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Modeling the Noise in NarrowBand Power Line Communication

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Abstract

In this paper, we present a model for the noise in narrow-band power line communication. We first derive a statistic model for the distribution of noise in a narrow-band power line. The noise consists of three parts such as impulse noise, background noise, and narrow-band interference. For each part, we analyze its characteristics with the Markov Chain Monte Carlo (MCMC) method. The model is evaluated with extensive field measurement data and compared with a classical noise model. The evaluation results show that the proposed model can approximate the noise in narrow-band power line more accurately.

Keywords*: Power line communication (PLC), Orthogonal frequency division multiplexing (OFDM), Impulsive noise, Markov Chain Monte Carlo*

1. Introduction

1.1. Previous Art

It is well known that a power line channel constitutes a very hostile environment for data communication. In contrast to many other communication channels, the noise in a power line environment cannot be described by an additive white Gaussian noise (AWGN) model. In addition to colored background noise, it typically includes impulsive noise and narrowband interference [1]. Therefore, high-speed communication over power line networks requiring dedicated systems are able to better cope with the hostile channel noise. The design of the modulation and coding schemes adapted for the power line channel calls for detailed knowledge of the noise properties and simulating random noise from the distribution of the power line channel.

Power line noise has been studied in various other previous literatures. The statistic property of impulsive noise is built for broadband power line communication in [2], where the frequency range exceeds 20MHz. Its characteristic parameters are modeled using partitioned Markov chains [2, 3]; the power spectral density basic model of background noise is indicated in [4], where Hooijen analyzed the various types of noise present on powerl ine channels in frequency range from 9 to 95kHz; the narrow-band interference has definite statistic characteristic [5]. However, to the best of our knowledge, there have been no previous investigations about simulating a stochastic sample of power line noise and its application in performance analysis for OFDM receivers yet.

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1.2. Contributions

In this paper, we employ existing models and lots of field measured data to derive the statistic models of different noise for our test sites' power line channels, and simulate the random noise by sampling from these models. The rate of impulsive noise and the power of background noise are determined by measured data. The impulsive noise is sampled using improving MCMC algorithm; sampling from specific distributions, the stochastic sample of background noise and narrowband interference are generated. Combining three random noises can then get the simulation of power line noise. The simulation result is then compared with real noise. Also, the performance of the narrow-band OFDM receiver is evaluated by using the simulation noise. Because the receiver's signal frequency band is 10 to 95kHz, which belongs to CENELEC A frequency band [6], we chose to just research on power line noise in the frequency band.

2. Impulsive Noise Generation

The field measured is carried out at a transformer substation of a factory environment. Considering the different distribution of power line channel noise at different times of a day, the measured times are divided into three groups. The first group is captured during nighttime, which has "weakly noise"; the second group is recorded during the afternoon which has "heavy noise"; the third group is recorded during lunch break, which has "medium noise". The statistic models of the impulsive noise, background noise, and narrow-band interference are derived

2.1. Impulsive Function

Based on the information in [3], the train of impulses noise can be described by:

$$I_n(t) = \sum_{i=1}^{N} a_{Vi} * imp\left(\frac{t - t_{arr,i}}{t_{w,i}, t_{d,i}}\right) \tag{1}$$

Where we add $t_{d,i}$ in each impulse function $imp(t)$, because it consists of impulse-free times t_d and impulse times t_w, the arrival time of ith impulse is the end time of (i-1)th impulse, the first impulse arrival time is zero. Moreover, the time field of impulse noise shows the characteristic of sinusoidal oscillation with exponential attenuation, the $t_{arr,i}$ and $imp(t)$ so obtained is given by

$$imp(t) = \begin{cases} \exp(-dt) * \sin(2\pi f_0 t), t_{arr,i} < t \le \mathrm{t_{arr,i}} + \mathrm{t_w} \\ 0 \qquad , t_{arr,i} + \mathrm{t_w} < t \le \mathrm{t_{arr,i}} + \mathrm{t_d} \end{cases} \tag{2}$$

$$t_{arr,i} = \begin{cases} \sum_{i=2}^{N} (t_{w,i-1} + t_{d,i-1}) & i > 1 \\ 0 & i = 1 \end{cases} \tag{3}$$

Where the adjustable parameters d and f_0 are changed with t_w. Based on (1)-(3), the characteristic parameters t_w, t_d, a_v and the number of impulses N can entirely determine the time domain waveform of impulse noise.

2.2. Statistical Models

The impulses are detected by a peak detector, and the characteristic parameters of impulsive noise in these groups are listed in Table I. For periodic impulses, modeling is rather straightforward due to the deterministic behavior. For asynchronous impulses on the other hand, a statistical model is required. Since the weakly noise group mostly exhibits asynchronous impulses, we exploit partitioned Markov chain [3] to represent its characteristic parameters, including impulse width t_w, the distance between two impulse events t_d and impulse amplitude a_v. The probabilities are described as:

$$Pb = \sum_{n=1}^{N-1} \frac{p_{Nn}}{p_{nn}} (p_{nn})^x \qquad \text{for } x \geq 1. \tag{4}$$

Where p_{Nn} and p_{nn} are the transition probabilities of a Markov chain, x are discrete time instants. The ratio of two probabilities can be denoted as Pr, the diagonal probabilities can be denoted as Pd, then

$$Pb = \Pr 1 * (Pd1)^x + \Pr 2 * (Pd2)^x + ... \; for \; x \geq 1 \tag{5}$$

Pb Consists of a sum of weighted exponentials. Hence, the coefficients can be determined from measured distributions of t_w, t_d and a_v by curve-fitting techniques.

Figure 1 illustrates the model of characteristic parameters for the "weakly noise" group. The result of Pb according to (4) is plotted together with the measured distribution and the random sampling statistics. The simulating random sampling from the model parameters is based on the MCMC algorithm. Because we research on CENELENC A frequency band, the sampling frequency is selected to be 0.4MHz, which is just a narrow-band OFDM sampling frequency [7]. As a result, the simulating is carried out for $4*10^5$ steps with a sampling time of t_a=2.5us. This Figure shows the model fitting rather well with the measured data.

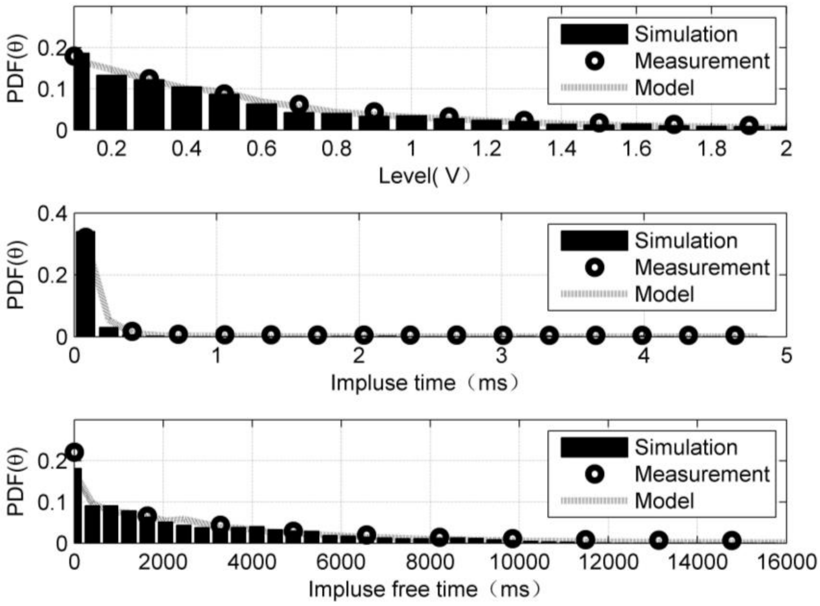

Figure 1. The Pb of Characteristic Parameters: Measured Statistics, Model and Random Sampling Statistics

2.3. Generation of Random Noise

It can be proved that the Markov chain, which represents every characteristic parameter as irreducible, aperiodic, and possesses an invariant distribution Pb. Therefore, it is reasonable to simulate the random sampling using MCMC algorithm.

The statistical models of t_w and a_v (Figure 1) have fast decline probabilities distribution; it is already below 10^{-4} after the twentieth sample points. So we use the classical Metropolis-Hastings (MH) algorithm [8] to simulate the random number of t_w and a_v. The histogram of simulation result can completely fit the statistical model curve.

To t_d, the probabilities distribute from 0 to 16000ms; it includes 200,000 sample points, and using classical algorithm is very difficult to reach convergence. The Multiple-Try Metropolis (MTM) algorithm [9] is proposed. The algorithm generates several correlated samples; from these, a "good" one is chosen. In this algorithm, the target distribution and proposal distribution are statistical model Pb(x), and normal distribution N(x) respectively.

For getting new sampling, given a current state x_0, the weight function are constructed as

$$w(x, y) = \frac{Pb(x)}{N(x \mid y)} \qquad (6)$$

The relationship between acceptance function and weight function is

$$\alpha = \frac{\sum_{j=1}^{k} \omega(y_j, x_0)}{\sum_{j=1}^{k} \omega(x_j^*, y_l)} \qquad (7)$$

Where k trials $y_1, ..., y_k$ are drawn from the symmetric proposal function $N(y_j \mid x_0)$. Then $Y = y_l$ is selected among the y's according to weight function $\omega(y_j, x_0)$ as in (6); A "reference set" $x_1^*, ..., x_{k-1}^*$ is generated from proposal distribution $N(\cdot \mid y_l)$ and Let $x_k^* = x_0$. Finally, y_l is accepted or rejected according to probability α.

In general, including more statistical information in the algorithm can improve performance; comparing with the classical MH, the MTM makes large step-size jumps without lowering the acceptance rate.

Table 1. Characteristic Parameters of Impulsive Noise

Groups	Average Disturbance Ratio	Average Impulse Rate
Weakly noise	**0.00641%**	**1.02** s^{-1}
Medium noise	**0.3671%**	**57. 1** s^{-1}
Heavily noise	**1.207%**	**161.5** s^{-1}

The number of impulses is determined based on measured data. The observation during the simulation of random noise is set to 1s. From Table 1, the impulse rate r_{imp} and disturbance ratio d_r can be represented as

$$\begin{cases} r_{imp} = N_A + N_P \\ d_r = \sum_{i=1}^{N_A} t_{w,i} + \sum_{i=1}^{N_P} t_{w,i} \end{cases} \quad (8)$$

Where N_A and N_P are the number of asynchronous impulses and periodic impulses respectively. From the results of consecutive measurements of the r_{imp} and d_r in different groups, Table 1 can be explained by the number and origin of the impulses. The heavily noise group is dominated by a high number of periodic impulses with very short impulse width, while the weakly noise group mostly exhibits asynchronous impulses and the periodic impulses can be ignored. So when the transition from 'weakly noise' group to 'heavily noise' group happens, the number of periodic impulses also rapidly increases, which is typical for power supplies operating in increasing work hours. Because the scenario is the same, the asynchronous impulses remain constant in the three groups. Then N_A, N_P and t_w of periodic impulses can be derived as follows,

$$\begin{cases} N_A = r_{imp\_wa} \\ N_P = r_{imp} - N_A \\ t_{w\_p} = \dfrac{d_r - d_{r\_wa}}{r_{imp} - r_{imp\_wa}} \end{cases} \quad (9)$$

Where r_{imp_wa} and d_{r_wa} are the weakly noise group statistical average values, t_{w_p} is the impulse width of periodic impulses. Now that we get all parameters for the simulation model, any impulse rate of impulse noise can be generated.

3. Power Line Noises Generation

Since we already explored impulsive noise random sampling in previous section, the random numbers of background noise and narrow-band interference is simulated in this section for generating power line noise.

The power spectral density of background noise is found to be a decreasing function [4] of the frequency in the CENELENC A frequency band, on average equal to

$$B_s(f) = 10^{(K - M*10^{-5}*f/Hz)} \text{ [W/kHz]} \quad (10)$$

Changed the Unit of (10) into dBm, we get,

$$B_s = -M*10^{-4}*f + (10*K + 30) \quad [dBm] \quad (11)$$

Taking all spectra measured at different groups, we find the coefficient 'M' of 'f' determining the slope, and 'K' determining the power for background noise. However, the 'M' is not constant in our test site. K and M was taken based on least-squares curve fitting methods, exploiting the central limit theory of great numeral [10]; K and M can be shown to be approximately Gaussian distributed: K~N(-5.64,0.5), M~N(-3.95,3). Therefore, the simulation of background noise can be drawn by sampling Gaussian distributed. The power of simulation can be raised by increasing K. Then, using time-frequency domain conversion method, the random number is transformed into time domain.

The narrow-band interference is then simulated. It mostly is sinusoidal signals with modulated amplitudes caused by ingress of broadcast stations. Narrow-band interference is represented in terms of its envelope and phase components as follows:

$$N_n(t) = \sum_{i=1}^{N} r_i(t) * \cos[2\pi f_i t + \psi_i(t)] \quad (12)$$

Where the random variable ψ_i representing phase is uniformly distributed inside the range 0 to 2π and the random variables r_i representing envelope is Rayleigh distributed. The spectral power concentrates around midband frequency f_c. We get narrow-band interference by simulating random numbers from these specific distributions.

Finally, we can generate power line noise through the addition of the random sampling of these three noises.

4. Evaluation

In the proposed model, the noise is a No-Gaussian random process defined by (2). We estimate the impulse rate and disturbance ratio (r_{imp}, d_r) by the measurement of noise, and then exploit (4) to compute the characteristic parameters.

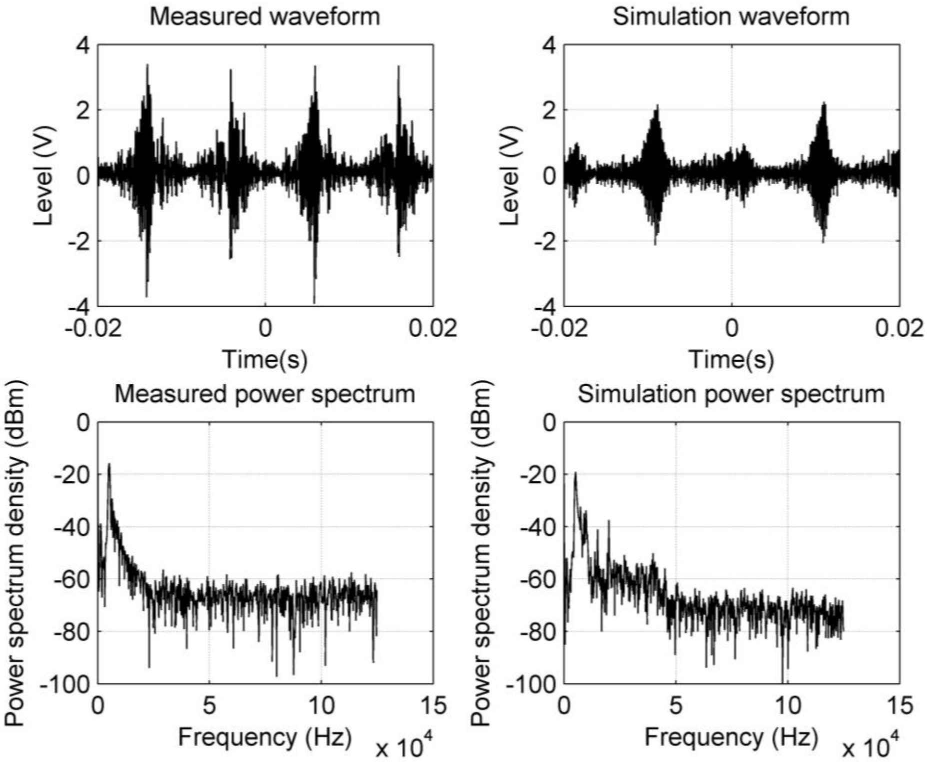

Figure 2. Comparing the Result of Measured and Simulation

Figure2 is an example of noise waveform and power spectral density generated from this model and the measured data. It is interesting that the generated noise waveform is similar to that of the original noise. The parameters are as follows: r_{imp} =157 s^{-1}, d_r =4.71%. To validate the simulation data, r_{imp} and d_r are computed. These values of simulation data are as follows: P=-71.2dBm, r_{imp} =154 s^{-1}, d_r =4.708%; the average power of measured data is -70.81dBm. The values of simulation are very close to measured data. Of course, the results of the comparison of noise waveforms do not have large significance. To verify the proposed model, a comparison of simulated data and field-measured data is presented in this section. We select five representative groups of field measured data with different (r_{imp} , d_r), the simulation time is 20s. In each group of measurement, 100 subgroups of random noises were generated based on the proposed model, the statistic of (r_{imp} , d_r) and mean power is analyzed and compared with the original.

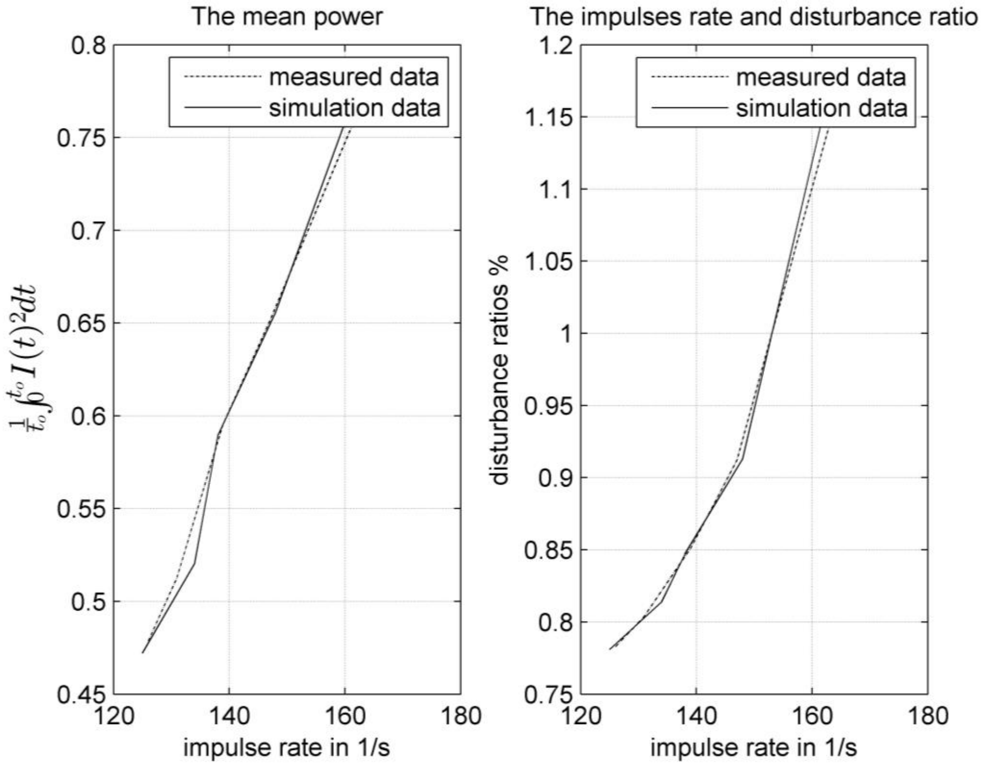

Figure 3. Comparing the Result of Measured and Simulation

As can be seen in Figure 3, the impulse rates, disturbance ratios, and mean power of the simulated data approximate the measured data.

4. Conclusions

In this paper, a random model representation of the noise in narrowband power line communication systems was introduced. This model can express time variant and No-Gaussian features of the noise in power lines. Therefore, it provides a benchmark for design and evaluation of communication systems under the time variant colored power line noise environment.

The suggested model has taken into account background noise and impulse noise components, which describe the PLC channel's noise. The characteristic parameters describing each component were studied, as well as their statistical properties. All of these properties were taken under consideration in order to comprise our noise model, which made it as realistic as possible under the conditions of a power-line channel.

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