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Measurement method of the LV network for the PLC PRIME transmission and its application

Streszczenie.** Ocena sieci nN dokonywana jest metodą pośrednią, polegającą na pomiarze wartości PER i estymatora wartości FER. Zaproponowano, odpowiednie metody interpretacji wyników pozwalające na wymierną ocenę oraz prognozowanie jakości transmisji w standardzie PLC PRIME w sieci nN. Proponowane metody zostały zweryfikowane w rzeczywistej sieci telemetrycznej przeznaczonej do odczytu liczników energii elektrycznej. W pracy również przedstawiono wybrane zagadnienia implementacyjne oraz ogólny opis aplikacji pomiarowej. **Metoda badania sieci LV do transmisji PLC PRIME

***Abstract**. The indirect method is proposed for the assessment of the susceptibility of LV network for PLC PRIME transmission. The method depends on determining the value of PER and FER estimator under different transmission conditions then the appropriate interpretation of PER and FER with regards to services for which PRIME interface has been developed. The proposed method was verified in real telemetric network for automatic electricity meters reading. The paper presents also selected implementation issues of the method and application notes.*

Słowa kluczowe: interfejs PRIME, PLC, Smart Metering, ocena jakości transmisji, błędy teletransmisyjne.
Keywords: PRIME interface, PLC, Smart Metering, quality assessment, error performance.

Introduction

PRIME (PoweRline Intelligent Metering Evolution) interface is an international standard of the narrowband Power Line Communication (PLC) transmission over the Low-Voltage (LV) power lines. This interface was finally defined in the year of 2012 and published at the beginning of 2013 year as ITU-T G.9904 recommendation [1]. Most technical effort is concentrated on LV power line channels owing to the huge development of PLC in smart metering, smart grid and remote data acquisition and distribution [2]. PRIME interface is considered and currently implemented for an automatic meter reading (AMR) communication systems in many European countries.

This communication system as well as any other requires appropriate methods of measurement, testing and quality assessment. Quality assessment is usually subject to the two common areas of communication metrology i.e. quality of services assessment and quality of physical links or networks assessment. There is no indication that in the case of communication systems, based on PRIME interface, is different they need efficient diagnostic methods in physical, network and services layers, too.

It can be stated that the current quality of service assessment and diagnostic methods for PRIME are sufficiently developed as a result of many implementations of AMR management systems, dedicated for PRIME. There is also no need to develop specific diagnostic methods for the network layer, because according to the PRIME definition it is based on MAC (Media Access Control) specification and is well known solutions used in computer networks. A situation with development of the diagnostic methods for the physical layer looks quite different. Both AMR systems suppliers as well as energy distribution operators are aware of the need to develop and implement a measurement system to assess the susceptibility of LV networks for the narrowband PLC transmission. The interest of AMR systems suppliers on physical network assessment methods grows due to the need to guarantee the customer services on a given, quantifiable level in a particular LV network. Energy distribution operators or smart metering system operators need the same (as energy distribution operators) measure equipment for maintenance purposes.

LV network parameters, which have the essential impact on the PLC transmission, are: a load impedance seen by transmitters, colored background and impulsive noises, attenuation of power lines and reflective distortion caused by the long power lines. It is difficult to find a relation between these parameters of the LV network and the quality of the services offered by PLC transmission. There is no complex model, which describes these relations. In [3] the analysis and modeling of impulsive noises were described, the Authors of [4] considered the similar problem for PRIME communication using simulating methods. In [5] the analysis and modeling method for both types of noises were presented to describe the effect on the broadband PLC transmission. There are many papers that treat influence of the network impedance on PLC transmission, which even give us application solutions [6]. In literature, different studies have been presented on the behavior of the PLC transmission in the presence of terminated or unterminated branches but the phenomena of the reflectance was not considered. The last problem is that even if the complex model of LV network parameters, which describes the quality of the narrowband PLC transmission, would be found then the acquisition of these parameters will be expensive and time-consuming. Aware of these problems, in this paper the indirect method is proposed for the assessment of the susceptibility of LV network to PLC PRIME transmission. The proposed method can be classified both as in-service and as out of service measure method and depends on determining the value of PER and FER under different transmission conditions. Then the appropriate interpretation of PER and FER with regards to services for which PRIME interface has been developed. The advantage of the proposed method is that it can be easily implemented and is cheap. The paper also presents the measurement sample application written in Python programming language, which can be run on a PC computer as well as even on a smart phone.

Measurement mechanisms of the PRIME interface

The specification of PRIME interface includes some measurement and testing mechanisms. Most of them are realized in higher layers. In the physical layer (PHY) we have only seven statistical attributes. They may be classified in two types: electrical attributes and functional ones. The electrical attributes together with received strength signal indicator (RSSI) and signal to noise ratio (SNR) give us information about receiving signal condition, including some information about a transmission medium. Functional physical attributes are five counters namely: the counter of dropped Tx frames, the counter of dropped Rx frames, the counter of total Rx frames, the counter of incorrect CRC (Cyclic Redundancy Check) and the counter of CRC failures. All three firsts frame counters are not particularly useful, because these counting processes can also be realized from the application level. CRC counters would be very useful if CRC were calculated over the whole PHY frame but not only over its header. The general structure of the PHY frame is shown in Figure 1.

Fig. 1. General format of the PHY frame structure

Each PHY Frame starts with a preamble lasting 2.048 ms, which is followed by twice longer header then by a different length payload. The waveform of the sample PRIME frame is presented in Figure 2.

Fig. 2. Waveform of the sample PRIME frame with zoomed preamble and fragment of the header

Presented above waveform represents BPSK modulated frame with forward error correction (FEC) turned on.

Payload organization in the proposed method

In order to detect errors in the payload field, and not only in the header, 16-bits CRC field is added by application at the end of the accessible part of the payload. All bits of the payload are accessible with the exception of: first two bits, which are fixed to zero; optional 8 flushing bits (Fb) and optional padding field (Pf) of length from 0 to 8. Besides the CRC-16, the accessible part of the payload is a test sequence or a portion of it. These two fields, further, will be called a packet. Such organized payload field is presented in Figure 3.

Fig. 3. Payload structure used in the proposed method

Unlike the header, that is protected by 8-bits CRC, the packet (together with two zeros) is protected by 16-bits CRC, which is the remainder of the division of protected bits by the polynomial $x^{16}+x^{12}+x+1$.

The test sequence can be a user defined string of bits or any of the pseudo random bit sequence of maximum length (PRBS) [7] defined in ITU-T O.15x recommendation series.

PRBS signals are well known signals in the domain of objects identification but mostly in the quality assessment of digital transmission paths. A PRBS signal meets required statistical properties to provide conditions closest to the real traffic but also is used, in the proposed method, because of packets synchronization necessity. Packets synchronization is necessary to provide both frame error ratio (FER) and packet error ratio (PER) assessment, having only access to received packets from the level of an application.

The problem of synchronization will be discussed further.

Measurement architecture and measurement modes

The access point to the LV network is a standard PRIME modem. The PRIME modem is connected to a computing unit via serial port. Tablets, PCs, notebooks etc. can act as the computing unit if only running the presented measurement application is possible. One or more PRIME modems can be connected to the same computer. Three modems can be connected to one computer, when there is a necessity to check three mains phases simultaneously. PRIME modem can be connected to the computer even when there is a big distance between them, in such a case networking transmission services must be applied. Examples of some measurement configurations due to proposed architecture are presented in Figure 4.

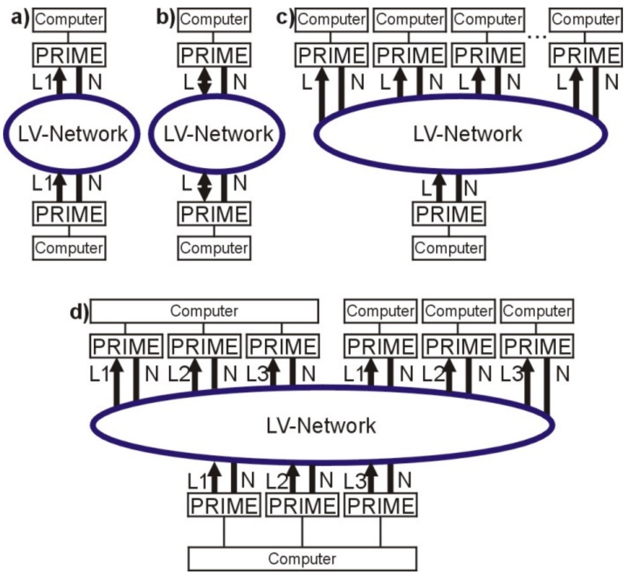

Fig. 4. Typical measurements configurations: a) the simplest, b) bidirectional, c) broadcasting, d) 3-phases

In Figure 3, the d-configuration is the example of handling several PRIME modems on one computer whilst the b-configuration is example of bidirectional path testing. It should be noticed that if there is more than one transmitter and more than one receiver in the LV network, except the situation in Figure 3-d, transmitting test signals have to differ from each other in order to enable receivers to identify declared path. The path declaration is realized on a receiving side by the choice of a test sequence, such that is transmitted by one and only one modem on the remote side of the path.

There are proposed and applied two measurement modes:

- with sweeping of modulation types and FEC,
- with fixed modulation type and optional FEC.

The sweeping mode is very useful taking into account changeable character of transmission conditions of the LV network, which is strongly affected by the presence of unmatched and time-variant loads [8]. Using the sweeping mode gives us information about quality of the received signal modulated with all possible modulations and their options. The fixed modulation mode is useful when there is a necessity to determine the performance of the system using a specific type of modulation and its options.

The measurement mode has to be configured only on the transmitting side. Such convenience is a consequence of carrying of information about the type of modulation in the frame header. There are three types of modulation and each of them can have enabled or disabled FEC function, what gives as six transmitting options.

Traffic generation and received data analysis

With only access to received packets from the level of an application, there is necessity to declare the test sequence on the receiving side in order to provide FER and PER assessment. Thus, in theory, if telemetry system was working it would be possible to assess the LV network on the basis of the monitoring the system. However, in practice it would be impossible. Firstly, because the MAC addresses would have to be known and declared, secondly, because a single node generates too low traffic, thirdly, because the payload is not protected by any frame check sequence e.g. CRC. And fourthly, the proposed method is dedicated especially for the low voltage network in which the telemetry system is not used yet (before installing or commission). These reasons cause necessity to generate traffic by the system itself.

The use of PRBS, as test signals in proposed method, allows not only to assess the quality but also to solve problems of packets synchronization and auto detection of the type of the PRBS signal. These opportunities are results of the specific correlation features of the PRBS. Auto detection is performed using the analysis of the estimator of normalized correlation coefficients of the received signal and a set of four applied reference PRBS signals which mathematically describes the following formula:

(1)
$$K_{xy}(m) \overset{\Delta}{=} \frac{1}{L}\sum_{i=0}^{L-1} x_i y_{i+m}$$

where x is reference PRBS; y is received signal; $L = 2^{l-1}$ is the length of the reference sequence; l is degree of the generator polynomial and Kxy is the normalized, estimated value of the correlation between x and y.

If there is no error in received signal and all zeros were mapped to -1, Kxy may have two values: 1, which is further called a characteristic coefficient, and $-1/L$; additionally the characteristic coefficient occurs once per sequence. After the detection of the receiving signal type there is a possibility to determine the number of bit errors (BE) in the received signal. Using (1) and knowing the fact that every single bit error decrements the characteristic coefficient by $2/L$ [9] it is possible to calculate the bit error ratio (BER) over the whole received stream of bits, but not only per the single payload or per the sequence. Calculation is made using the following formula:

(2)
$$BER = \frac{1}{2}\cdot\sum_{r=0}^{r=\frac{N}{L}} 1 - K_{xy}(t_p + r\cdot L)$$

where N is the observation period and t_p is propagation time being actually the position of the first characteristic coefficient occurrence.

The method

According to the PRIME specification terminology, the proposed measurement method is done in the PHY layer, even though this layer does not support access to frames but only to packets, both error free and errored. Nevertheless proposed method provides to evaluate the number of not received frames due to the implementation of synchronization mechanisms. In this method, it is considered that the number of received frames is the sum of errored packets, error free packets and missed frames. To assess the value of PER and FER algorithm presented in Figure 5 was applied.

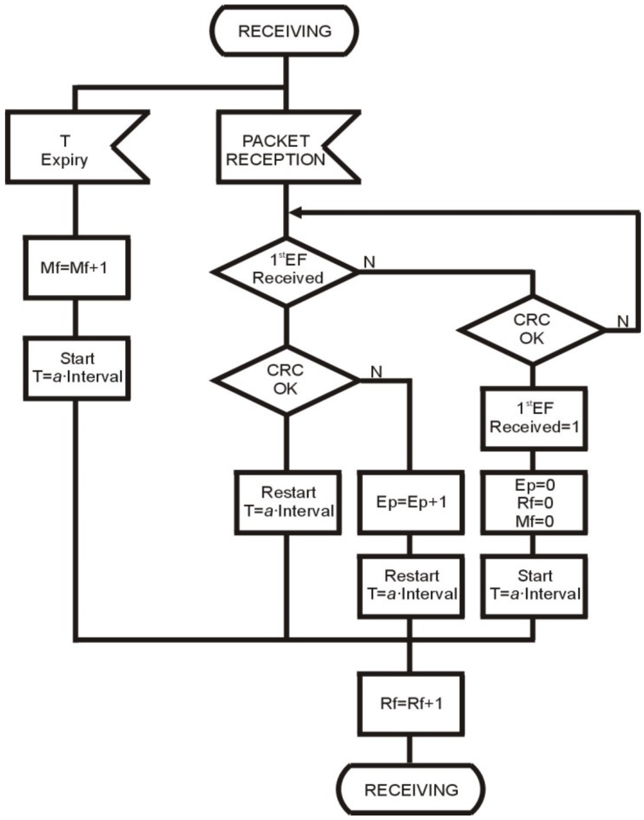

Fig. 5. Algorithm for FER and PER assessment

These algorithm bases on two events: '*Timer T Expire*' and '*Packet Reception*'. The measurement commences after reception of the first error free packet. This condition changes variable '*1st EF Received*' form value zero to one and reset three counters: Ep – errored packets counter, Rf – received frames counter and Mf – missed frames counter. The measurement ends when Rf counter reaches a predetermined value.

Value of FER is calculated from the formula:

(3)
$$FER = \frac{Mf}{Rf}$$

whilst value of PER is calculated from:

(4)
$$PER = \frac{Ep}{Rf - Mf}$$

Taking into account the commencement measurement condition value of PER is in the range [0, 1) because at least one packet must be error free to start and initial counters, what also results from algorithm, thus, $Ep < Rf - Mf$. From the same reason value of FER is in the range [0, 1) because $Mf \leq Rf + 1$. Therefore the relation between FER and PER

derived from (3) and (4) should be used with the following limitations: $PER < 1$, $FER < 1$ and $Ep > 0$, hence also $PER > 0$. The relation is:

(5)
$$FER = 1 - \frac{Ep}{PER \cdot Rf}$$

Therefore, to describe the quality of the links both FER and PER should be considered, even more to avoid a situation of the lack of the statistical material, which is required for the reliable assessment, also Ep and Mf are reported as a result.

Additionally, having access to all the packets both these errored and error free and using PRBS as test signal, it is easy to assess the BER value using (2). Knowing the BER value is not particularly useful for assessing the susceptibility of low-voltage (LV) networks for the PLC transmission but it can be useful at the stage of the communication scheme planning [10] e.g. choosing the optimal frame length.

The drawback of presented method is providing synchronization between transmitting and receiving frames, what is the cost of FER assessment possibility from the application level.

Synchronization problem

Although the frames are transmitted synchronously by the application, they can only be received asynchronously, even if the same computer manages the transmitting modem and receiving one. The reason of this situation is that access to the modem is via asynchronous serial links and also that serial ports are asynchronously handled by most of operating systems. Consequently, packets transmitted at equal intervals are received at differential intervals. If the interval between received packets is longer than between transmitted ones, two events occur instead of one, they are *T_Expiry* fallowed by *Packet_Reception*. Solution to this problem is to lengthen the time of the timer T on receiving side by multiplying *Interval* parameter (which must be set to equal value on both sides) by a, what shows the algorithm presented in Figure 5, the value of a should be bigger than 1 and less than 2. However, this solution eliminates the problem of unwanted *T_Expiry* events occurrence it causes a new problem of missed frame miscounting. This problem is best illustrated by example under conditions when none frames are received in some period. In period equals to n·*Interval*, approximately n·a missed frames are counted instead of n. Such a period may end with two cases: expected Rf number reaching or *Packet_Reception* event reception. The second case requires the correction of the Mf number consisting in the Mf reduction. Dividing Mf by a is not a precision correction because real *Interval* values differ slightly on both sides and also because corrected Mf value very often is not an integer value.

Solution to this problem could be a packets numeration, but the fragment of the frame containing the frame number would be a sensitive piece of a frame – any error on these positions makes impossible to decode the actual number on the receiving side.

After the n-*Interval* period, it is assumed that from –k up to k frames might be overcharged. If the fragment of the PRBS sequence fills the payload, the bit pattern in the received frame must fit into one of the 2k+1 generated at the receiving end. Using correlation analysis, even when the received frame is significantly errored, assignation of adjustment value – adj is still possible. Thus, the adjustment of Mf value is to determinate the value of adj, what is done using the following formula:

(6)
$$R_{sf}(m) \stackrel{\Delta}{=} \sum_{i=1}^{W} s_i f_{i+m}$$

where s is a stream of received W-bits; whilst f is the $W(2k+1)$-bit length fragment of the PRBS sequence calculated on received side (first bit of this fragment is W(n/a–k)-bit in the whole PRBS stream); W is the length of the payload and R_{sf} is the estimated value of the correlation between s and f.

Results obtained from (6) are grouped into 2k+1 equal blocks containing W results each. To explain how adj value is determinate the example illustrated in Figure 6 is used.

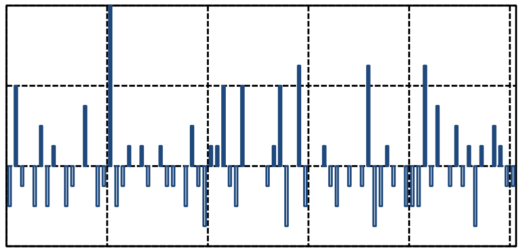

Fig. 6. An example results of R_{xy} calculation grouped in 5 blocks, which are numbered from -2 to 2, for W=16 and k=2, received packet is error free.

If the packet is error free, adj is the number of block in which maximum R_{sf} value occurred. For the above example adj=–1, because maximum occurred in second block in which $R_{sf}(17)=16$ and it is the maximum value among all eighty results.

The second example is shown in Figure 7. In this example all conditions are the same except the fact that received packet was errored with the BER of $1.25 \cdot 10^{-1}$.

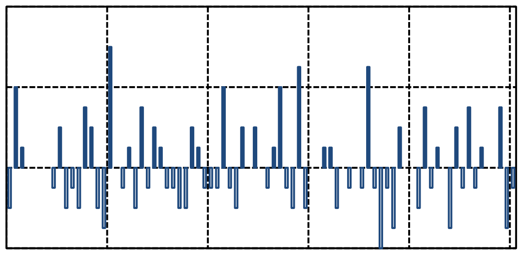

Fig. 7. An example results of R_{xy} calculation grouped in 5 blocks, which are numbered from -2 to 2, for W=16 and k=2, received packet's errored.

As it can be noticed, the maximum value differs from the example shown in Figure 6, but it occurred in the same position, so adj value can still be determined properly. So the precision number of Mf is n+adj where n is after the rough correction (has new value) by dividing by a.

At the end it is worth to notify that not all R_{sf} values have to be calculated. Using the correlation propriety of PRBS signals, which says that in one sequence of only one R_{sf} can correlate, calculations should be done only for such m values that (m mod W)=1. From experiences the typical value of k can be 3 for 24-hour test.

Results interpretation

The result is a pair of FER and PER values. It is proposed two methods of results interpretation. The first method is so called PASS/FAIL method, whilst the second method is ITU-T G.821 recommendation [11] based method.

The PASS/FAIL method should be used for a rough assessment of the LV network. This method consists in mapping a point (FER, PER) on the two-dimensional space limited by a curve described as a dependency of PER(FER) or FER(PER). In theory curve should be non-increasing, in practice it should be decreasing. Implemented examples of curves are shown in Figure 8.

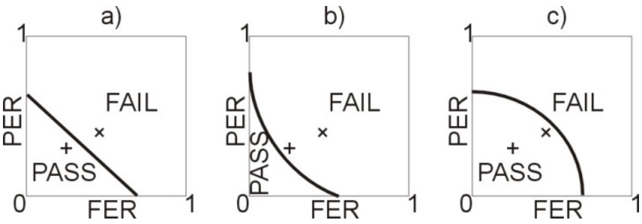

Fig. 8. Two results (+ and × pairs of FER and PER) interpreted on the basis of three levels of restrictiveness: a) medium, high and low.

The result + is better than result ×. Of course, measurements must be done for the same transmission parameters if we want to compare them or should be done for the LV network in the same period to decide which parameters are more suitable for this LV network. Three restrictiveness levels, presented in Figure 8, are predefined – hardcoded in the application. The fourth curve is user-defined. The choice of the curve type depends on communication system solution e.g. maximum length of the packet or if the retransmission functions, at the PRIME MAC layer, are implemented or not.

The second method gives us more detailed results. This ITU-T G.821 based method is suitable for PRIME performance analysis because originally it was addressed for digital systems with similar bit rates as are defined for PRIME. In proposed method not all G.821 parameters are used. The parameters those were implemented from G.821 are unavailable time (UT) and unavailable time (AT). The sum of UT and AT gives seconds total (ST), what is time of a LV network observation. A period of unavailable time begins when none packet in each second is not received for a period of ten consecutive seconds. These ten seconds are considered to be unavailable time. A new period of available time begins with the first second of a period of ten consecutive seconds each of packets reception. The result is percentage of UT in ST period, the less value the better. The ITU-T G.821 based method is particularly useful in smart metering because it is service-oriented and not links quality oriented method, what best describes the following example: during the n-seconds period PER value was 0.5, if all errors occurred one by one during in any of n/2-seconds period, the UT value would be 50% as well as AT, but if every second packets were errored in all the period, the UT would be 0%. Of course, this example includes two extreme cases when AT=50% and AT=100% under conditions of the same PER. As it can be noticed in G.821 method packet errors are only considered, it is because packets are closer to the service layer then frames are; though the proposed method does not exclude an identical results interpretation based on frame errors to determine UT and AT, if need be.

Conclusion

Proposed methods can be classified as error performance at physical and data link layers. The use of PRBS, as test signals enabled the FER estimator assessment form the level of the data link layer. Knowing FER together with PER makes it has a much bigger statistical material than this obtained only from PER analysis. Despite this, the required measurement time is still the same as in other methods of error performance which based on statistical sample test, i.e. at least 24 hours. The superiority of the method is to obtain a larger number of diverse statistical material at the same time.

The proposed method has been verified in real telemetric network for automatic electricity meters reading. The results of measurement strongly correlated with SLA (Service Level Agreement) parameters used to evaluate the services supported in smart metering. It was not possible to verify proposed method, using another independent measurement method, because so far there is no measuring apparatus evaluating the LV network for data transmission based on PRIME standard.

Implementation of two methods of automatic results interpretation enables the assessment realization of the LV network even by untrained personnel.

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