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On the statistical characterization of hybrid PLC-wireless channels

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ABSTRACT

This work aims to increase the understanding and bring the attention to the use of the so-called hybrid power line communication-wireless (PLC-wireless) channel, which is here defined as the equivalent channel that results from the concatenation of PLC and wireless channels, for data communication purposes. In this regard, we discuss about statistical modeling of average channel attenuation, root mean squared delay spread, coherence bandwidth and coherence time, which are among the main features used to characterize data communication channels. Based on a set of measured PLC-wireless channels in in-home facilities, which cover distances lower than 2 m and between 2 m and 6 m, and frequency band between 1.7 MHz and 100 MHz, statistical modeling of the aforementioned set of features is analyzed and compared when several statistical distributions are taken into account. Based on four well-established information criteria, we show the statistical distributions offering the best fits. Furthermore, we show that for the majority of these features, the best two statistical distributions for each of them achieve very similar performance in terms of the chosen information criteria and, as a consequence, both of them may be adopted to statistically model these features.

1. Introduction

Smart grids are the natural evolution of the traditional electric power grids to a new paradigm that embraces intelligence, flexibility, reliability and renewable energy sources [1]. In smart grids, information and energy may flow in a two-way direction among generation and consumers or prosumers [2]. To fulfill these two-way information and energy demands, smart grids heavily rely on telecommunication infrastructures that allow interactions among several entities (e.g., smart meters, smart appliances, smart reclosers and smart transformers) widely spread across the electric power grids.

As detailed in [3], the architectures of telecommunication infrastructures may cover home areas network (HAN), business area network (BAN), neighborhood area network (NAN), metropolitan area network (MAN), rural area network (RAN), centers of operation and substations. Aiming to provide these infrastructures for assisting smart grids deployments, several technologies shall be pursued. Among them, it is interesting to drive the attention to the wired ones, which were designed for coaxial cables, telephone lines, fiber optics and power lines. Regarding wireless solutions, there is a variety of technologies covering licensed and unlicensed frequency bands. The proposition, development and deployment of pervasive or ubiquitous telecommunication infrastructures, which are capable of fulfilling the demands of all players in the smart grids scenario, is still a challenging problem that lacks a definitive solution. This problem is worsened when the concepts of smart city and Internet of Things (IoT) are brought to the center of discussions because the telecommunication infrastructures must be designed to address all of their demands.

Among the aforementioned technologies, the power line communication (PLC) systems have received worldwide attention due to its suitability for fulfilling smart grids demands [4,5]. As a matter of fact, PLC systems constitute an interesting alternative for smart grids due to their pervasive nature, which greatly reduces installation costs and deployment time. Also, PLC can play an important role in smart grids since PLC devices can work as a transceiver and a sensor at the same time [5]. As the majority of electric power system infrastructures are already installed, significant savings on the investment to deploy PLC systems are achieved in comparison to other technologies [6]. Actually,

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only wireless technologies are comparable to PLC ones in terms of cost of deployment [4].

Similar to other data communication media, electric power grids show advantages and disadvantages, which are well-reported in the literature. Among them, we bring our attention to the fact the power lines are unshielded and the physical contact with electric power grids for becoming a node in a PLC data network is mandatory. The former fact means that PLC systems can interfere with and suffer from other telecommunication systems operating in the same frequency band. As a result, there are restrictive regulations for using PLC systems around the world (i.e., US, Brazilian and European regulations [7–10]). The latter fact states that we can only access PLC systems with inductive or capacitive coupling devices, which can be a challenging and costly approach when voltage level increases or power lines can not be easily accessed (i.e., underground electric power systems in metropolitan area). Also, the connection of coupling devices to medium- and high-voltage electric power grids demands precaution due the voltage levels [11,12]. In addition, the necessity of physical connection among PLC transceivers and electric power grids cannot allow mobility with PLC systems. As a matter of fact, it has been recognized that mobility can be introduced in PLC systems by assuming that power lines work as antennas [13].

In this context, one may recognize hybrid PLC-wireless channels as an interesting alternative for addressing some emerging telecommunications needs and demands (i.e., smart grids, smart city and IoT). However, proper specification and design of hybrid PLC-wireless data communication systems rely on a complete modeling of these channels through some of their well-established main features. In this direction, some statistical analyses of channel features estimated from a measurement campaign of hybrid PLC-wireless channels in Brazil were presented in [13]. The analyzed channel features comprise average channel attenuation (ACA), root mean squared delay spread (RMS-DS), coherence bandwidth (CB) and coherence time (CT). However, statistical models for hybrid PLC-wireless channels are missing in the literature, something that may postpone or make difficult the dissemination of the usefulness of such kind of channels for assisting the spectrum scarcity problem and the astonishing increase of data communication demands related to smart grids, smart city and IoT.

Aiming to bridge this gap, this paper introduces statistical models for the ACA, RMS-DS, CB and CT features for hybrid PLC-wireless channels. Thus, this work is an important tool to validate future models that can be proposed to represent this kind of communication channel, since mathematical models are usually applied in the design of communication systems. Indeed, several models for some channels features/behaviors can be found in the literature for wireless and PLC channels. In relation to wireless channels, for instance, Rayleigh, Nakagami and Rice statistical models have been used to describe multipath fading envelope, while log-Normal distribution is indicated to model shadowing [14]. In its turn, statistical distributions are used to model some PLC channel features, as can be seen in [15] and [16], where the models are validated through a set of channels measured in Spain and USA, respectively.

In this work the statistical distributions yielding the best models for the considered set of channel features are chosen based on the inspection of the log-likelihood, Akaike information criterion (AIC), Bayesian information criterion (BIC) and the efficient determination criterion (EDC). All statistical modelings address the frequency band ranging from 1.7 MHz up to 100 MHz and take into account two cases for the hybrid PLC-wireless channel: *short-path* channel (up to 2 meters distance far from the outlet) and *long-path* channel (between 2 and 6 meters far from the outlet). The attained results show that the ACA feature is better fitted by the skew-normal distribution for both *short-* and *long-path* channels. Also, the RMS-DS feature is better fitted by the log-logistic distribution for the *short-path* case, whereas the inverse Gaussian is the statistical distribution that best fits the *long-path* case. In addition, the log-normal distribution offers a quite similar RMS-DS fit to the optimal ones in both cases, but it should be avoided for including negative numbers in its support set, whereas the RMS-DS feature is necessarily positive. Regarding the CB feature, the best fit is yielded by the log-logistic distribution for the *short-path* channel, while the t-Student distribution offers the best fit for the *long-path* channel. Finally, the logistic distribution achieves the best fit for CT in the *short-path* channel, whereas the skew-normal distribution provides the best fit for the *long-path* channel.

To introduce these results, the rest of this paper is organized as follows: Section 2 outlines the hybrid PLC-wireless data communication system, while Section 3 summarizes the measurement setup and campaign carried out to measure these channels. Section 4 describes the procedure to estimate the channel parameters considered in this work. Section 5 details the chosen information criteria to evaluate the statistical modeling. Finally, Section 6 focuses on the statistical modeling based on numerical results, while Section 7 emphasizes our concluding remarks.

2. The hybrid PLC-wireless communication system

The use of hybridism within data communication systems is being considered as a promising solution to deal with astonishing and growing demands for telecommunication infrastructures in smart grids, smart city and IoT. The parallel and/or serial deployment of power line communication, wireless communication and visible light communication technologies [17,4] is attractive as it allows one to maximize the usage of channel resources and diversity, thus improving coverage, reliability, flexibility and throughput.

Among all the possible technology combinations, PLC and wireless channels are attracting much attention as the majority of devices/equipments are powered by and connected to an electric power grid and wireless communication has become a pervasive technology. In other words, these devices/equipments can use both the electric power-grid infrastructure and the air for data communication purposes. While the combination of PLC and wireless channels is interesting and, as a consequence, constitute challenging issues for carrying out researches and investigations, there is a very specific combination of PLC and wireless channels that has been forgotten during the past years. In fact, the communication process that starts in a PLC device and ends in a wireless device (or vice versa), through a combination between wireless and PLC channels, was initially considered at the beginning of the past century [18]. Though the lack of tools and technology to push it forward and the focus in wireless-only solutions have reduced or even stopped the development of devices based on this kind of channel. Due to the spectrum scarcity and the increasing demand for data communication, however, all data communication media have to be considered and, as a consequence, the combination of PLC and wireless channels may be re-investigated for assisting the widespread deployment of telecommunication infrastructure in demanding scenarios such as smart grids, smart city and IoT.

In [19], the hybrid PLC-wireless channel, which is defined as the concatenation of PLC and wireless channels, was discussed for data communication purposes. The main idea behind such a channel is to exploit the benefits of electromagnetic unshielded power lines (which is often seen as an undesired characteristic [20,13]), eliminating the necessity of physical connection to these lines. The resulting configuration overcomes the lack of mobility in PLC systems and provides a path through relevant obstacles which often impair the propagation of wireless signals, leading to an alternative, flexible and improved version of PLC systems fulfilling fixed and mobile data communication demands.

Basically, the aim is to provide a hybrid data communication system that is constituted by PLC and wireless transceivers with capacity to communicate with each other in the same frequency band. Such combination can be implemented with the power lines acting as antennas for the PLC transceivers and full-duplex or half-duplex communication