CYCLOSTATIONARY NOISE MODELING IN NARROWBAND POWERLINE COMMUNICATION FOR SMART GRID APPLICATIONS

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ABSTRACT

A Smart Grid intelligently monitors and controls energy flows in an electric grid. Having up-to-date distributed readings of grid conditions helps utilities efficiently scale generation up or down to meet demand. Narrowband powerline communication (PLC) systems can provide these up-to-date readings from subscribers to the local utility over existing power lines. A key challenge in PLC systems is overcoming additive non-Gaussian noise. In this paper, we propose to use a cyclostationary model for the dominant component of additive non-Gaussian noise. The key contributions are (1) fitting measured data from outdoor narrowband PLC system field trials to a cyclostationary model, and (2) developing a cyclostationary noise generation model that fits measured data. We found that the period in the cyclostationary model matched half of the period of the main powerline frequency, which is consistent with previous work in indoor PLC additive noise modeling.

Index Terms— Powerline Communications, Smart Grid, Noise Modeling, Cyclostationarity, Linear Periodically Time-Varying (LPTV) Systems

1. INTRODUCTION

The increasing energy demands of the future necessitate non-traditional energy generation and management techniques. The concept of the *Smart Grid* addresses this issue by intelligently monitoring and controlling energy flows in the electric grid. A vital part of the Smart Grid revolves around providing reliable communication links between various agents in the network. A strong candidate for such a role is powerline communication (PLC) [1]. PLC technologies such as the TURTLE and TWACS have been in use by electric utilities for remote metering applications for two decades [1]. However, new Smart Grid applications demand much higher data rates than the one provided by those early PLC technologies. As a result, there has been a lot of interest in developing what is called high data rate *narrowband* ($3-500$ kHz) PLC systems for remote metering and load control. Examples of such systems are the ongoing standards such as ITU-T G.hnem and IEEE 1901.2 and the proprietary PRIME and G3. These systems employ OFDM modulation to provide data rates up to hundreds of kilobits per second.

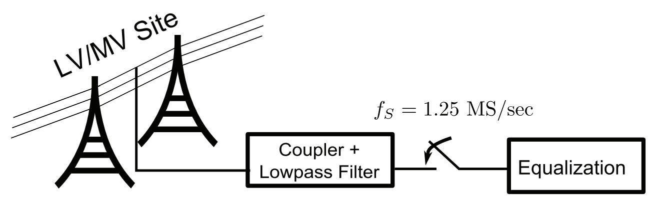

Fig. 1. The measurement setup listens to the powerline communication band on low-voltage (LV) and medium-voltage (MV) lines, and samples the noise traces at 1.25 MS/sec.

The attractive aspect of PLC is the possible deployment over the existing power grid, thereby saving the cost of a new infrastructure. The downside is that this infrastructure, originally designed for one-way power transfer, is a hostile environment for communication systems. Time-varying non-Gaussian noise and time-varying frequency selective channels are the two primary impairments affecting reliable PLC [1, 2]. This paper focuses on noise modeling for narrowband PLC systems. We refer the reader to [2] for PLC channel models.

There has been significant interest in characterizing PLC noise due to its impact on communication performance. Various noise models have been proposed to capture the noise characteristics in PLC environments in frequency ranges up to 20 MHz. Generally, PLC noise can be viewed as an aggregation of various types of noise [2, 3, 4]. Many properties of PLC noise have been studied empirically in [3]. However, these studies focus on the noise in the $0.2-20$ MHz range and thus are more applicable for broadband PLC sys-

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tems. Less work has been done on characterizing narrowband PLC noise. An exception is the periodic noise model proposed in [5] for the very low frequency PLC and the *cyclostationary Gaussian* proposed in [6] that captures the temporal cyclic behavior that dominates narrowband PLC noise. However, this model ignores the time-varying spectral behavior of the noise which limits its applicability to narrow single carrier systems, making it inappropriate for OFDM systems. This spectral variation results from the noise being the superposition of various noise processes with different generation mechanisms (such as homes, heavy industry). Furthermore, the measurements used in [6] were taken in indoor environments and don't generalize readily to outdoor environments such as the ones employed by utilities.

In this paper, we present measurements results from a low voltage site. Then, we propose a passband cyclostationary noise model for narrowband PLC that accounts for both the time and frequency properties of the measured noise. The proposed model is computationally tractable and can be exploited by the PLC modem for link adaptation. This work has been done in the context of the IEEE P1901.2 standardization effort [7].

2. MEASUREMENT SETUP

The measurement setup is shown in Figure 1. The analog to digital converter (ADC) connects to a low voltage or medium voltage power line through a coupler and listens to the PLC environment under signal silence. Since we are interested in narrowband PLC noise, a low pass filter with a cut-off frequency of around 500 kHz is utilized. The output of this filter is sampled at a sampling rate $f_S = 1.25$ MS/sec. Before analyzing the data, we remove the effect of the spectral shape of the acquisition equipment through equalization.

3. DATA ANALYSIS

Communication systems models need to capture both the temporal and spectral properties of the noise. A commonly used technique for non-stationary signal analysis is the *Short-Time Fourier Transform* (STFT) [8]. The resulting spectrogram (magnitude of the STFT) of a noise trace collected at a low voltage site is given in Figure 2. This noise exhibits strong cyclostationary features in time and frequency domain with period $T = T_{AC}/2 \approx 8.3$ ms. In addition, there is a higher concentration of noise power in the lower frequency band with broadband impulses occurring every T and some weaker narrowband interference. A complete analysis of 22 low voltage and medium voltage sites are given in [7].

4. CYCLOSTATIONARY GAUSSIAN MODEL

The *Cyclostationary Gaussian Model* (CGM) is a cyclostationary model proposed in [6] to model the dominant noise

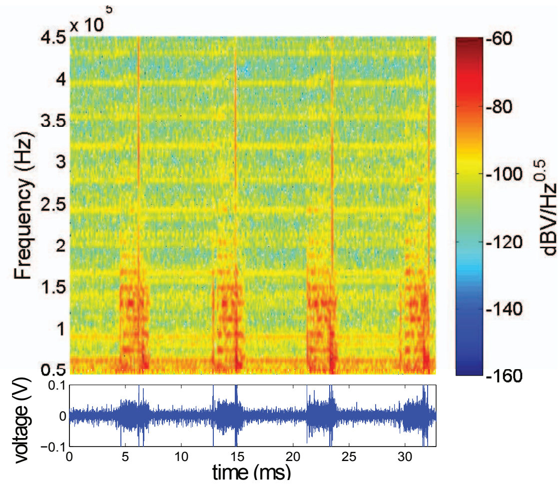

Fig. 2. Spectrogram of a noise trace at a low voltage site [7]. The noise displays the cyclostationary features both in time and frequency.

in narrowband PLC systems. According to this model, the passband noise samples are modeled as zero-mean Gaussian random variables with a periodic time-varying variance $\sigma^2[k]$ of period N; i.e.

$$s[k] \sim \mathcal{N}\left(0, \sigma^2[k]\right), \quad \sigma^2[k] = \sigma^2[k + lN] \tag{1}$$

where k is the time index and $l \in \mathbb{Z}$. The period $N = T f_S$ where f_S is the sampling frequency[1]. The variance $\sigma^2[k]$ is modeled as a sum of L sinusoids with $3L$ parameters. The resulting noise process $s[k]$ is cyclostationary with autocorrelation given by

$$r_s[k, \tau] = \mathbf{E}\left\{n[k]n[k+\tau]\right\} = \sigma^2[k]\delta[\tau]. \tag{2}$$

As expected, $r_s[k, \tau] = r_s[k + N, \tau]$. Due to $\delta[\tau]$, the spectrum of this process is white in frequency with time-varying power. As a result, the CGM shapes the resulting $s[k]$ with an LTI filter $h[k]$ to produce a decaying spectral profile independent of time. The LTI filter is chosen to fit the spectral shape of the background noise typically assumed to be exponentially decaying [2]. The autocorrelation of the resulting process $n[k]$ is given by

$$r_n[k, \tau] = \sum_m h[m]\sigma^2[k - m]h[\tau + m]. \tag{3}$$

While still periodic, the resulting correlation is coupled with $\sigma^2[k - m]$ and the resulting spectrum no longer corresponds to the shaping filter $h[k]$. Furthermore, there is no physical basis for choosing the sinusoid as the parametric form for $\sigma^2[k]$. This leads to a huge expansion in the parameter space, particularly if the noise envelope has sharp transitions as seen in Figure 2, requiring large amount of data and complexity for parameter estimation ($50 - 100$ AC cycles [6]).

[1] f_S is assumed to be aligned with T to result in $N \in \mathbb{N}$.

5. PROPOSED CYCLOSTATIONARY MODEL

The CGM models the noise process as an excitation of an LTI system $h[k]$ by a cyclostationary input $n[k]$ given in (1). While accurate for background noise, a single LTI system $h[k]$ doesn't capture the time variation of the spectral content shown in Figure 2 which represent the aggregation of various physical phenomena. This mismatch in the spectral domain makes this noise model inappropriate for modern PLC standards that employ OFDM [2]. Given the limited applicability of CGM to OFDM systems, we propose a noise model for narrowband PLC that takes into account both the spectral and temporal properties of the noise.

5.1. Spectral Modeling

Figure 2 shows that the noise spectral content has three distinct regions in each period T where the spectrum has similar shape corresponding to a specific generating physical phenomena: a low power background noise region ($0-5$ ms in Figure 2), a high power interference region ($5-7$ ms in Figure 2), and a broadband impulse of duration ≈ 0.3 ms. In general, a given period of duration T can be divided into M intervals $\mathcal{R}_1, \cdots, \mathcal{R}_M$ where the noise spectral shape remains unchanged (M is between 2 and 4 [7]). If we assume that the noise is stationary in each interval $\mathcal{R}_i$, then we can model the noise in that interval as a response of an LTI filter $h_i[k]$ to a stationary input $s[k]$. Accordingly, the noise can be modeled as the response of a *linear periodically time-varying* (LPTV) system $h[k,\tau]$ to a stationary input $s[k]$ where

$$h[k,\tau] = \sum_{i=1}^{M} h_i[\tau]\mathbf{1}_{k\in\mathcal{R}_i}, \quad 0 \le k \le N-1 \qquad (4)$$

and $h[k+lN,\tau] = h[k,\tau]$ where N is the discrete period corresponding to half the AC-cycle T, $l \in \mathbb{Z}$, and $\mathbf{1}_{\mathcal{A}}$ is the indicator function ($\mathbf{1}_{\mathcal{A}} = 1$ if $\mathcal{A}$, 0 otherwise). As a result, the noise $n[k]$ is given by

$$n[k] = \sum_{\tau} h[k,\tau]s[\tau] = \sum_{i=1}^{M} \mathbf{1}_{k\in\mathcal{R}_i} \sum_{\tau} h_i[\tau]s[\tau]. \qquad (5)$$

This can be interpreted as sequential filtering of the stationary input $s[k]$ by a sequence of LTI filters $h_i[k]$ (See Figure3). The LTPV system approach is further motivated by [9] where the indoor PLC channel response was shown to be well approximated by a LPTV filter consisting of a sequence of time invariant filters.

5.2. First-Order Statistics of the Noise Samples

The LPTV filtering operation models the second order statistics of the cyclostationary noise. In this section, we examine the first-order statistics of the cyclostationary noise $n[k]$ to determine the appropriate excitation stationary process $s[k]$

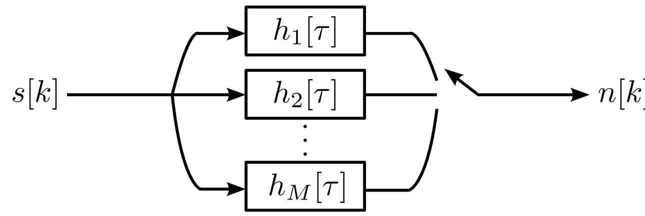

Fig. 3. Noise generation model: $n[k]$ is the result of sequential filtering of stationary input $s[k]$ by a sequence of LTI filters $h_i[\tau]$.

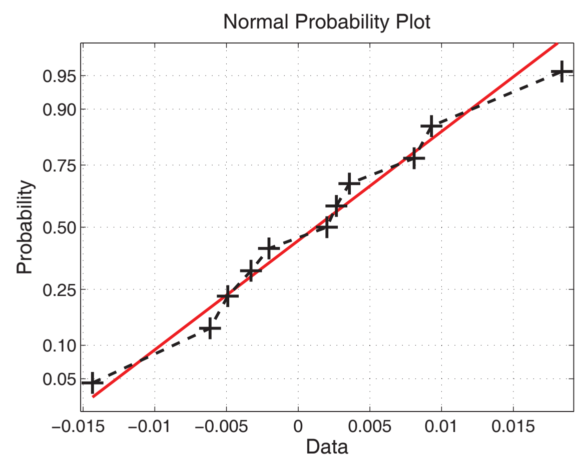

Fig. 4. The normal plot for 12 samples from the subsampled $n_{k_0}[l]$ for some k_0. The closeness of the data points to the red line indicates that the samples follow a normal distribution.

($n[k]$ is a weighted sum of $s[k]$ samples). For a cyclostationary process,

$$p_k(z) = p_{k+lN}(z), \quad l \in \mathbb{Z} \qquad (6)$$

where $p_k(z)$ is the pdf of the noise sample $n[k]$. As a result, the pdf $p_k(z)$ can be estimated from the pdf of the subsampled process $n_k[l] = n[k+lN]$. Figure 4 indicates that the normal distribution can be a good fit for the subsampled sequences $n_k[l]$. The Lilliefors test for normality over a noise trace of 12 periods shows that 95% of the submsampled sequences $n_k[l]$ fit the normal distribution at a significance level $\alpha = 0.01$. Since filtering a Gaussian process by a linear system produces another Gaussian process, $s[k]$ can be modeled as a Guassian process. To simplify the estimation of the shaping filters $h_i[k]$, we make $s[k]$ a unit power Gaussian white noise.

5.3. Parameter Estimation

The proposed model is parametrized by the number of stationary regions M, the region intervals $\{\mathcal{R}_i : 1 \le i \le M\}$, and the LTI filters $\{h_i[k] : 1 \le i \le M\}$. The number of stationary regions M and the region boundaries can be inferred by visually inspecting the spectrogram such as the one in Figure 2. Furthermore, the stationary assumption during each interval $\mathcal{R}_i$ allows for an efficient automated region detection in the time domain that can be implemented on an PLC receiver. In particular, under the assumption that each LTI filter $h_i[k]$ has a different power $\|\mathbf{h}_i\|^2$ (as is typically the case [7]), each noise sample $n[k]$ will have a power given by

$$\mathbf{E}\left\{n^2[k]\right\} = \|\mathbf{h}_i\|^2, \qquad k \in \mathcal{R}_i \tag{7}$$

due to the stationarity assumption. This means that noise samples within each region have equal powers. As a result, a simple thresholding scheme might be adopted to differentiate regions in the time-domain. Furthermore, a PLC modem can set the thresholds γ_i to correspond to its adaptive coding and modulation thresholds; thus estimating only the noise parameters that are relevant to the communication performance.

The LTI filters $\{h_i[k] : 1 \leq i \leq M\}$ are spectrum shaping filters. Designing these filters requires a spectrum estimate for each region $\mathcal{R}_i$. Parametric and non-parametric techniques for spectral estimation are discussed in [10]. The trade-off between using either method is estimation accuracy vs. generalization error. Parametric models produce more accurate estimates under the correct model assumptions but suffer under model mismatch. On the other hand, non-parametric models generalize well but suffer from an increased noise floor. In narrowband PLC, the spectral shapes vary significantly between sites and the time of the day and may include narrowband interferers [7]. As a result, non-parametric models are more appropriate for designing robust PLC systems for field deployment. Given an estimate of the spectrum $\hat{S}_i(\omega)$ during $\mathcal{R}_i$, an estimate of the autocorrelation sequence $\hat{r}_i[\tau]$ during that same interval can be obtained by taking its IDFT. This sequence can be then used to design the appropriate spectrum shaping filter $h_i[k]$ [10]. In addition, frequency domain filtering using FFT can be applied using the spectral estimate $\hat{S}_i(\omega)$ followed by an IDFT operation.

6. MODEL FITTING

The application of the proposed model to narrowband PLC, in particular OFDM, depends on its accuracy in modeling the spectral properties of the PLC noise. We apply the proposed modeling procedure to the data displayed in Figure 2. By visual inspection, we determine $M = 3$ and the intervals $\mathcal{R}_1, \mathcal{R}_2$, and $\mathcal{R}_3$ corresponding to the regions described in Section 3. The corresponding spectral estimates $\hat{S}_1(\omega), \hat{S}_2(\omega)$, and $\hat{S}_3(\omega)$ are estimated using the Welch's method [10]. Applying frequency domain filtering to a unit power AWGN noise, the spectrogram for the generated noise is given in Figure 5. As shown in Figure 5, the fitted model generates noise samples whose spectral and temporal traces resembles closely that of the original data.

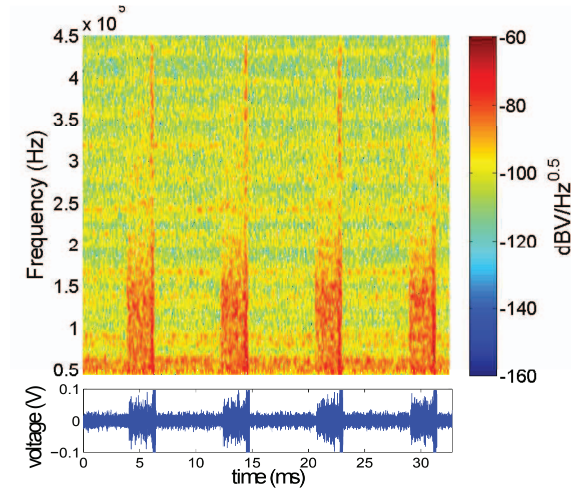

Fig. 5. The spectrogram of the fitted model: a close match to the spectrogram of the PLC noise given in Figure 2.

7. CONCLUSION

In this paper, we proposed a novel cyclostationary model based on filtering a stationary process with an LPTV system. This model captures the behavior of narrowband PLC noise both in time and frequency domain which makes it appropriate for OFDM systems. Furthermore, PLC modems can exploit this model for performing link adaptation.

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