Analysis of the level of SNR in the PLC channel based on the results of mathematical and physical modelling

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Abstract. One of the most pressing challenges still existing in modern communication systems based on PLC (Power Line Communication) technology is distortion of the original signal when it passes over the communication channel. This article is concerned with the assessment of the impact of the PLC channel on a signal, which was carried out by physical and mathematical simulation tools. The goal of the research is to find correspondences between the mathematical model and the real-world PLC channel. In this article, the real-world PLC channel is represented as a physical model, which was executed with the Texas Instruments evaluation kit. The mathematical model considered was executed with Matlab environment. The SNR (Signal-to-noise Ratio) parameter was used for the assessment of the impact of the PLC channel on a signal in the physical model. The LQI (Link Quality Indicator) parameter was used for the same purpose in the mathematical model. According to the results of the investigations, it is identified that the mathematical model corresponds in its properties to the real-world PLC channel. Therefore, the developed mathematical model is suitable for further investigations of the processes occurring in the real-world PLC channel.

1. Introduction
One of the most pressing challenges still existing in modern communication systems based on PLC (Power Line Communication) technology is distortion of the original signal when it passes over the communication channel [1-4]. This effect is due to the existence of various noise and disturbance in the communication channel. Among all the impacts on a signal, the white Gaussian noise and multipath-propagation effect are the most commonly encountered ones [5-7]. The channel impact on a signal is characterized by the SNR (Signal-to-Noise Ratio) parameter. The SNR parameter represents a non-dimensional quantity equal to the ratio of the power of the useful signal to the noise power (1).

$$SNR = 10 \log_{10} \left( \frac{P_{signal}}{P_{noise}} \right) = 20 \log_{10} \left( \frac{A_{signal}}{A_{noise}} \right),$$

where $P$ is an average power of a signal; $A$ is a root-mean-square amplitude of a signal.

The studies of the SNR in the PLC channel have been conducted by many scientists. In [9] J. Meng and X. Ding describe the research of the characteristics of the additive white Gaussian noise and the narrow-band noise during data transmission using three modern technologies of the communication construction over the PLC channel. These technologies are direct-sequence spread spectrum (DSSS), orthogonal frequency division multiplexing (OFDM) and ergodic chaotic parameter
modulation (ECPM). In the work of Jose Antonio Cornes co-authored with other scientists [10], the characteristics of the narrow-band PLC channel are analyzed, and the utilization efficiency of the PLC technology for the development of smart meters infrastructure is estimated. In the course of their investigation the main characteristics of the PLC channel were studied; among other things, the noise evaluation in the communication channel was made. According to the authors, the investigations described in the article were conducted under the urban conditions as well as in the countryside. In one of the papers of the scientists’ team in the person of Javier Matanza, Sadot Alexandria and Carlos Rodriguez-Morcillo, the investigation of the performance of the PLC channel which uses PRIME as a data transfer standard is described [11]. During the research, scientists designed simulation models of the PLC channel using Matlab and OMNeT++ environments.

This article is concerned with the analysis of the SNR level in a PLC channel. In our work, it was decided to start the research by using modelling tools to study the behavior of signals in the PLC channel and to estimate how the channel impacts the signal. The reason for this is that simulation allows determining optimal values of the SNR required for correct signal transmission at minimum cost. In addition, simulation is the most flexible tool which allows simulating various conditions of the data transmission medium and various methods to protect the signal from noise and disturbance. It is necessary to verify the findings of modelling comparing them to the real-world values in order to minimize deviations peculiar to the mathematical model.

In the article, the real-world PLC channel is represented as a physical model, which allows conducting an assessment of the impacts of various noise and disturbance on a signal. The physical model was executed with the Texas Instruments evaluation kit [12]. The mathematical model considered was executed with Matlab environment. All investigations were based on the G3-PLC standard. The SNR (Signal-to-noise Ratio) parameter was used for the assessment of the impact of the PLC channel on a signal in the physical model. The LQI (Link Quality Indicator) parameter was used for the same purpose in the mathematical model. Such choice is due to the fact that each of the simulation instruments supports different parameters characterising the communication channel state. The goal of the research is to conduct an experiment and to find correspondences between the mathematical model and the real-world PLC channel.

2. Materials and methods

The PLC technology uses power lines as a data transmission medium. There are various strategies for using the voltage cable as an instrument of communication. These strategies are contingent on the requirements put forward by the area of application of the PLC technology [13, 14]. As a result, there have been developed many standards [15, 16] which include recommendations for using the PLC technology. The PLC OFDM specification is the most commonly used among the narrow-band PLC technologies, and it is offered by PRIME [17] and G3-PLC [18] alliances.

The main difference of the G3-PLC standard from the PRIME standard is in a more complicated mechanism of encoding with adding the Reed-Solomon code as an adjunct to the convolutional encoding. Unlike the PRIME, G3-PLC uses the fallback data rate, which provides better noise immunity [19]. The results of the research of M. Hoch support this fact [20]. In his publication, M. Hoch compares physical layers of both standards using theoretical analysis and the results of mathematical modelling. As a result, he states that the G3-PLC is more resistant to the narrow-band noise influences. Therefore, high reliability and long transmission distance make the G3-PLC standard more preferable for designing large networks.

The study described in our article is based on the G3-PLC standard. The G3-PLC standard prescribes to use the LQI parameter as a relative value in the capacity of the characteristic describing the state of the channel over which the data transmission is realized. The LQI represents an integer value within limits of 0x00 to 0xFF. The corresponding LQI values are equidistributed over this numeric range. The LQI value equals the average SNR value which falls within the range from -10 to 53.75 in increments of 0.25 dB, which amounts to 255 units [18].
The LQI parameter has a positive correlation with the possible capacity of the communication channel. So, if the LQI has a high level, it is possible to use a higher-order modulation, which leads to an increase of the communication channel capacity. The same communication line can have different carrying capacity when different modulation types are used. Thus, the modulation type which maximizes the use of the power line features should be chosen.

The research of the PLC channel was conducted based on the mathematical model built earlier [21]. The model was designed by Matlab tools, and it corresponds to the G3-PLC requirements (figure 1).

![Figure 1. Simulation model of the PLC transceiver built using Matlab environment.](image1)

The schematic diagram includes the following blocks:
- Data generator. It generates a required bit sequence and sends it to the modulator block;
- OFDM modulator. It modifies the original bit sequence by scrambling, encoding, interleaving and modulation. The input data of this block is the sequence of the OFDM symbols which are transmitted further over the communication channel;
- PLC channel. It impacts on the OFDM symbols by entering the noise, disturbances, fading and multipath-propagation effect with various dispersal profiles. After that, data is sent to the demodulator block;
- OFDM modulator. It performs operations opposite to the modulator block. The output data of this block is the original bit sequence;
- Spectral analyzer. It shows a spectrogram of the bit sequence during the simulation start;
- Visualization block. It allows keeping track of the number of transmitted bits and the bit error.

![Figure 2. Model of the PLC channel.](image2)

A binary sequence was used as the original signal in the model. This binary sequence is transmitted to the PLC channel after all transformations (figure 2). The PLC channel, in its turn, contains the white Gaussian noise and simulates the signal multipath-propagation with various dispersal profiles. Then, the signal is demodulated, and the obtained results are compared with the
output signal. Basing on this comparison, it is possible to estimate the impact of the PLC channel on the signal depending on the used modulation type.

For evaluating conformance of the PLC channel which was designed in the simulation environment Matlab to a real-world PLC channel, it was decided to conduct physical modelling of the PLC channel with noise simulation. We use the term "model" to mean a simplified representation of the PLC channel with two transceivers (figure 3). During physical modelling, the Texas Instruments evaluation kit was used. The operation modes of this kit correspond to the G3-PLC standard and allow estimating the state of the PLC channel in real time [22].

Figure 3. Schematic diagram of the physical model of the PLC channel.

Figure 3 represents a schematic diagram of the physical model, which consists of evaluation boards, a PLC channel and a personal computer. One of the boards serves as a transmitting modem, and the other one serves as a receiving modem. The transmitter and the receiver are connected to each other by a power line with the multipath propagation. The noise source generates the Gaussian noise and the impulsive noise in the communication channel. The personal computer shows the network parameters in real time and generates data for the transmitting modem.

As a result of the physical modelling, intervals of the SNR values were determined for the following conditions:
- between two nodes with the simplified structure of the PLC channel;
- between two nodes with noise simulation in the simplified structure of the PLC channel;
- between two nodes with the complex structure of the PLC channel.

Using the term "complex structure of the channel", we mean that the channel has segments with a twisting of wires. As the noise source, various electrical appliances making the disturbance in the communication channel were used. During the observation over the channel physical model, it was noted that running the electric motors and running the microwave ovens made the heaviest influence of the disturbances on the PLC channel.

3. Results and discussion

During simulation modelling, the data transmission at an SNR level equal to 20 dB in Rician and Rayleigh channels with white Gaussian noise was reviewed. Figures 4.a and 4.b show the diagrams of bit error rate (BER), i.e. the dependence of the ratio of the number of symbols received with error on the total number of the received symbols, depending on the SNR level at various modulation types. Figure 4a represents the diagram of BER in the Rician PLC channel. Figure 4b represents the diagram of BER in the Rayleigh PLC channel. As it is seen from the diagrams, DBPSK and DQPSK modulations are the most acceptable.
Figure 4. Dependence of the BER level on modulation type in (a) Rician and (b) Rayleigh PLC channels.

During the physical modelling, a list of SNR values in the PLC channel under various data transmission conditions was determined. The results of the experiment are represented in table 1.

Table 1. The results of the physical modeling.

| Condition                                         | Modulation type | BER, % | SNR, dB |
|---------------------------------------------------|-----------------|--------|---------|
| Between two nodes with the simplified structure of the PLC channel | DBPSK           | 0      | 20      |
|                                                   | DQPSK           | 0      | 16      |
|                                                   | D8PSK           | 0      | 17      |
| Between two nodes with noise simulation in the simplified structure of the PLC channel | DBPSK           | 0      | 16      |
|                                                   | DQPSK           | 0      | 16      |
|                                                   | D8PSK           | 0      | 18      |
| Between two nodes with the complex structure of the PLC channel | DBPSK           | 49.70  | 0       |
|                                                   | DQPSK           | 48.13  | 0       |
|                                                   | D8PSK           | 50.57  | 2       |

From the table 1, it can be observed that SNR lies in the range from 0 to 20 dB representing 40 and 120 LQI, correspondingly. Analyzing the table data, it can be concluded that the percentage of errors in the signal at the receiver increases and the SNR value decreases with the complication of the communication channel. It should be noted that data were transmitted without changing and loss in the PLC channels in which the segments with the twisting of wires are absent. The SNR value is variable, but it has a high value despite the noise influence (figure 5 and figure 6). In the case of the complex structure of the PLC channel, communication works with a high data loss because the signal dies away in the segments with a twisting of wires. In these segments the SNR value is <= 0 dB (figure 7).
Figure 5. The SNR level between two nodes with the simplified structure of the PLC channel.

Figure 6. The SNR level between two nodes with noise simulation in the simplified structure of the PLC channel.

Figure 7. The SNR level between two nodes with the complex structure of the PLC channel.

Therefore, the SNR values represented in the table 1 were averaged by the software of the evaluation kit during physical modelling. In such a way, after analyzing the results obtained during the experiment and the results obtained by simulation modelling, it can be concluded that the designed model allows investigating the PLC channel to the full extent.

4. Conclusions
During the research with the use of the Texas Instruments evaluation kit, we realized a physical model of the PLC channel which conforms to the G3-PLC standard. During the experiment, the list of the SNR values which corresponds to various states of the PLC channel was received. When analyzing the obtained results, it was found that the received SNR values lie in the range from 0 to 20 dB. The BER is about 50% at the values of SNR in the range from 0 to 2 dB regardless of the chosen modulation type. Similar results were observed during the mathematical modelling. During data transmission in the range of the LQI values from 4 to 80 (that is 0-10 dB in converting values to SNR), a considerable increase of errors is also observed.
The comparison of the experimental data with the results of the mathematical model designed in the Matlab environment has confirmed correspondence of the properties of the simulated channel to the properties of the real-world PLC channel. Thus, the designed mathematical model can be used for investigating real-world PLC networks. In the future, it is planned to use this model for designing a heterogeneous communication system based on the radio channel and PLC channel.

Acknowledgment

This work was financially supported by the Ministry of Education and Science of the Russian Federation, agreement no. 14.577.21.0230, unique project identifier: RFMEFI57716X0230.

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