Comparative analysis of the signal power density in a real PLC channel and a simulation-based NS-3 environment

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Abstract. Communication organization over the power lines is complicated by a row of negative factors. One of the main disadvantages of the Power Line Communication (PLC) technology is the existence of various types of noise in the communication channel, which impedes transmission of a signal. As a result, there is a need to minimize the influence of noise on a signal. It is necessary to make a dynamic choice of frequencies suitable for data transmission in the case when the noise minimization is impossible. It is expedient to investigate the spectral power density of a signal during data transmission over the PLC channel to determine the least noisy frequencies. In this article, the investigation of the spectral power density of a PLC channel is described. The research is conducted by simulation modelling in the NS-3 environment and experimentation in a real-world block of flats. The goal of the research is to evaluate conformance of an NS-3 model to a real-world PLC network. During the analysis of the experimental results and simulation modelling results, there was drawn a conclusion that the spectral power density distribution of a signal and noise in the model differs from the real-world PLC channel.

1. Introduction

The advantage of the Power Line Communication (PLC) technology is simplicity of its implementation. Existing power line infrastructures are used for the PLC network construction. Therefore, there is no need for installation of additional cables [1]. Data transmission is performed by analog electric signal overlapping upon the AC current which has a frequency equal to 50 or 60 Hz [2]. Nevertheless, communication organization over power lines is complicated by a row of negative factors [3, 4]. One of the main disadvantages of the PLC technology is the existence of various types of noise in the communication channel, which impedes successful data transmission. In connection therewith, there is a need to minimize the noise impact on the signal [5, 6]. If noise minimization in the channel is impossible, it is necessary to frequencies selection suitable for data transmission. This selection has to occur dynamically depending on the current state of the PLC channel. It is expedient to investigate the spectral power density of the signal during data transmission over the PLC channel for determination of the least noisy frequencies.

Many scientists have been studying the signal and noise spectral power density in the PLC channel. In A. Pinomaa's work [7], research of the PLC channel in the low-voltage DC networks is
presented. In M. Mosalaos's work [8] the borders of periodic impulsive noise, synchronous impulsive noise and background noise are studied by comparison of the authors' mathematical simulation results with mathematical simulation results of other scientists. In [9], Karl F. et al conducted a research on the cyclical spectral analysis of the PLC channel in the frequency band 3 - 200 kHz. In [10], the authors researched the signal spectrum, data transmission rate and noise-emission level in the PLC channel. Investigations have been conducted in a dwelling house and in a small-scale manufacturing enterprise. In Dirk Benyoucef's work [11] research of the spectral-noise density in the PLC channel is presented. In this research, they designed an adaptive mathematical statistic model of noise in the power line. Measurements for the model were taken in residential units and in office units. The frequency interval under study was 0-30 MHz. In [12], the author presented a research on both broadband and narrowband PLC channels. The research was performed using the NS-3 simulation modelling environment. In this research, a mathematical model of the PLC channel was designed. The model included parameters of the physical and network layers. The result of the research is the development of a PLC module for the NS-3 environment.

The main task of the article is to study the signal and noise spectral power density in a real-world PLC channel and in a simulation model. High reliability of the simulation modelling results will allow us to design networks based on PLC channels easier as well as to reduce the costs of PLC network’s engineering. Also, the research is necessary for a determination of the frequencies which are satisfactory for data transmission. Therefore, the goal of the research is to evaluate the conformance of the PLC NS-3 simulation model to the real-world PLC network models obtained from the block of flats.

2. Materials and methods

PLC networks are divided into narrowband and broadband PLC networks according to the frequency interval and transfer time [13]. Broadband transmission is used in systems which process large quantities of data (e.g., local networks, IP telephony, Internet, video observation, integrated security systems, etc.). Narrowband transmission is used in systems which do not require processing of large quantities of data. The examples of systems which use narrowband transmission are Automated Process Control Systems, Automatic System for Commercial Measurement of Power Consumption, Access Management and Control Systems, Fire Safety System, Smart houses, different kinds of extensions of dispatcher systems, etc. [14]. Investigations presented in this article are based on G3-PLC Standard, which requires the use of the narrowband frequency interval when data is transmitted over power lines. Narrowband frequency interval is 10 – 200 kHz, and it is more responsive to disturbance [15]. Frequently, sources of the disturbance and noise in the PLC channel are electrical appliances which are connected to the power line or are near it. There are three main categories of noise [16]:

- narrowband noise;
- additive white Gaussian noise;
- impulsive noise.

Narrowband noise is concentrated on the narrow band of frequencies, and it is due to various factors. Additive white Gaussian noise is equally distributed over all frequencies of the PLC channel. Impulsive noise is characterized by a row of disturbances. These disturbances are short-time, and they are different in their spectral power density. All the listed noises can be present in the communication channel both singly and combined with each other [17]. Besides the noise, the overlapping effect for signals which are transmitted from other network nodes exists in the PLC channel. Such effect is called interference [9].

Noise has its own spectral power density in a specific region of frequencies. Spectral power density is a function which describes the distribution of measures of power to unit intervals of frequency [18]. Within the research of spectral power density, a block of flats was reviewed. In the reviewed block of flats, the data transmission over the narrow-band PLC channel in CENELEC-A (35.9 – 90.6 kHz) and CENELEC-B (98.4 - 121.9 kHz) frequency bands was realized [19].
Spectral power density determination has been realized by simulation modelling in the NS-3 environment. This model includes parameters of both physical and network layers [20]. In particular, it includes network topology and spectral power density of signal and noise. The NS-3 environment does not contain a module for the PLC network simulation. Therefore, an outside module for the PLC network simulation in NS-3 environment [12] has been used. The spectral power density values for simulating in the PLC module are calculated using the following formula:

\[ rxPsd = txPsd \cdot |H(f)|^2 \]  

where \( rxPsd \) - received spectral power density,
\( txPsd \) - spectral power density of the transmitted waveform,
\( |H(f)|^2 \) - magnitude square of the channel transfer function.

Formula (1) is used in methods CalculateRxPowerSpectralDensity() and GetAbsSqrCtf(), are owned to class PLC_ChannelTransferImpl [21]. In this case, the value of a transfer function is a result of the original signal \( x(t) \) Fourier transformation from the temporary domain to the frequency domain.

Measurements of spectral power density in a real-world block of flats have been obtained for evaluating conformance of characteristics of the designed model to characteristics of the real-world PLC-network. The overall schematic diagram of the PLC network for the block of flats in which the experiment was performed is displayed in figure 1.

![Overall schematic diagram of the PLC network in the real-world block of flats](image)

**Figure 1.** The overall schematic diagram of the PLC network in the real-world block of flats.

The block of flats includes two wings consisting of 16 floors. There are three nodes of the PLC network set on each floor. Each PLC node is connected to the main electric cable of the house. Data from nodes is transmitted to the Data Acquisition and Transmission Device (DATD). The DATD is also connected to the main electric cable at the inlet of the building, and it has the function of a repeater. The main task of the DATD is data collection from network nodes by means of electrical meter polling, data processing and forwarding this data to the server. During the experiment in the block of flats, levels of the spectral power density in the PLC channel when data is transmitted from the DATD to network nodes and in reverse direction were researched. A spectral analyzer was used for the measurements taking. It was connected to the PLC channel at two points: in one of the network nodes and at the point which was located above the DATD.

3. Results and discussion

As a result of the experiment, the characteristic of the signal spectral power density in the PLC channel of the block of flats was received (figure 2). Figure 2 shows that the data is transmitted over a
single carrier frequency. During the analysis of the experimental data, the frequencies which are appropriate for data transmission were determined. These frequencies are in the range of 60 to 122 kHz. According to the G3-PLC Standard, three sub-bands from CENELEC-A and all sub-bands from CENELEC-B are included in this range.

According to simulation modelling in the NS-3 environment, frequencies which are suitable for data transmission are also located in the range from 60 to 122 kHz. It is a testament to the fact that parameters of the simulation model correspond to most parameters of the real-world PLC network. However, a more uniform distribution of the signal power is observed in the simulation model. Obvious power surges of a signal along all the reviewed frequency intervals are absent in the model. This is due to the absence of random deviates when the power of a signal is distributed to the chosen ranges. A graph of the signal and noise power distribution which was obtained during simulation modelling is presented in figure 3.

**Figure 2.** Signal and noise power distribution in the real-world PLC channel.

**Figure 3.** Spectral power density of signal and noise of the simulation model.
During the experiment in the block of flats, frequencies which are suitable for data transmission were selected manually. Then data transmission over the PLC channel using a DATD in the frequency interval from 91 to 121 kHz was triggered. The data transfer process observed during the experiment is represented in figure 4. For the purpose of approximating the results of simulation modelling to the real conditions, there was made a decision to increase the noise level in the communication channel and also to divide all the reviewed ranges into several sub-ranges for a more detailed analysis. This made it possible to form a more realistic model in the NS-3 environment with a more random distribution. Herewith, the spectral power density of the signal remained equal to the averaged value (-34.5 dB). Distribution of signal and noise spectral power density in the model of the channel was administered over the CENELEC-A and CENELEC-B frequencies ranges. A graph of signal spectral power density resulting from simulation modelling after modification is represented in figure 5.

**Figure 4.** Distribution of the signal and noise spectral power density at the moment of data transmission.

**Figure 5.** Distribution of the signal and noise spectral power density at the moment of the simulation modelling.
During the analysis of the spectrogram, the levels of maximal and minimal energy usage were determined. It was noted that the level of noise power in the frequency interval from 10 to 60 kHz is increased by 5dB when the energy usage is maximal. Figure 4 shows data transmission in the segment of CENELEC-A along two carrier frequencies. The signal transmission with the orthogonal frequency separation in the frequency interval CENELEC-B is shown in figures 4 and 5. Figure 4 represents the results of the experiment; Figure 5 represents the results of the simulation modelling. Besides self-interference, the PLC channel is sensitive to the electric wiring quality and to the distance between network nodes. As network nodes are gradually moved away from the DATD, the power of the received signal is decreased by up to 33.3% in relation to the power of the transmitted signal. This fact is due to the fading of a signal and different values of impedance of the mediator nodes. Herewith, the level of the noise power remains the same. Besides, data can be transmitted to the receiver with distortions, or data transmission to the receiver may fail. This information is proved true by the analysis of the spectograms received when a spectral analyzer was connected to the PLC channel through network nodes. Figure 6 represents the graph of the signal power distribution when there was a connection to the network node.

![Figure 6. The signal and noise power distribution when there was a connection to the network node.](image)

4. Conclusions
When analyzing the results of the experiment and the results of the simulation modelling, there was drawn a conclusion that the spectral power density of signal and noise in the model differ from the real-world PLC channel by the absence of random deviates when signal power is distributed. All values which were analyzed during simulation modelling are predictable; their logic is revealed easily and does not envisage the random noise generation. It is necessary to enhance the noise impact on the communication channel using random distribution over the frequency interval to approximate the model to the reality. In addition, there was made a resolution to research parameters of the PLC channel in the separate segments of the observed frequency interval for a more detailed analysis of the modelling results. The modified model, which has properties similar to the real-world PLC network, will allow us to facilitate the research of the PLC channel. The more detailed analysis of spectral power density of the signal and noise will allow us to automate the process of subcarriers dynamic selection to transmit data depending on the current state of the PLC channel. Dynamic amending of the subcarriers will allow improving data transmission quality and enhance the reliability of
communication. It is planned to use the modified simulation model in the design of a heterogeneous communication system based on PLC and Radio Frequency channels.

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References

[1] Yousuf M S and El-Shafei M 2007 Power Line Communications: An Overview - Part I Innovations in Information Technology (4th International Conference on Innovations) 218-222

[2] Makarenko S I and Fedoseev V E 2014 Multichannel communication systems. Secondary networks and subscriber access networks [in Russian – Sistemy mnogokanal’noj svjazi. Vtorichnye seti i seti abonentskogo dostupa] (Saint-Petersburg: Mozhaisky Military Space Academy printing house) 179

[3] Nevstrukov I A and Kirillov A V 2007 Electromagnetic compatibility of systems of data transmission via power grids Electrotechnical and information complexes and systems [Elektrotehnikeskie i informacionnye kompleksy i sistemy - in Russian] 3/4 1-10

[4] Feng J, Wang D, Li Y, Wang D and Qiao X 2016 Analysis of PLC transmission characteristics of urban distribution network International Conference on Civil, Transportation and Environment 805-812

[5] Gogoleva S A, Demidov A Y, Karataeva N A, Maykov D U and Voroshilin E P 2011 Assessing the impact of frequency detuning on the probability of bit error in the OFDMA communication systems Proceedings of Tomsk State University of Control Systems and Radioelectronics [Doklady Tomskogo gosudarstvennogo universiteta sistem upravlenija i radioelektroniki - in Russian] 24/2 45-48

[6] Zajcev A P, Shelupanov A A, Meshherjakov R V, et al. 2009 Technical means and methods of information protection: Textbook for universities [in Russian – Tehnicheskie sredstva i metody zashhity informacii: Uchebnik dlja vuzov] (Moscow: OOO Izdatelstvo Mashinostroenie) 508

[7] Pinomaa A 2013 Power-line-communication-based data transmission concept for an LVDC electricity distribution network – Analysis and implementation Doctoral Dissertation in Technology

[8] Mosalaosi M 2014 Power line communication (PLC) channel measurements and characterization Master of Science Dissertation in Engineering

[9] Nieman K F, Lin J, Nassar M, Waheed K and Evans B L 2013 Cyclic spectral analysis of power line noise in the 3–200 kHz band Power Line Communications and Its Applications (ISPLC) (New Jersey: IEEE) 315-320

[10] Misurec J, Mrakava P and Adamko D 2011 Interference in power lines and data communication over narrow-band PLC (Brno: ISSN 1213-1539) 63-67

[11] Benyoucef D 2003 A new statistical model of the noise power density spectrum for powerline communication International Symposium on Power-Line Communications and Applications (Proc. IEEE ISPLC) 136-141

[12] Aalamifar F, Schlägl A, Harris D and Lampe L 2013 Modelling power line communication using network simulator-3 Global Communications Conference (GLOBECOM) (New Jersey: IEEE) 2969-2974

[13] Tonello A M and Pittolo A 2015 Considerations on narrowband and broadband power line communication for smart grids Smart Grid Communications (SmartGridComm) (New Jersey: IEEE) 13-18
[14] Fahad K, Sobia B, Umber N and Adnan Y 2012 An Overview of OFDM Based Narrow-band Power Line Communication Standards for Smart Grid Applications World Applied Sciences Journal 20(9) 1236-1242

[15] Klimov I Z and Shishkin A L 2011 A Noise Model of Residential Low Voltage Power Line Network Electronics, measuring equipment, radio engineering and communications [Elektronika, izmeritel'naja tehnika, radiotehnika i svjaz - in Russian] 51/3 107-110

[16] Chebotayev P, Klimenko A, Myakochin Y, Polyakov I, Shelupanov A, Urazayev D and Zykov D 2017 Research of communication quality assessment algorithm according to the standard G3-PLC AIP Conference Proceedings 1899/1 060016

[17] Korki M, Hosseinzadeh N and Moazzeni T 2011 Performance evaluation of a narrowband power line communication for smart grid with noise reduction technique IEEE Transactions on consumer electronics 57/4 1598-1606

[18] Skljar B 2004 Digital communication: Theoretical foundations and practical application [in Russian – Cifrovaja svjaz: Teoreticheskie osnovy i prakticheskoj primenenie] (Moscow: Izdatelskij dom Viljams) 1099

[19] ITU-T. G.9903 Narrowband orthogonal frequency division multiplexing power line communication transceivers for G3-PLC networks 2014 (International Telecommunication Union, Geneva)

[20] Pospelova I, Chebotayev P, Klimenko A, Myakochin Y, Polyakov I, Shelupanov A and Zykov D 2017 Research of G3-PLC net self-organization processes in the NS-3 modeling framework AIP Conference Proceedings 1899/1 060017

[21] ns3:PLC_ChannelTransferImpl Class Reference Site of the ns-3 PLC model, available at: http://www.ece.ubc.ca/~faribaa/ns3_plc/doc/html/classns3_1_1PLC__ChannelTransferImpl.html#ab46c85b0bd89898e3cb62f4fda438a1