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NB-PLC channel: Estimation of periodic impulsive noise parameters and mitigation techniques☆

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ABSTRACT

Narrowband Power Line Communication (NB-PLC) plays a key role in the deployment of smart grid, since it is a widely spread technology for smart grid applications and systems, like the Advanced Metering Infrastructure (AMI) system. In this paper, we study the characteristics of the NB-PLC channel and noise. A method is proposed to estimate the occurrence and duration of the dominant category of noise, the periodic impulsive noise, which greatly degrades the signal quality. A technique is proposed to mitigate the noise effect, with the use of Luby Transform (LT) codes. The proposed scheme exploits the features of the dominant noise on the NB-PLC channel and mitigates its effect especially in highly noisy environments. An estimation algorithm of the burst time occurrence and its duration is introduced. The system can estimate these parameters with an accuracy in the range of 10^{-4} and it can work even without channel state information. The proposed scheme is compared to two popular NB-PLC technologies, namely the PRIME and G3-PLC, whereas the results show that it can be very effective under severe noise conditions.

1. Introduction

The electrical grid undergoes significant changes to form the future smart grid, where the control and monitoring applications will enable an efficient energy management and the integration of Renewable Energy Sources (RES) will be facilitated. Smart metering applications play a key role in the smart grid since they allow for power consumption monitoring and control, whereas they can transform the consumer into an active player in reducing energy consumptions. Narrowband Power Line Communications (NB-PLC) is a technology that has been widely used for smart metering purposes, for the accomplishment of the national smart meter roll-outs by European countries as well as for the realization of numerous smart grid projects [1]. Furthermore, NB-PLC is examined for additional smart grid applications, like the IP data transmission [2]. Two popular technological solutions for NB-PLC are the PRIME [3] and G3-PLC [4] specifications, which constituted the main basis for the standards proposed by ITU and IEEE [5].

Since NB-PLC is a key technology for smart grid applications, it is considered of vital importance to analyze the NB-PLC channel and its characteristics. We consider the Low Voltage (LV) network, since the PRIME and G3-PLC specifications are widely used for smart metering applications in this type of network [1]. The NB-PLC channel and noise do not present the same characteristics with the Broadband PLC (BB-PLC) case. The attenuation in lower frequencies is greater than in higher ones and the noise shows different behavior [6]. There have been several attempts in the literature to model the NB-PLC channel and noise characteristics and mitigate their effect. A statistical characterization of the channel has been presented in [7], whereas in [8] channel characterization along with a channel emulation method is proposed. The NB-PLC channel characteristics are also studied in [9] (50–500 kHz) and in [10] (150–490 kHz). In [11] the channel transfer function is modeled and the capacity of NB-PLC channels is derived. Channel and noise impairments are also modeled in [12], accompanied by an attempt to mitigate their effects. The noise characteristics in the 3–200 kHz band are studied in [13], whereas a first-order Markov modelling of the noise based on measurements is presented in [14]. A mathematical noise model also based on measurements is presented in [15], where the cyclostationary nature of the NB-PLC noise is noted. This characteristic of the noise is also highlighted in [16]. In [17] a narrowband interference model is presented for OFDM (Orthogonal Frequency Division Multiplexing) NB-PLC systems.

The noise and channel characteristics are presented in [18], where a packet repetition technique is suggested to mitigate the noise effect. Impulsive noise mitigation is examined in [19], using the Sparse

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Bayesian Learning method, whereas in [20] non-parametric methods are used for this scope. Different interleaver usage for noise mitigation is presented in [21]. Coding has also been examined for noise mitigation techniques; for example in [22], a mixture of the PRIME and G3-PLC coding schemes is proposed, and in [23] the Gabidulin codes have been used. Finally Fountain codes have been studied for noise reduction on the NB-PLC channel [24].

Fountain codes are found to be very effective on the erasure channel. A special type of erasure correcting codes, the Luby Transform - LT codes, was introduced by Luby [25]. The main concept is that data are processed in packets. The receiver can reconstruct the original data if a specific number of packets or above are received. This number depends on the code's design. In [26], it has been shown that the effect of impulsive noise could be mitigated by exploiting the properties of the LT codes on the BB-PLC channel. The potentiality of treating the most erroneous packets as erasures at the receiver, thus reducing or even eliminating the impulsive noise effect, has motivated the usage of these codes in this research work.

In this work, we firstly examine the NB-PLC channel and noise characteristics of an OFDM-based system (LV network). It should be mentioned at this point that NB-PLC has been also examined for the Medium Voltage (MV) network [27,28]. The MV PLC channel is described by three parameters, line length, transmitter impedance and receiver termination, which are considered stable with time for a specific network configuration [27]. As a result, the MV PLC channel is rather static, which is not the case for the LV PLC system. Analysing the MV PLC channel is out of the scope of this work.

In this paper, we implement the channel and noise characteristics in a simulation system with the scope of depicting the actual NB-PLC channel and noise conditions in the most accurate way. To complete the simulation system we also utilize the main parameters of the PRIME and G3-PLC technologies. We propose to use LT codes instead of the PRIME and G3-PLC coding techniques in order to mitigate the impulsive noise. The idea is to create the conditions of an erasure channel, where LT codes are proved to be effective. Due to the properties of the cyclostationary noise in a NB-PLC channel, some packets are highly affected by impulsive noise, whereas others are not, in a periodic way. To distinguish these packets, we propose an estimation algorithm for evaluating the burst time occurrence and duration. For this purpose, a small packet sequence - known at the receiver - is transmitted. No coding or noise mitigation is applied on this sequence, so that the packets to be affected by impulsive noise can be identified more easily. The algorithm is based on the periodic noise characteristics, whereas a synchronized clock is required at the receiver. For a continuous data reception the receiver can mark the packets that are expected to be hit by periodic impulsive noise as erasures. The LT decoder's properties allow the original data to be recovered without using those packets. This fact is positive for channels that introduce burst errors, where a sequence of packets is affected, and this is the reason why we selected LT codes for this work. The resulting performance is compared to the one obtained by the PRIME-based and G3-PLC-based.

The rest of the paper is organized as follows. Section 2 describes the NB-PLC channel and noise model used. In Section 3 the LT codes characteristics are described. In Section 4 the proposed scheme is presented and the system's performance is compared to the one obtained by PRIME and G3-PLC technology. Section 5 presents some concluding remarks.

2. System model

2.1. NB-PLC channel model

The attenuation characteristics of the NB-PLC channel vary depending on the location where the measurements have been carried out [7], [12], thus making it difficult to define a global transfer function. For the BB-PLC channel, a widely used model is based on multipath propagation [30]. Although the multipath phenomenon is not the main reason for frequency selective attenuation in the NB-PLC channel [6], it is shown that, when the exact network topology is not known, a multipath based transfer function can result in depicting the channel properties, as they are stated in the literature. The channel frequency response selected for this work entails parameters from statistical distributions and depicts the general characteristics of the NB-PLC channel. It is given by [12,18,30]:

$$H_{ch}(f) = \sum_{r=1}^{N_p} g_r e^{-a(f)d_r} e^{-j2\pi f(d_r/u_p)} \tag{1}$$

In the above equation, N_p stands for the number of multipath components. The factor d_r/u_p represents the time delay of each path, with d_r the length of the path and u_p the velocity of signal propagation. The parameter g_r is a weighting factor for the attenuation of each path and $\alpha(f)$ is a frequency dependent attenuation coefficient. It should be noted that the parameters of the above transfer function, used in our simulations, have been selected so as to depict the properties of the NB-PLC channel; details on the parameters' values can be found in [18]. It is worth mentioning that the transfer function described above has not been the same for every transmitted packet. Instead, for each packet one out of nine produced transfer functions has been used; the parameters are $N_p = 5$, 10 or 15 and random values for g_r and d_r, as indicated in [18]. This method results in obtaining frequency selective attenuation at the extent of up to 25 dB, which is in accordance with the channel characteristics reported in [7,9].

2.2. NB-PLC noise model

The noise in the NB-PLC channel can be divided in 3 categories: background noise, noise due to narrowband interference and impulsive noise [13]. Although in the BB-PLC channel, the most destructive noise is the asynchronous impulsive noise, caused by connecting or disconnecting electrical devices on the network, in the NB-PLC case the dominant noise component is the cyclostationary impulsive noise [13,15,16,19,20].

This noise is mainly caused by power electronic devices that turn on and off depending on the electricity cycle. The noise impulses occur periodically with a repetition rate of half the AC cycle, while their duration lasts from 10% to 30% of a period [19]. To represent this type of noise, we have used periodic AWGN (Additive White Gaussian Noise) impulses with a period of 10 ms, corresponding to half the European mains frequency (50 Hz). It is noteworthy that the transmitter and receiver have no information about the exact time of the impulse occurrence. To depict this in the simulation system, we have considered that the first impulse occurs at a time instant that is uniformly distributed in [−3 ms,7 ms] [18].

Narrowband interference is created by broadcasters in the long wave range and also by switching mode power supplies with operation frequencies above 20 kHz. This type of noise varies very slowly in time and the bandwidth of a narrowband interferer can be considered to follow a uniform distribution in [5 kHz, 20 kHz] [18]. In order to include the effect of such noise in our simulation system, we have considered that the interferer has a centre frequency (f_c) around the middle of the OFDM carrier frequencies that are used for data transmission. As a result, the worst case of interference is taken into account. It is considered that f_c is uniformly distributed in [f_c − 20 kHz, f_c + 20 kHz], where f_c is given by:

$$f_c = \frac{f_{u1} + f_{u2}}{2} \tag{2}$$

The parameters f_{u1} and f_{u2} stand for the initial and last carrier frequencies used to transmit information data respectively and they are defined as follows:

$$f_{u1} = f_{tr1} + N_{null}\cdot\Delta f \tag{3}$$