Research Article

Errors Nature of the Narrowband PLC Transmission in Smart Lighting LV Network

Piotr Kiedrowski

Telecommunication and Computer Science Institute, University of Science and Technology (UTP), 7 Kaliskiego Street, 85-789 Bydgoszcz, Poland

Correspondence should be addressed to Piotr Kiedrowski; piotr.kiedrowski@utp.edu.pl

Received 11 September 2015; Revised 30 November 2015; Accepted 13 December 2015

Academic Editor: Javier Matanza

Copyright © 2016 Piotr Kiedrowski. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This paper presents characteristics of the Frame Error Rate versus Signal to Noise Ratio obtained from Smart Lighting LV network. These characteristics are the results of carrying out many field-trials in three locations. During the one-year tests period lighting systems evolved from the traditional, gas-discharge not individually dimmable system to LED or gas-discharge Smart Lighting system controlled with the use of PLC technology every lamp individually. A different influence of the frame length on the FER(SNR) characteristic for the gas-discharge and LED LV networks led to examining the bit errors distribution. The bit errors distribution characteristics of the narrowband PLC transmission over the Smart Metering LV network are also presented in this paper. All the presented data in this work are the results of the long time field-trials, which were verified in the lab conditions.

1. Introduction

Smart Lighting low voltage (LV) network is a power network between a MV/LV transformer and loads in which all the loads are dimmable lamps. The only exceptions to this rule are traffic concentrators which, unlike the lamps, do not practically affect the impedance of the LV network. Smart Lighting systems may be supplied from general purpose LV networks or from Smart Lighting LV networks. Supplying the lighting systems from general purpose LV network is getting rarer and concerns mainly rural areas and suburbs. Smart Lighting systems allow controlling every lamp individually, where basic control functions are brightening and dimming as well as turning-on and turning-off. To control every lamp individually (not the entire street as it was with older systems) a last mile communication network must be employed. This part of the Smart Grid communication networks has a decisive impact on the cost of implementation and operation of the whole communications system. Thus very cheap short-range devices (SRDs) have been used to deploy last mile wireless or PLC (Power Line Communications) networks. Both the Smart Metering and the Smart Lighting, last mile communication systems based on PLC or RF technology, create a specific kind of the distributed sensor networks.

Smart Metering solutions based on RF technology are very similar to Wireless Sensor Networks (WSNs) [1] in both their topology and hardware solutions.

One of the differences between Smart Metering and Smart Lighting last mile networks is their topologies. Smart Metering networks in most cases create a mesh topology whilst Smart Lighting networks a link topology. Using the PLC technique in three-phase network, as in most cases, there are two variants of the topology of the Smart Metering communication network, namely,

(a) three links with shared modem topology,
(b) topology with three independent links.

In Figure 1 two examples of variants are presented.

Using the three links with shared modem variant the traffic concentrator works in the hub mode, whilst using three independent links’ variant it works in the router mode. Thus, sending information to any lamp supplied from L1, this information will also be received by some lamps supplied from L2 and L3, when variant (a) is used. There are of course other differences between Smart Metering and Smart Lighting last mile communications; a good example can be services.
Using Figure 1(a), it is easy to imagine the difference between the last mile Smart Metering realized in RF and PLC technology. In the case of RF, connections between lamps are independent from power lines but they depend mainly on physical distances between nodes (lamps).

The differences between Smart Metering and Smart Lighting in topology and services are the main reasons, which cause a need to create new communication protocols dedicated just to last mile Smart Lighting communication networks. The development of communication protocols has always been dictated by the necessity to implement new services or by new possibilities given by better technology. A good example can be Frame Relay technology, which replaced X.25, when new, better (more reliable) links have been applied in telecommunications. These two main reasons resulted in the existence of so many “made to measure” communication protocols. With Smart Lighting the situation is similar; it needs to have its own dedicated communication protocol or set of protocols, which meet all the specific requirements. The specific requirements for Smart Lighting are inter alia

1. fast autoconfiguration of the network,
2. the ability to work across all CENELEC bands,
3. in space and time multichannel working,
4. real-time services supporting,
5. data transfer asymmetry (more data is downloaded).

All these requirements are difficult or impossible to meet by interfaces designed for Smart Metering, for example, PRIME or G3 [2–5].

To develop a new communication protocol, knowledge of the behavior of lower layers is very useful, because it allows optimizing the parameters of the protocol. The physical layer is the lowest layer. The behavior of the PLC physical links is generally described by the primary and secondary parameters of the power line [6, 7] as well as by noise models [8]. The possibilities of the physical data transmission interfaces are described by FER (Frame Error Rate) versus SNR (Signal to Noise Ratio) or PER (Packet Error Rate) versus SNR.

Author of the paper as the person responsible for ensuring the last mile communication in the Smart Metering System carried out series of tests. The Smart Metering system is currently developed by University of Science and Technology in Bydgoszcz (UTP), Poland, and Orion Electric Poland under the GEKON Project supported by the National Centre for Research and Development and also by the National Fund for Environmental Protection and Water Management. In this paper FER(SNR) obtained for different frame length are presented. The study included lamps equipped with LED or gas-discharge light sources. The differences in the characteristics of FER(SNR) for different light sources have led to a detailed examination of the error nature of narrowband PLC transmission in Smart Lighting LV network. The outcomes of this research are presented in this work.

2. Test-Beds, Measurement Conditions, and Method of Data Collection and Presentation

Analysed data were obtained as a result of many field-trials carried out in three locations: Kamienna Street in Bydgoszcz City, Nieszawska Street in Torun City, and UTP Campus. In addition to these locations, observations were also done on separate Smart Lighting LV network test-beds prepared for studies related to the GEKON project.
The longest power line section of Kamienna Street LV network is 1.5 km long, with the traffic concentrator located at 500 m from one of the ends of the section. This section contains 100 lamps (terminal nodes) installed on 50 poles. The old gas-discharge light sources are used on this street. This network was used for testing the PLC transmission, that is, modulation types, methods of data correction, and of course transmission coverage.

One-section Nieszawska Street LV network has a length of 3 km with two traffic concentrators located in the middle. The LV network on Nieszawska Street contains 108 lamps; there is one lamp on every electric pole. The old gas-discharge light sources have been used during the three-month period of testing. They have been subsequently changed to LED. This network was used for functional testing, including traffic concentrators protection on/off switching.

UTP Campus LV network is not separated, dedicated to street lighting supplying only; it also supplies offices, classrooms, and labs. Both gas-discharge and LED light sources were used during the tests. This network consisted of 36 lamps.

Tests carried out on the lab test-beds were done with the different types and numbers of lamps. These tests were done for the results verification and also when we wanted to have condition impossible to obtain in the field, for example, transmission over the overhead power lines.

All data for the analysis were collected in traffic concentrators. Analyzed data were erroneous or error-free frames received by the traffic concentrator with the different values of SNR. When 3-phase LV network was under test, the traffic concentrator presented in Figure 1(a) was employed, whilst testing 1-phase LV network we employed traffic concentrator presented in Figure 1(b), using only one port. The SNR range of the frame reception was from 0 dB to 34 dB. Both traffic concentrators and lamps were equipped with our own construction modems based on STMicroelectronics ST7580 chip. To ensure the long range transmission the multihop [9] communication protocol has been designed and to ensure adequate data transfer reliability the multipath technique [10] was also implemented. An exemplary data flowchart for one traffic concentrator-lamp action is presented in Figure 2. In this diagram, the differences in time of the same frame reception by lamps are not shown, because the differences of the propagation times are negligible compared to the time of the frame transmission.

The whole action presented in Figure 2 lasted from timestamp A to timestamp N. In this example, lamp 1 and lamp 2, which are within range of the traffic concentrator, have to act as relay because the destination lamp is out of range of the traffic concentrator. Three types of frames were received by the traffic concentrator: commands (presented in red), responses (presented in green), and ACK/Cancel (presented in blue). The ACK/Cancel frames are always relayed by all the lamps that act as relay. Every relaying process starts after 60 ms plus random time (from 0 to 500 ms) for each lamp independently. The relay timer can be stopped if the command frame is expected to be relayed and the response frame was received or if the response frame is expected to be relayed and the ACK/Cancel was received. Such a situation happened at the time of E, which did not allow lamp 1 to send a copy of the command frame. The command frame was received by the traffic concentrator at the time of D; actually it was a copy of the command originally sent by traffic concentrator at the time of A and copied by lamp 2 at the time of C. Assuming the same bit rates for all the exchanged frames, the time duration of the command frame is B-A = D-C. At the time of C the destination lamp did not receive the command frame because it was out of the traffic concentrator transmission range; this happened only at the moment of D, thanks to multihop technique. After a negligibly short time at the time of D the destination lamp sent the response frame, which was received again by intermediate in the transmission nodes, that is, lamp 1 and lamp 2. This frame was also received by the traffic concentrator but with errors detected thanks to FCS (Frame Check Sequence) implementation. The correct response frame reception took place at time G, after sending it by lamp 1 at the moment of F (this time lamp 1 has overtaken lamp 2 in the frame relaying process; random time delay in lamp 1 was shorter than in lamp 2). At the end of the information exchanging process, the traffic concentrators sent ACK/Cancel frame, immediately after error-free response frame reception. Three copies of ACK/Cancel were received: one erroneous (from the destination lamp) and two error-free from lamp 1 and lamp 2.

In the above example, 6 frames have been received by the traffic concentrator. This example was very simple, just to explain multihop and multipath techniques and also to explain how data are collected in the traffic concentrator.
Field-trials showed that even more than 10 frames may be received after sending one command by the traffic concentrator. During the one information exchanging action, frames received by traffic concentrator may usually have three lengths. Sometimes they may have two lengths or the same lengths, but this is rather an atypical situation. These situations can happen when command and response frames have the same length or when command and response frames do not carry any packet payload; in this case all the received frames have the shortest possible lengths. The shortest frames in presented solution have the length of 23 bytes and consist of

(i) four-byte preamble,
(ii) two-byte unique word,
(iii) one-byte transmission mode indicator,
(iv) one-byte length indicator,
(v) fourteen-byte frame payload (packet),
(vi) one-byte FCS.

For the frames longer than 23 bytes the structure is the same except the fact that frame payload is longer than 14 bytes because it contains also the packet payload. The ACK/Cancel frames are always the shortest ones. The typical length of the response frames is 24 bytes but the length of these kinds of frames can also be a quite long, for example, when registers of the lamp are readout in burst mode. There is no typical length of the command frames; they may have length from 23 bytes up to 250 bytes.

When all the lamps are in the direct communication range of the traffic concentrator, no command frame can be received by it. This situation is presented in Figure 3, which shows the oscillogram with 5 different frame signals recorded from 1-phase LV power line during the one querying process. The oscillogram was taken off close to the traffic concentrator.

The waveform in Figure 3 contains five frames; two of them were transmitted by concentrator and three were received by it. The first frame (from the left) is the 33-byte command frame sent by traffic concentrator using BPSK (Binary Phase-Shift Keying) coded modulation. The second frame is the 55-byte response frame sent by the queried lamp also using BPSK coded modulation. It is easy to notice that the level of the signal of the response frame is lower than the level of the signal of the command frame. The third frame is the 23-byte ACK/Cancel sent by traffic concentrator with the same signal level and the same kind of modulation that command frame was sent. The fourth and fifth frames are also the 23-byte ACK/Cancel frames copied and sent by two far lamps (not queried at the moment); their signals are weaker because they are far from the concentrator; also their duration is shorter because they were sent using QPSK (Quadrature PSK) modulation, which allows transmitting data twice faster than BPSK modulation. Above example shows us differences in the shapes of the frames as a result of the transmission in the noisy environment, attenuation, and the length of the frame.

Every received line frame is extended by PLC modem with the information about its level and SNR and sent to the microcontroller. After a frame reception, the traffic concentrator updates its two-dimensional array. Every element of this array has two records: erroneous frames counter and error-free frames counter. One frame reception causes updating only the one counter of only one element of the array. This element is indexed by the SNR value and the length value. The SNR values are natural numbers or zero. For the given SNR and length, the FER value is calculated by dividing the value of the erroneous frames counter and the sum of the value of the erroneous frames counter and the value of the error-free frame counter. This is formalized by

\[
\text{FER} \left( \text{SNR}, L \right) = \frac{\text{ef}_{\text{SNR}, L}}{\text{ef}_{\text{SNR}, L} + \text{eff}_{\text{SNR}, L}},
\]

where \(L\) is the length of the frame, \(\text{ef}_{\text{SNR}, L}\) is the value of the erroneous frame counter of the two-dimensional array element indexed by SNR and \(L\), and \(\text{eff}_{\text{SNR}, L}\) is the value of the error-free frame counter of the same element in which the \(\text{ef}_{\text{SNR}, L}\) value is stored.

The FER value does not only depend on SNR and the length of the frame. It also depends on frame modulation and also if PLC modem was configured to work in single or dual channel mode. Using the fact that presented Smart Lighting communication system was designed to work in single channel mode only results in this condition are presented. All the types of PSK frame modulation, supported by ST 7580, were tested but to understand the errors nature of the narrowband PLC transmission in Smart Lighting LV network only not coded kinds of modulation are considered in this paper; this modulation is BPSK, QPSK, and 8PSK (8-phase PSK) with their bit rates 9600 bits/s, 19200 bits/s, and 28800 bits/s, respectively. In Figure 4, as an example, two charts are showed; they presented the same data but in different form: chart (a) has logarithmic axis of ordinates, which is more commonly used, whilst chart (b) has linear, which will be used in this paper only when it is necessary.

Regardless of which type of charts in Figure 4 is analyzed, it is clearly seen, from the curves, a well-known principle...
that BPSK modulation is more reliable but the cost of its robustness is the low bit rate; it is twice lower than the bit rate offered by QPSK. The reason for using two types of modulation is to increase reliability in this communication system, which is based SRDs. The most sensitive moment of exchanging data, using multihop technique, is the moment of the original packet sending, rather than sending a copy of it. The original packet can only be sent by one node while its copy can be sent usually by many intermediate nodes. Sending copies of the same packet by a few intermediate nodes significantly improves the reliability of transmission and also allows using faster though less reliable kind of modulation.

3. Differences in FER(SNR) Characteristics of LED and Gas-Discharge Lamps

Many tests were done to answer two questions, namely: which kind of modulation is optimal and what is the maximum length of the frame for the narrowband PLC transmission over the Smart Lighting LV network?

For the short frames, practically, there was no difference whether analyzed data were collected from the Smart Lighting LV network supplied LED or gas-discharge lamps. Of course there was also no difference in FER(SNR) curves when different types of lamps were used to illuminate the road.

As metrics of the difference between two curves an averaged difference of FERs has been used; it may be calculated from

$$\overline{D} = \frac{1}{256} \sum_{\text{SNR}=0}^{255} [\text{FER}_A(\text{SNR}) - \text{FER}_R(\text{SNR})],$$

(2)

where \(\overline{D}\) is averaged difference of FERs, \(\text{FER}_A\) is assessed curve of FER(SNR), and \(\text{FER}_R\) is reference curve of FER(SNR).

The constant 256 is used in formula because there are theoretically 256 possible values of SNR, when ST7580 is applied. In practice, all values of SNR were always in range from 0 to 34; higher values than 34 never occurred. Nevertheless, formula (1) gives indefinite value when both counters of the same element are zero. This situation takes place when the element is indexed by SNR that has never occurred during the observation period. In such a case it is assumed that \(\text{FER}_A(\text{SNR}) - \text{FER}_R(\text{SNR}) = 0\).

As an example the absolute value of \(\overline{D}\) which describes the difference between two curves presented in Figure 4 is about 0.13, which is a quite high value, given that \(\overline{D} \in [-1; 1]\). On the other hand, the absolute value of \(\overline{D}\) is nothing but a surface area between the red curve and blue curve in Figure 4(b).

The averaged difference of FERs, that is, \(\overline{D}\), will be used in this paper to describe differences in two FER(SNR) curves in the measurable way.
The first difference between LED and gas-discharge Smart Lighting LV networks in FER(SNR) characteristics was noticed during testing the influence of frame length on FER. The difference is as follows: for the same transmission condition (including the type of the modulation) the influence of the frames length on FER is smaller when they are transmitted over the LV network which supplies the gas-discharge lamps than over the LV network which supplies the LED lamps.

The above relationship was found for all the tests carried out. As an example in Figure 5 the set of four FER(SNR) curves is presented.

Using data presented in Figure 5 the ratio of $\overline{D}_{\text{LED}}$ to $\overline{D}_{\text{gas}}$ is about 2.32, which means that the length of the frame has bigger influence on transmission reliability over the LV network which supplies LED lamps. By analyzing the data in Figure 5, it can also be concluded that the transmission in an LED light source environment is more reliable; it is a wrong conclusion as evidenced by results of the experiment, which are presented in Figure 6.

Eight curves presented in Figures 5 and 6 are the results of three 48-hour tests; all the tests were performed in the same separated LV network, dedicated only to the lighting purposes. Test number 1 took place in April 2015 where all the light sources were gas-discharge. Two curves as a result of this test are presented in Figure 5; exactly the same two curves are also presented in Figure 6. Test number 2 took place in August 2015 after replacing gas-discharge type lamps with LED ones. Two curves as a result of this test are presented in Figure 6. Replacement of gas-discharge type lamps with LED ones caused deterioration of the FER(SNR) characteristic. This deterioration can be described by $\overline{D} \approx 0.008$ for the short (23 bytes) frames and by $\overline{D} \approx 0.01$ for the long (80 bytes) frames. Using data presented in Figure 6 the ratio of $\overline{D}_{\text{LED}}$ to $\overline{D}_{\text{gas}}$ is about 2.81, which means that again the length of the frame has bigger influence on transmission reliability over the LV network which supplies LED lamps. Test number 3 took place in September 2015 in the same conditions (LV network and LED lamps); the only difference was that the 1 mH coil was added at the input of the LED lamp power supplies. It was done to increase the input impedance of the lamp (at PLC transmission band) and to separate the high frequency noise generated by the lamp from the transmission media (LV network). The results of this procedure are shown in Figures 7(a) and 7(b).

About 15 dB noise reduction together with the increase of input impedance had significant, positive influence on FER(SNR) characteristics (comparing these in Figures 5 and 6). It also proved that there is a quite big difference in FER(SNR) characteristics depending on length of frames when they are transmitted over the LV network, which supplied LED lamps.

The results of the August and September tests also confirmed the performance observations noted on the lab test-beds. Using them it can be concluded that

1. the type of the lamps (gas-discharge or LED) in Smart Lighting LV network does not determine the performance of the transmission in narrowband PLC technology;
2. the frame length has a significant impact on the transmission performance when LED lamps are applied;
3. the frame length has rather small impact on the transmission performance when gas-discharge lamps are applied.

The third conclusion is more noticeable when less sophisticated kind of the PSK modulation is used, which is demonstrated in Table 1.
Knowing the fact that in the frequency of ten kHz the impedance of the gas-discharge LV network is higher than the impedance of the LED LV network and also that small differences in FER(SNR) versus frames length have no relation with the level of noises in the transmission band, the distribution of the bit errors was studied. The results of these studies are presented in the next section.

4. Bit Errors Distribution

Knowing the original format of the frame, both the BER (Basic Error Rate) and the bit errors distribution can be estimated. In this work the focus is only the bit errors distribution. The distance between two bit errors is defined as the difference between \( m \) and \( n \), where \( m \) and \( n \) are the bit positions (the number of the bits in frame) one which the error occurred; additionally \( n > m \) and also there are no errors on the positions between \( m \) and \( n \). The smallest distance between two bit errors is 1. The biggest, detectable distance between two bit errors is \( 8L - 1 \), where \( L \) is the length of the frame. The percentage occurrence of distances between two bit errors is just the bit errors distribution.

For the bit errors distribution assessment, all the frames that had more than one error were examined. If there are \( x \) bit errors in the frame, it is possible to determine \( x - 1 \) distances.

In Figure 8 the bit errors distribution versus bit distance obtained from observations in the LV network which supplied LED lamps is presented.

Analysis of the data contained in the graph of Figure 8 proves well-known rule, namely; the biggest probability of the next error occurring is on the next bit after the erroneous bit \([11]\). The chart of the bit errors distribution has a decreasing trend.

For comparison, in Figure 9, the bit errors distribution versus bit distance obtained from observations in the LV network which supplied gas-discharge lamps is presented. The difference between charts presented in Figures 8 and 9 is evident; the bit errors distribution characteristic of gas-discharge lamps has extra oscillation. The period of this oscillation is about 95 bits. Knowing that the BPSK modulation was used during the test, the time for 95-bit transmission takes about \( 9.9 = 95(1/9600 \text{ bits/s}) \) milliseconds. The frequency of the European LV network is 50 Hz, which means that the peak of the sinusoidal signal occurs every 10 ms. To make sure that the differences between FER(SNR) characteristic of LED and gas-discharge are caused by power distribution 230 V/50 Hz signal the next analysis was carried out. The analysis was to determine the period of the oscillation in bit errors distribution characteristics for the different modulation types (i.e., also different bit rates). For the analysis, data from Kamienna Street were used. The results are as follows: for the QPSK modulation oscillation period is 194 bits (about 10.1 ms) and for the 8PSK modulation oscillation period is 290 bits (about 10 ms). For these two modulation types, bit errors distribution characteristics were determined for the bit distance in the range of 1 to 1599.
5. Conclusion

In this work no problem was solved. This paper describes the characteristic phenomenon for the narrowband PLC transmission in Smart Lighting LV networks, which supply gas-discharge lamps. To highlight this phenomenon all the presented transmission parameters and characteristics were compared with the same obtained from LED Smart Lighting systems. Most of the experiments were carried out in the same physical LV network, which supplied different types of lamps, making the results of experiments more credible and easier to analyze.

The test results presented in this paper may be particularly useful in the PLC communication protocols designing as well as in their parameterization. Knowing bit errors distribution characteristics of not coded types of modulations can be very beneficial when selecting the method of forward error correction [12, 13] or if the implementation of the peak noise avoidance algorithms makes sense.

The small impact of the frame length on the FER(SNR) characteristic in gas-discharge Smart Lighting systems causes a lack of need of data portioning during transmission. In other words, shortening the length of frames does not improve communication performance.

Currently, Smart Lighting systems are implemented in many countries. This process may take place in three different ways:

1. installing the lamps already equipped with communication modules,
2. adding communication modules to already installed “smart ready” lamps, which were originally equipped with DALI or 0–10 V lighting control interface [14],
3. adjusting existing quite new gas-discharge lamps to be individually controlled.

Presented in this work, results can be helpful in the realization of any of the above processes as well as after replacing old overhead power lines with new cable ones.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research was supported by the National Centre for Research and Development and also by the National Fund for Environmental Protection and Water Management under the realized GEKON Program (Project no. 214093).

References

[1] X. Cai, Y. Duan, Y. He, J. Yang, and C. Li, “Bee-Sensor-C: an energy-efficient and scalable multipath routing protocol for wireless sensor networks,” International Journal of Distributed Sensor Networks, vol. 2015, Article ID 976127, 14 pages, 2015.
[2] ITU-T Recommendation G.9904 (10/2012), “Narrowband orthogonal frequency division multiplexing power line communication transceivers for PRIME networks,” 2013.
[3] ITU-T, “Narrowband orthogonal frequency division multiplexing power line communication transceivers for G3-PLC networks,” ITU-T Recommendation G.9903 (5/2013), 2013.
[4] V. Oksman and J. Zhang, “G.HNEM: the new ITU-T standard on narrowband PLC technology,” IEEE Communications Magazine, vol. 49, no. 12, pp. 36–44, 2011.
[5] J. Matanza, S. Alexandres, and C. Rodriguez-Morcillo, “Difference sets-based compressive sensing as denoising method for narrow-band power line communications,” IET Communications, vol. 7, no. 15, pp. 1580–1586, 2013.
[6] D. Cooper and T. Jeans, “Narrowband, low data rate communications on the low-voltage mains in the CENELEC frequencies—part I: noise and attenuation,” *IEEE Transactions on Power Delivery*, vol. 17, no. 3, pp. 718–723, 2002.

[7] P. Kiedrowski, “Transmission proprieties of overhead and cable LV power lines—the comparison in the frequency spectrum from 3 kHz to 150 kHz,” *Solid State Phenomena*, vol. 237, pp. 251–256, 2015.

[8] D. Cooper and T. Jeans, “Narrowband, low data rate communications on the low-voltage mains in the CENELEC frequencies—part II: multiplicative signal fading and efficient modulation schemes,” *IEEE Transactions on Power Delivery*, vol. 17, no. 3, pp. 724–729, 2002.

[9] A. Aghvami, A. Aijaz, M. R. Akhavan, and S. Choobkar, “On the multi-hop performance of receiver based MAC protocol in routing protocol for low-power and lossy networks-based low power and lossy wireless sensor networks,” *IET Wireless Sensor Systems*, vol. 5, no. 1, pp. 42–49, 2011.

[10] P. Kiedrowski, B. Dubalski, T. Marciniak, T. Riaz, and J. Gutierrez, “Energy greedy protocol suite for smart grid communication systems based on short range devices,” in *Image Processing and Communications Challenges 3*, vol. 102 of *Advances in Intelligent and Soft Computing*, pp. 493–502, Springer, Berlin, Germany, 2011.

[11] W. Nowicki, *Podstawy Teletransmisyi 1*, Wydawnictwa Komunikacji i Łączności, Warsaw, Poland, 1971.

[12] S. Dhlan, “Forward error correction techniques suitable for the utilization in the PLC technology,” in *Proceedings of the 15th International Conference on Systems, Signals and Image Processing (IWSSIP ’08)*, pp. 41–44, Bratislava, Slovakia, June 2008.

[13] S. Mudriievskyi and R. Lehnert, “Performance evaluation of the G.hn PLC PHY layer,” in *Proceedings of the 18th IEEE International Symposium on Power Line Communications and Its Applications (ISPLC ’14)*, pp. 296–300, IEEE, Glasgow, Scotland, April 2014.

[14] F. J. Bellido-Outeirino, J. M. Flores-Arias, F. Domingo-Perez, A. Gil-De-Castro, and A. Moreno-Munoz, “Building lighting automation through the integration of DALI with wireless sensor networks,” *IEEE Transactions on Consumer Electronics*, vol. 58, no. 1, pp. 47–52, 2012.