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On channel estimation for power line communication systems in the presence of impulsive noise[☆]

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In this paper, two maximum-likelihood (ML) channel estimators that are robust and perform consistent channel estimation in the presence of impulsive noise (IN) for power line communication (PLC) systems are proposed and analyzed. The two estimators differ on the way they exploit the estimated IN to determine the coefficients of the channel impulse response. In the first approach, the channel estimator treats the estimated IN as a deterministic quantity; in the second as a random quantity. The performances of both estimators are analyzed and numerically evaluated. As it will be shown, between the two proposed estimators, the one that is based on the random approach outperforms the deterministic one in all typical PLC scenarios. However, the deterministic approach-based estimator can perform consistent channel estimation regardless of the IN behavior with less computational effort and becomes an efficient channel estimation strategy in situations where high computational complexity cannot be afforded.

1. Introduction

The smart grid envisions the electrical power distribution network as a physical infrastructure that relies on communication technologies to efficiently deliver the generated power to the end consumers [1–3]. Due to the extensive outreach of power lines in electric grids, using them also for the purpose of data transmission is considered as an economically efficient way to support the communication requirements of smart grid applications [4]. In order to serve as a communication backbone for the smart grid, power line communication (PLC) however has to overcome many impairments that make the power line environment harsh for reliable data transmission [5,6].

One of the major drawbacks for PLC is the power line itself. Power lines were originally designed to transmit electrical energy only and severely impair communication signals bearing frequencies higher than the fundamental operating frequency of the electrical signal (50 Hz or 60 Hz). In a typical power line network, where there are multiple branches and impedance mismatches along an electrical path, a communication signal transmitted through it is typically reflected multiple times before reaching the receiving node [5]. As a result, the transmitted communication signal is received via multiple paths and is severely affected by the frequency selectivity of the channel [7]. In order to overcome the resulting frequency

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selectivity, modern PLC systems exploit multicarrier modulation techniques based on orthogonal frequency division multiplexing (OFDM) [8]. The simple single-tap equalization feature of OFDM allows easy equalization of the symbols against the frequency selectivity of the power line channel, provided the channel is accurately estimated [9]. Typically in order to estimate the channel, pilot symbols that are also known to the receiver are transmitted. Upon receiving the signal, the receiver exploits the known pilot symbols to estimate the channel coefficients and use them to equalize the received symbols.

Apart from the channel frequency selectivity, randomly occurring impulsive noise (IN) in the power line environment also hinders reliable data transmission. Due to the operation of the power converters along with other essential electrical components that are used for the efficient delivery of electrical power, random IN inevitably arises in the electrical network [1]. The brief duration of the IN in time domain leads to a wide band effect in the frequency domain. As a result, when such noise occurs during data transmission, the energy of IN spreads among all the subcarriers of an OFDM based PLC system. The spread of energy takes place while demodulating the received signal by performing fast Fourier transformation (FFT) on the time domain samples that are affected by the IN [10]. In such a hostile environment, the pilot symbols used to estimate the channel are also severely affected, making precise channel estimation a challenging task [11].

The problem of estimating the channel in the presence of random IN for an OFDM based PLC system has gained a lot of attention in recent years [9,11–16]. Conventional approaches follow least-squares (LS) channel frequency response (CFR) estimation, typically in conjunction with the IN mitigation scheme. The LS estimator which shows optimum performance in the presence of additive white Gaussian noise (AWGN) tends to loose its optimality in the presence of IN. Therefore, in order to exploit LS estimation of CFR coefficients, channel estimation schemes in [11–14] exploit a threshold dependent nulling technique to reduce the power of the IN samples present in the received signal before estimating the channel. However, due to the non-linearity of the IN mitigation scheme, some samples of the IN might still be present in the received signal. In such a situation, the estimate of the CFR obtained as an output of the LS channel estimator is not accurate [17]. To enhance the performance of channel estimation schemes based on LS in conjunction with non-linear IN mitigation scheme, denoising algorithms that reduce noise from the estimated coefficients of the CFR are proposed in [9,15,16]. In order to remove noise from the estimated CFR coefficients, the proposed algorithms typically follow domain transformation techniques. As a first step, the estimated coefficients of the channel in frequency domain are transformed into time domain to generate the impulse response of the channel. After the transformation, the significant taps that bear most of the channel energy are then determined based on a threshold value. The remaining samples in the channel impulse response (CIR) are nulled and a new CFR is generated based on the denoised impulse response of the channel. However, the use of such threshold dependent approach to identify the most significant channel taps in time domain shows inconsistent behavior in PLC environments with IN. Hence, channel estimation strategies that are not only robust, but also consistent in harsh power line environment are required to exploit PLC based technologies to support smart grid applications.

In order to precisely estimate the channel in the harsh power line environment where the IN is prominent, a better performance than the conventional channel estimation strategies can be achieved, if instead of trying to suppress the IN affected samples in the received signal, the IN is estimated and used in the process of the estimation of the channel [18]. To do so, the sparse IN present in the received signal can be estimated by using the signal processing schemes like the ones proposed in [19–21] can be used. Exploiting the observations, in terms of estimated IN and the received signal, a likelihood function can be defined. The channel coefficients can now be determined by estimating them as parameter values that maximize the likelihood function.

Maximum-likelihood (ML) estimation of the channel by exploiting the estimated IN for PLC systems has not yet been widely explored. In one of our prior works, reported in [18], we showed some preliminary results on how the estimated IN samples can be used to estimate the channel for PLC. The results show that channel can be estimated with better precision in the presence of IN by exploiting the ML technique. To this end, in this article we propose two ML channel estimators that exploit the estimated IN to robustly estimate the CIR in an impulsive-noise power line environment for OFDM based PLC systems and study their performance. In order to formulate the ML channel estimators, we begin by assuming that the IN is estimated and is available to the receiver for further exploitation. The estimated IN, in terms of power and the IN sample locations, is then further exploited by taking two different approaches to derive two ML channel estimators. In the first approach, the estimated IN samples are treated as a deterministic quantity and an ML CIR estimator in closed form is derived. In the second approach, the estimated IN is considered as a random quantity and an ML channel estimator that is based on an iterative approximation of the CIR coefficients using a robust likelihood function is derived. Furthermore, the performances of the proposed estimators in typical PLC scenarios are analyzed and the variances of the estimation errors along with their respective Cramer-Rao bounds are evaluated. In order to assess the performance of the proposed estimators in scenarios where errors are made during IN support estimation, the performances of both estimators are also analyzed when the IN support is underestimated and when the support is overestimated. As it will be shown, based on the numerical validation of the performance of the proposed estimators, the random ML estimator outperforms the deterministic ML estimator in all typical PLC scenarios. However, the deterministic ML estimator performs consistent estimation of the CIR coefficients with significantly less computational effort than the random ML estimator, at the expense of robustness.

This document is divided into seven sections. In Section 2, we briefly outline the OFDM based PLC system model that is considered in this work. In Section 3, both ML channel estimators are derived and the variances of both estimators are evaluated in Section 4. The determination of Cramer-Rao bounds (CRBs) of both estimators along with numerical validation of the performance of proposed estimators are done in Section 5, for which the simulation results are presented in Section 6. Finally, the paper concludes with a brief summary in Section 7.