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Characterization of Brazilian in-home power line channels for data communication

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ABSTRACT

This paper focuses on the characterization of Brazilian in-home power line channels for data communication when a sounding-based approach is applied. Based on a measurement campaign carried out in seven Brazilian residences, a statistical characterization of frequency response magnitude, average channel gain, coherence bandwidth, root mean squared delay spread, coherence time, achievable data rate, additive noise and access impedance are presented, considering the frequency bands from 1.7 up to 30, 50 and 100 MHz. Comparative analysis considering previous contributions show disparities and similarities among typical in-home power line channels measured in different countries. The attained results reveal that average channel gain in Brazil is higher than in other countries, the linear relationship between average channel gain and root mean squared delay spread and the inverse relation between coherence bandwidth and root mean squared delay spread are confirmed. Moreover, these results show that coherence bandwidth in Brazil is wider than in European countries, root mean squared delay spread in Brazil is shorten than in US and European countries and coherence time in Brazil is shorter than what is previously reported in the literature.

1. Introduction

There is a growing interest in the use of electric power grids for data communications purposes. In fact, power line communication (PLC) systems and their applications have been investigated by academic and business sectors. As electric power grids were not originally designed for data communication purposes, they constitute a challenging medium, in which the transmitted signals suffer severe attenuation and are strongly corrupted by colored and impulsive noise. Also, the diversity of topologies of electric power grids and the dynamic of the connected devices (loads) make these grids hard to characterize and model.

In this sense, an expressive effort for the characterization of PLC channels is needed in order to allow a better exploitation of such challenging and opportunistic data communication medium. Indeed, there are some contributions in the literature about this issue and they can be classified according to the voltage level and frequency bandwidth. For instance, the outdoor PLC channel can be evaluated for low-voltage [1], medium-voltage [2,3] and high-voltage [4]. Also, underground medium-voltage PLC channels are evaluated in [5] while [6] deals with overhead conductors. For the indoor-PLC channel case, there is the following subdivision: residential or commercial buildings (usually referenced as in-home) [7,6], and in-vehicles (cars [8], ships [9] and aircrafts [10]). Finally, the PLC channel characterization can be performed by considering distinct bandwidths, usually classified as narrowband and broadband. The narrowband PLC comprises the frequencies up to a few hundreds kHz and are used for low data rate applications [11,12]. On the other hand, for broadband PLC systems the investigated bandwidths are those limited to the frequency of 30 MHz [13], which is regulated in some European countries, and to the frequency of 100 MHz [7], in which data rate in the order of 1–2 Gbps can be achieved. In Brazil, the telecommunication regulatory authority allows that broadband PLC systems operate in the frequency band from 1.7 up to 50 MHz which is a frequency band that lacks characterization. There are also few works that provide analysis covering the frequency band of up to 300 MHz [14,15].

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Focusing on the in-home PLC scenario, some few contributions related to developed countries can be highlighted. For PLC channels in Spain, [16] presented results of channel attenuation and noise, for frequencies up to 30 MHz, while [17] considered other features, such as the average channel gain (ACG), the delay spread and the coherence bandwidth (CB). Also, [18] discussed the normality/lognormality natures of the ACG and delay spread. More recently, [14] analyzed the ACG, CB and root mean squared delay spread (RMS-DS) considering the frequency band from 1.8 up to 100 MHz and also expanding the upper frequency edge to 300 MHz. In [19,13], the in-home PLC channels in some urban and suburban United States (US) residences were characterized in terms of ACG and RMS-DS, considering the frequency band ranging from 2 up to 30 MHz. The results reported for in-home PLC channels in France are found in [7,20], where the PLC channel is evaluated in terms of ACG, CB and RMS-DS, for frequencies up to 100 MHz. The analysis related to the time varying behavior of PLC channel was addressed in some few works, such as [21,22], and lacks a more thorough statistical analysis. Furthermore, there are few works that address the analysis of access impedance [14,23].

This work aims to offer the first characterization of in-home PLC channels in Brazil, constituting an important reference to support future efforts in modeling and designing in-home broadband PLC systems. Preliminary results were reported in [24], in which the average channel attenuation (ACA), the RMS-DS and the achievable data rate were briefly discussed from a small set of measured Brazilian in-home PLC channels, considering the frequency band ranging from 1.7 up to 30 MHz. In this contribution, three distinct frequency bands, 1.7 up to 30 MHz (Band A), 1.7 up to 50 MHz (Band B) and 1.7 up to 100 MHz (Band C), are considered. The Band A agrees with telecommunication regulation over PLC systems imposed by some European countries [13], Band B comprises the regulation for Brazilian telecommunication regulatory authority to PLC systems [25], and Band C represents a tendency for future PLC systems since data rate in the order of 1–2 Gbps can be achieved [26]. In this regard, a measurement campaign was performed in seven middle class places in an urban area, totalizing 245 different channel configurations (only 27 channel configurations were taken into account in [24]), for which the following features were estimated and statistically characterized:

- Channel frequency response (CFR): It allows quantify the attenuation introduced by the PLC channel in each frequency.
- Average channel attenuation (ACA): It is the mean attenuation introduced by a PLC channel.
- Root mean squared delay spread (RMS-DS): It is related to the channel dispersion due to multipath phenomena.
- Coherence bandwidth (CB): It reflects how flat the channel frequency response is.
- Coherence time (CT): Period of time in with the PLC channel can be considered time invariant.
- Power spectrum density (PSD) of the additive noise: Gives the power distribution of the noise in respect to the frequency.
- Achievable data rate: It is the maximum data rate that can be transmitted through the PLC channel.
- Access impedance: Impedance at the power line access point.

Also a discussion about temporal variation of some channel parameters and their correlation with the mains signal are presented. Finally, the results are compared to those discussed in the literature for in-home PLC channel in other countries.

The remainder of this work is organized as follows: Section 2 presents the complete setup used for the PLC channel characterization, Section 3 describes the performed measurement campaign, whereas Section 4 briefly presents the computation method applied to estimate the desired PLC channel features. In Section 5, the results are presented and discussed, while the work conclusions are summarized in Section 6.

2. Measurement setup

The characterization of the measured Brazilian in-home PLC channels was supported, for the most part, by estimates of the CFR. Complementary characterization were performed though measurements of the noise PSD. A CFR measurement setup illustration is depicted in Fig. 1. As we can see, the setup consists of three main components:

- Signal generator: It is an equipment composed of an arbitrary signal generator board mounted in a rugged computer. A predesigned sounding sequence is loaded into it and converted to an analog signal to be injected into the PLC channel under analysis. The signal generator has 12 bits of resolution, can generate signal in the range of ±870 mV and its data sheet can be accessed in [27].
- Data digitizer: It acts as a receiver, acquiring the transmitted sounding signal after its propagation through the PLC channel, and converts it into a digital representation for the subsequent analysis. The adopted acquisition board has 16 bits for quantization. It was set to operate with a resolution of, approximately, 30.5 μV and has an embedded anti-aliasing filter. Some additional technical information can be accessed in [28].
- Coupler: Circuitry used to connect both the signal generator and the data digitizer to the PLC channel under analysis. The coupler is essentially a capacitive passband filter [29], blocking the main voltage signal (60 Hz in Brazil) that can damage the equipment (signal generator and data digitizer) and avoiding aliasing.

The signal used to estimate the CFR of PLC channel under analysis is loaded into the signal generator (transmitter) and converted in an analog signal at the rate of $f_s = 1/T_s = 200$ MHz. This transmitted signal is composed of Hermitian symmetric orthogonal frequency division multiplexing (HS-OFDM) symbols [30] and result in a baseband signal in time domain. Each symbol has $2N = 4096$ binary phase shift keying (BPSK) modulated subcarriers and a cyclic prefix (CP) composed by the last 512 samples appended at the beginning of the symbol. At the data digitizer (receiver), the distorted and corrupted version of the generated signal (due to its propagation through the PLC channels) is stored at a sample rate of $f_s = 200$ MHz.

With the possession of the discrete-time version of both the generated and acquired (extracted) signals, a channel-estimation method is performed. The method encompasses the following functionalities [31]:

- Sampling-frequency offset (SFO) correction: It is necessary because the clock sources in the signal generator and data digitizer are different. The technique applied to correction of SFO used in this work is based on a cubic interpolation [32].
- Input-output timing synchronization: This step is based on the CP redundancy incorporated to the HS-OFDM symbol [33]. The correlation operator is used in order to identify the beginning of each symbol within the data recorded at the receiver.
- Channel estimation: A CFR estimate is obtained using the transmitted and received symbols, both in frequency domain.
- Channel estimation enhancement: This procedure was proposed in [34] and it is used to mitigate the noise effects in the CFR estimates. Assuming that the CIR length is lower than the length of the transmitted signal, thus the last samples of the estimated channel impulse response are just noisy coefficients that can be disregarded (replaced by zero), to attain a more reliable estimate. In this work we assume that the length of the CIR is equal to the length of the CP.