the dashboard of the vehicle and all loads except to the motors. The 12V circuit is powered by the DC/DC converter that, in turn, is directly connected to the 48V battery pack. Physically, the DC/DC converter is connected to the derivation board where the fuses are installed. The fuses protect the loads from overcurrents. The derivation board and the DC/DC converter are placed in the front part of the vehicle. Indeed, the battery pack is under the driver seat.

As an application of the PLC technology, we imagine a communication between the dashboard and a unit installed on the back of the vehicle. A practical example of such configuration is the camera-to-display link detailed in Section V. This application is quite common in current commercial vehicles, where it is implemented on dedicated wiring.

The first PLC device is connected to the rear lights, in particular, the left one, and the second PLC device is connected to the lighter. We denote the connection points as rear port and front port, respectively. The wiring interested by the PLC

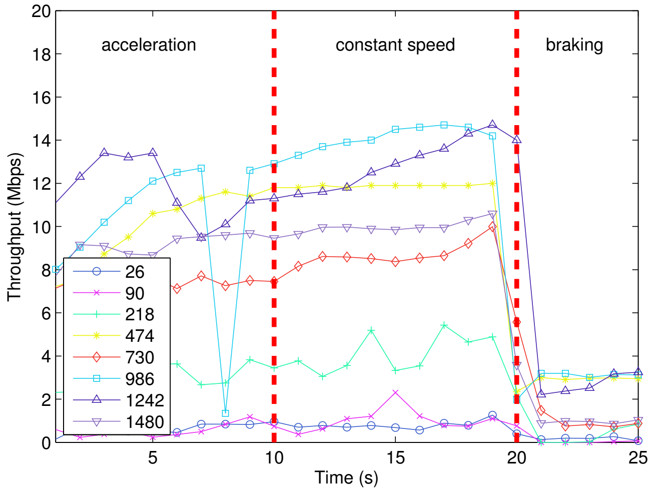

Fig. 3. Throughput of the rear-to-front link during the standard test. The legend reports the packet dimension in bytes.

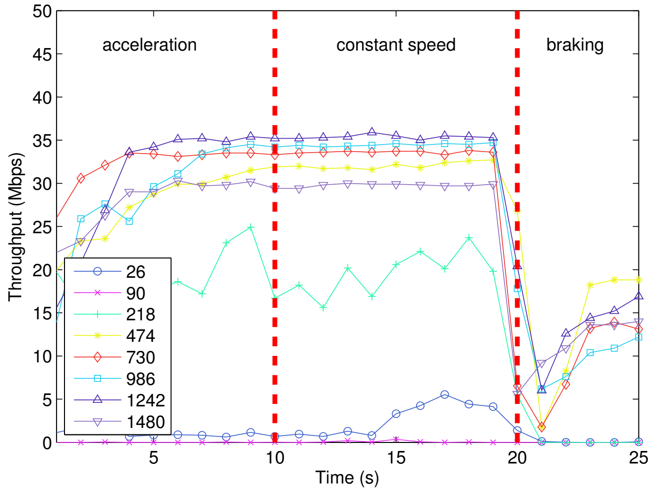

Fig. 4. Throughput of the front-to-rear link during the standard test. The legend reports the packet dimension in bytes.

signal is schematically depicted in Fig. 2 as a bold red line. Physically, the wiring consists of the cable between the rear light and the derivation board, the fuse of the rear light, the fuse of the lighter circuit and the cable between the derivation board and the lighter. We do not target other connection points as they do not provide any further information due to the low complexity and compactness of the vehicle. Namely, all the other loads are fed from the dashboard through a fuse, as the connection points that we consider.

IV. Experimental Results

We herein disclose the results of the preliminary experimental activity that we have performed to validate in-vehicle PLC. The study addresses the quality of the transmission link detailed in Section III-B. The main focus is on the high-level metrics, as data rate (throughput), delay and jitter of the delay, and results are presented in Section IV-A. Further results about the noise, and the channel attenuation and the line impedance are also provided in Section IV-B and IV-C, respectively.

A. High Level Performance

We aim to compute the metrics during realistic operating conditions, e.g., during acceleration, braking or constant-speed traveling. In this respect, we define a standard-condition test (SCT) that lasts 25 seconds and consists of the three phases reported in Table II.

TABLE II. Phases of the Standard Test

Phase No.	Duration (s)	Description
1	0 - 10	Acceleration from 0 to 20 kmh
2	10 - 20	Constant speed at 20 kmh
3	20 - 25	Braking to stationary

During SCT, we assessed the performance of the PLC transmission. Firstly, we focused on the throughput. The throughput is the maximum possible data rate without losses or errors. We measured the actual throughput of a UDP transmission at nominal speed of 100 Mbps (Fast Ethernet). We performed the measure in compliance with RFC 2544, a well-known reference standard for testing the performance of communication devices that operate at level 2 of the ISO/OSI stack. According to RFC 2544, we ran tests for different frame dimensions, i.e., the payload of the UDP packet. The standard specifies the following dimensions (in bytes) $D \in \{26, 90, 218, 474, 730, 986, 1242, 1480\}$. The throughput varies with the frame dimension as a function of the channel characteristics. We measured the experimental throughput at time intervals of 1 second with Iperf, a standard free software tool for the analysis of the link quality. We target both the communication from the rear port to the front port, rear-to-front (R2F), and from the front port to the rear port, front-to-rear (F2R). Differences are expected due to different noise conditions on termination ends. Figs. 3 - 4 show the results for R2F and F2R communications, respectively. The main outcomes are the following.

- As expected, the throughput depends on the communication direction. Rear-to-front, the throughput never exceeds 16 Mbps. Front to rear, it can be up to 35 Mbps.
- The optimal frame dimension is about 986 and 1242 bytes. Rear-to-front, the frame duration of 986 bytes ensures the best throughput during constant speed and braking phases and we speculate that the abrupt variation during the acceleration is due to a measurement error. Front-to-rear, the curve of 986 bytes is aligned to that of 1242 bytes. Small frames yield to the worst performance.
- During acceleration, the throughput shows an increasing behavior and it settles to the highest values in about 5 seconds. During acceleration, the motor drivers face on heavy load conditions, but the noise they inject is acceptable for PLC purposes.
- During the constant speed phase, the throughput keeps constant regardless the frame dimension or the communication direction. Minor variations are shown front-to-rear, with a frame duration of 26 bytes.

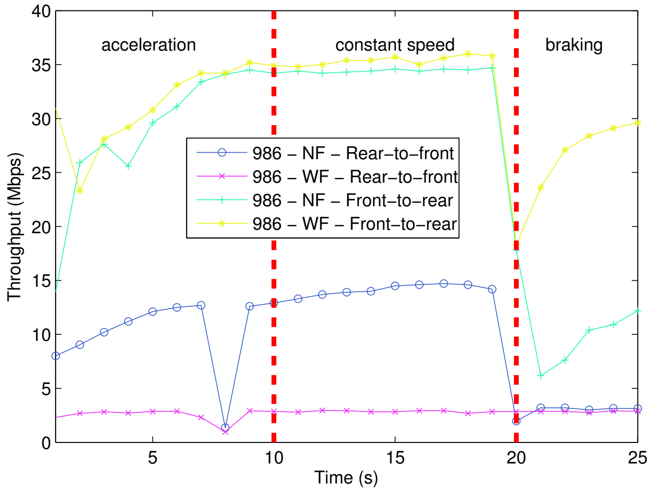

Fig. 5. Throughput results with frame duration of 986 byte. In the legend, NF and WF refer to the configurations without and with the filter between the DC/DC converter and the distribution board, respectively.

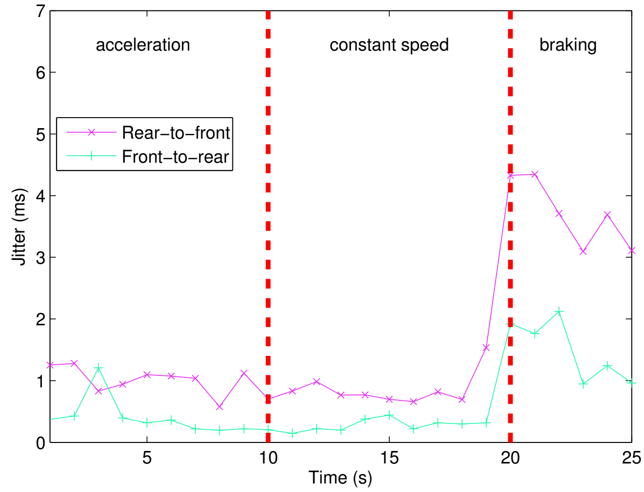

Fig. 6. Experimental delay and jitter for a frame duration of 986 bytes.

- The braking phase is the most interesting one, since the throughput experiences an abrupt decrease. Rear-to-front, the throughput flattens to values below 4 Mbps. Front-to-rear, the throughput firstly collapses, then it starts growing again. The disruptive event that takes place at the beginning of the braking phase is a noise impulse generated by the brake switch that controls the rear braking lights. Basically, the modems change modulation parameters to cope with the new channel conditions. Once the impulse ends, modems restore the parameters that provide a higher throughput. This adaptation process takes some seconds, during which we observe an increasing throughput.

For further details on noise, see Section IV-B. Now, let us study more in deep the role of the noise due to the DC/DC converter on the PLC performance. For this case, we add a low pass filter between the DC/DC converter and the derivation board to limit the amount of conducted noise due to the converter. Figure 5 shows the results. They have been obtained during standard tests, rear-to-front and front-to-rear with and without the filter, with a frame duration value of 986 bytes. We denote with NF and WF the measures without and with the filter. Note that NF results are also shown in Figs. 3-4.

The conducted noise generated by the DC/DC converter has a negligible impact on broadband PLC. In fact, the insertion of the filter does not provide any clear improvement of performance. As it can be noted, rear-to-front, when the filter is applied, the throughput decreases significantly during the acceleration and constant speed phases. Front-to-rear, during the same phases, the use of the filter does not provide any benefit and the performance are far below the rated throughput values of the PLC technology that we adopted.

We now address the delay. We define the delay as the round trip time (RTT) that can be estimated by the standard ping command. The delay keeps between 7 to 20 ms with minor exceptions.

A more quantitative analysis of delay variation is provided by the study of the jitter as described by RFC 1889. The jitter between packet j and packet i is given by

$$D(i,j) = (R_j - R_i) - (S_j - S_i), \tag{1}$$

where S_n and R_n are the real time protocol (RTP) timestamp and the RTP time of arrival of packet $n = i, j$, respectively. Figure 6 shows the jitter (in absolute value) front-to-rear and rear-to-front for a packet frame dimension of 986 byte. Braking yields to larger jitter values, of about 4 ms.

B. Noise Analysis

Throughput results reveal that the braking phase is the most detrimental and, further, that there is no apparent gain provided by the use of a low pass filter to limit the amount of conducted noise due to the DC/DC converter. Herein, we aim to corroborate these findings with a preliminary noise analysis. We measured the noise in the time domain with and without applying the low pass filter between the DC/DC converter and the distribution panel. The vehicle was switched on and stationary. We further measured the noise pressing the brake, to ensemble a condition close to that of phase 3 of STC. Fig. 7 shows the results. They refer to the noise measured at the front port, but similar findings have been obtained at the rear port. The noise waveforms are not synchronized since obtained by subsequent measurements. We note the following.

- The noise shows a large periodic component, with a repetition rate of about 40 μs.
- The maximum noise value is about 200 mV.
- The use of the filter does not yield any clear noise reduction. This result is consistent with that on throughput.
- Pressing the brake, the noise increases slightly, and the small increase is not sufficient to motivate the large performance reduction.

The brake event needs to be further investigated. In this respect, we measured the noise at the time instant when the brake pedal is pressed. We acquired both the noise at the rear and front

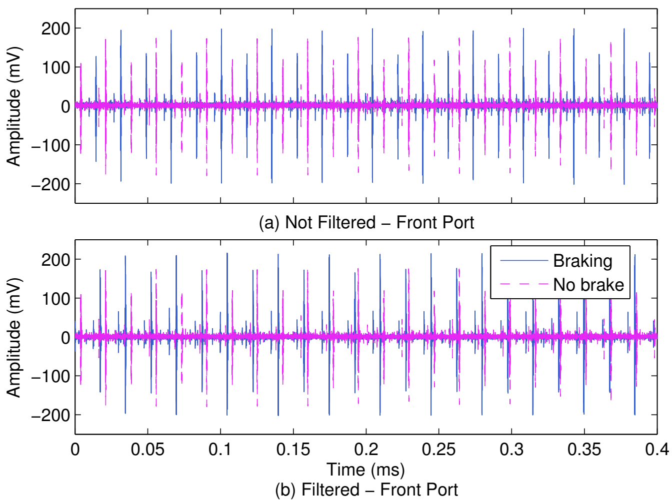

Fig. 7. Time-domain noise measurements at the front port.

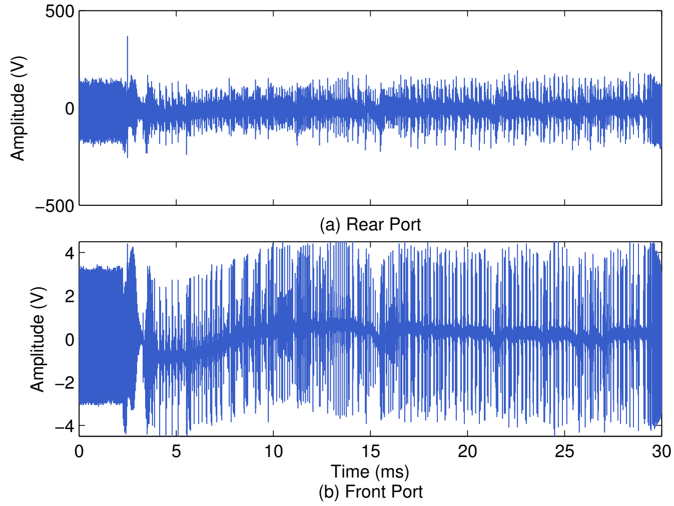

Fig. 8. Time-domain waveforms of the impulsive noise generated by the activation of the brakes.

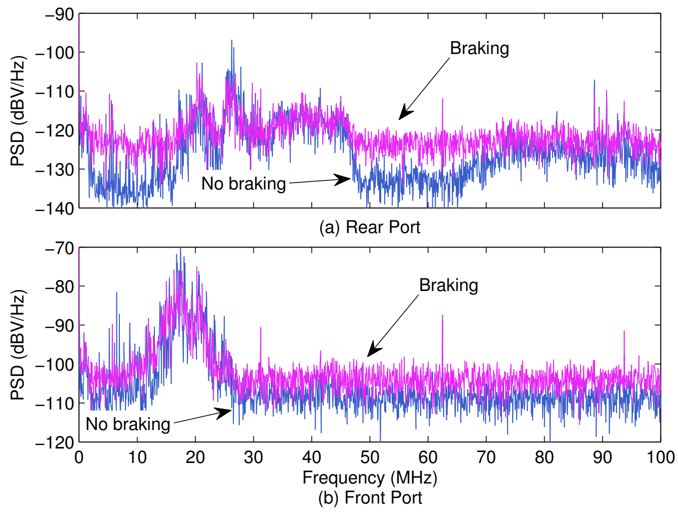

Fig. 9. Power spectral density of the impulsive noise generated by the activation of the brakes.

port. We triggered the DSO to the noise of the front port, at a level of 4 V. To magnify the amplitude variation, we let the DSO input impedance be 1 MΩ. Fig. 8 shows the results. The noise waveforms are synchronized, and the brake pedal is pressed at the time instant $t = 0$.

The apparent mismatch between the noise amplitude in Fig. 7 and in Fig. 8(b) are due to the different DSO impedance settings. We further note the large difference between the noise at the rear port and the noise at the front port, that motivate the throughput asymmetries of Figs. 3-4.

As speculated, the brake event generates a long noise impulse that impairs PLC. The impulse is long, more than 25 ms, and it yields to an abrupt variation of the noise time-domain waveform shape. In frequency, the variation can be described by means of power spectral density (PSD). We compute the PSD from the periodogram of the time domain noise acquisition $w(nT)$, i.e.,

$$P(m) = \frac{T}{L}\left|\sum_{\ell=0}^{L-1} w(\ell T)e^{-j2\pi m\ell/L}\right|^2, \left[\frac{V^2}{Hz}\right] \quad (2)$$

where T and L are the sampling period and the size of the acquisition window. We let $T = 4$ ns, $L = 2^{12}$ and we perform three acquisitions in time. For each acquisition we compute (2). Hence, we obtain the PSD as the average of the periodograms $P(m)$. Fig. 9 shows the results. As expected, the brake event yields to an increase of the noise PSD in the frequency range of interest for PLC. At the front port, the increase is limited, but we note that the noise is already high, with a floor of about -110 dBV/Hz. At the rear port, the noise increase is more significant, up to 15 dB.

C. Channel Response and Line Impedance

The study of the channel response and the line impedance herein disclosed completes the characterization of the in-vehicle scenario that we consider. We obtained the channel response and the line impedance from the scattering (s) parameters. We measured the s-parameters by means of a vector network analyzer and a coupler to protect the equipment from the DC signal. Hence, we computed the channel response and the line impedance as

$$H_{ij}(f) = \frac{s_{ji}(f)}{1 - s_{ii}(f)}, \quad (3)$$

$$Z_i(f) = 50 \cdot \frac{1 + s_{ii}(f)}{1 - s_{ii}(f)} \quad [\Omega], \quad (4)$$

respectively, where $i, j = 1, 2$, s_{ij} is the ij-th s-parameter, 50 Ω is the characteristic impedance of the cables connected to the VNA. By convention, the front port is 1, the rear port is 2. Fig. 10 shows the results about the channel response. We target the front-to-rear and the rear-to-front channel, with or without braking, with or without the low pass filter between the DC/DC converter and the distribution panel. We note the following.

- The mean attenuation is about 35 dB, comparable to that of the in-home scenario.
- The channel response is almost symmetrical (rear-to-

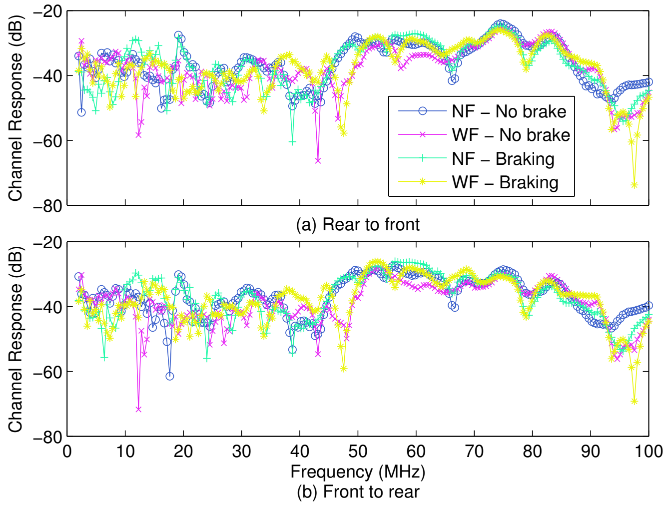

Fig. 10. Channel response in both directions, with and without the filter, during idle or braking phases.

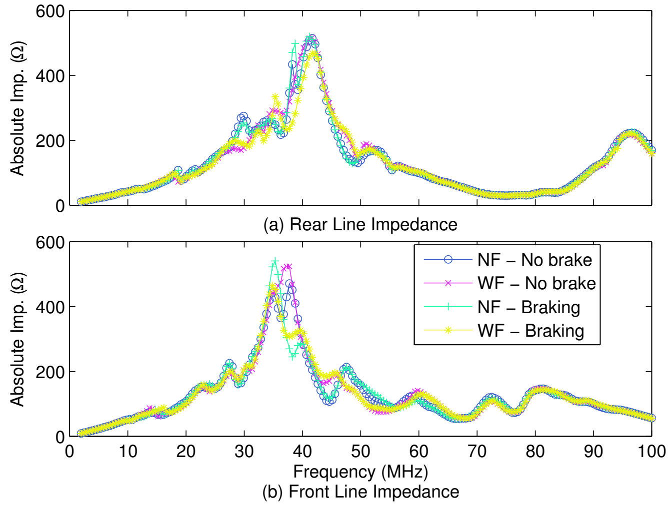

Fig. 11. Line impedance of both ports, with and without the filter, during idle or braking phases.

front and front-to-rear). Thus, the throughput asymmetries are only due to the noise differences.

- The channel response does not vary with or without braking. Thus, again, the throughput decay experienced during the braking phase is only due to noise.
- Channel variations due to the insertion of the low pass filter are minimal, though the wiring structure changes significantly.

Similar considerations apply to the line impedance. Fig. 11 shows the absolute value of the line impedance of the rear and the front port, with or without braking. Basically, the line impedance does not vary due to braking, or due to the introduction of the low pass filter. Furthermore, the mean value is quite high, about 130 Ω, with a peak at 40 MHz. In this respect, we note that PLC take advantage of a large line impedance.

V. In-Vehicle Video Streaming via PLC

Fig. 2 shows the system setup. Basically, on one end, we place the rear camera. The rear-camera is a low cost webcam. The webcam is a valuable choice as a simple and cost-effective solution for demonstration purposes, though it introduces some latency. The webcam is connected to an embedded PC equipped with an Ethernet port. The embedded PC enables the network streaming of the video content captured by the webcam over the Ethernet interface, where the PLC modem is connected. At the protocol level, the network streaming is handled as a RTP stream. On the other side, the PLC modem is connected to a second embedded PC that controls a compact LCD display. For the demonstration purposes of this work, we deployed VLC, a commercially-available software to stream video content. The streamed video is coded according to MPEG-4 specifications, at 20 frame-per-second and with resolution of 320 by 240 pixels. The delay due to caching is set about 200 ms. The quality of the received signal is good. The video flow is continuous. Only some frames are dropped during disruptive events, as braking. In this respect, we believe that a more robust coding scheme is sufficient to overcome such minor impairments.

VI. Conclusions

We have firstly provided a brief overview of the PLC technologies, and we have pointed out that broadband PLC is the best candidate as it provides the highest datarates, and operates at high frequencies, where the noise is less disruptive. In particular, we have identified HomePlug AV2 as the PLC standard for the application example herein considered.

We have customized a set of HomePlug AV2 devices to operate over the direct current (DC) network of the vehicle, we have tested the performance as specified by the RFC, and we have obtained the throughput during standard operating conditions, i.e., when the vehicle is accelerating, running at constant speed or braking. We have focused on a representative channel between a rear light and the lighter on the dashboard. Tests reveal that PLC establishes high-speed communications through the wiring of the vehicle. Throughput values of up to tens of Mbps have been measured, and 986 bytes is the best packet dimension. The transmission is asymmetric because the noise experienced at the termination ports is different. The braking phase is the most detrimental as the throughput collapses to values of few Mbps. In this respect, we have further analyzed the noise, the channel response and the line impedance. The noise is dominated by a main contribution that is periodic and that occupies the lower frequency range. In the higher frequency range, we speculate that the noise components are coupled and not related to the activity of the DC/DC converter. In fact, we have filtered the DC/DC converter to limit the amount of high frequency noise injected without observing clear improvements. Indeed, disruptive noise impulses have been observed during the braking phase, due to the activation of the brakes. Measures reveal that the impulse noise due to braking may increase the noise level in frequency of up to 15 dB. Indeed, the channel and the line impedance seem to be independent from the braking activity or the introduction the low pass filter to limit the noise due to the DC/DC converter.

Finally, we have validated the use of PLC for in-vehicle video streaming. Tests reveal that a streaming with good resolution and acceptable frame rate can be supported by PLC through the in-vehicle wiring.

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