http://dx.doi.org/10.5755/j01.eie.24.1.20149 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 24, NO. 1, 2018

Investigation of Narrow-Band Power-Line Carrier Communication System Performance in Rural Distribution Grids

Dzemo Borovina[1], Aljo Mujcic[2], Matej Zajc[3], Nermin Suljanovic[2]
[1]Elektroprivreda B&H,
Vilsonovo setaliste 15, Sarajevo, Bosnia and Herzegovina
[2]Faculty of Electrical Engineering, University of Tuzla,
Tuzla, Bosnia and Herzegovina
[3]Faculty of Electrical Engineering, University of Ljubljana,
Trzaska 25, Ljubljana, Slovenia
nermin.suljanovic@fet.ba

***Abstract*—This paper investigates error performance of the narrow-band (NB) power-line carrier (PLC) communication system from a distribution system operator (DSO) perspective, with measurement data collected in the rural 400 V distribution grid. The performance evaluation is founded on the three aspects: attenuation of the NB PLC channel, frequency of the signal to noise ratio (SNR) class occurrence detected in a receiver and bit error rate (BER) analysis. The true BER is estimated from the limited amount of collected data using error model based on Neyman type A contagious distribution, appropriate for communication channels with impulsive noise. Results confirmed that PRIME-based NB PLC deployments for smart metering applications are adequate in rural distribution grids, even in cases with high attenuation and articulated frequency variations in a PLC channel.**

***Index Terms*—Power-line carrier; Communication system performance; Measurement; Smart metering.**

I. INTRODUCTION

Distribution system operators (DSOs) strive to replace traditional power meters with smart meters, aiming at introduction of new utility services and applications. The idea of smart metering originated from the Automatic Meter Reading (AMR), a system that provides DSOs with the basic capability to collect consumption data remotely usually for the billing purposes. Inside the smart grid paradigm, AMR systems evolved into Advanced Metering Infrastructure (AMI), which is consumer-centric platform that provides monitoring of the energy consumption, power quality, renewable generation as well as distribution of pricing information [1], [2]. Loads and distributed generation are rapidly increasing in the grid, while the grid is usually not strengthened adequately. On the other hand, AMI may provide remote measurements of the voltage profile and power flows in the distribution grid, as well as data for electricity theft detection, reconstruction of the distribution network topology and contribute to the efficient grid utilization.

AMI is composed of smart meters at consumer's premises, Meter Data Management System (MDMS) in the control centre of a DSO and a communication network enabling two-way connectivity between smart meters and MDMS [2], [3]. If smart metering system is used for the periodical meter readouts only, requirements for the quality of service (QoS) of the communication network in AMI will be low. In the case that smart meters provide real-time consumption data for the purposes of automation and energy management systems, AMI must meet tighter requirements for the latency and availability [1].

There are two prevailing concepts for the AMI networking [2]. In the first concept, smart meters are connected with the MDMS directly through a packet-switched network. The second approach assumes application of a data concentrator, a device in between that collects data from smart meters and forwards aggregated data to MDMS through a network.

Various communication technologies compete to become a dominant technology for AMI deployment [4]. Competing technologies must meet communication requirements set up by AMI for proper operation [5]. On the other hand, power utilities give preference to a technology, which makes the development of their own communication infrastructure more efficient. Under such circumstances, a networking concept that deploys data concentrator and power-line carrier (PLC) communication technology appeared as adequate solution.

PLC is a communication technology that transfers data through low, medium and high voltage power lines. The need for the advanced communication infrastructure in the smart grid opens new market opportunities for the PLC technology [6].

Distribution power lines, designed primarily for the energy transfer, represent a frequency-selective communication channel with high attenuation, time-variable impedance and articulated impulsive noise [7]–[9]. As a result, PLC channel characteristics dictate application of complex communication techniques in PLC modems. Nowadays, PLC is a mature technology ready to be deployed in AMI networking.

Manuscript received 18 May, 2018; accepted 12 November, 2017.

PLC communication systems are classified according to the voltage level (high, medium and low voltage) and to the utilized frequency band (narrowband-NB and broadband-BB). NB PLC system operates in the frequency band bellow 500 kHz, where channel attenuation is lower and noise level is higher. In order to ensure satisfactory signal-to-noise ratio (SNR), PLC communication systems in this frequency range operate in the narrow band. Background noise level is much lower in the frequency range from 1.8 MHz to 250 MHz, allowing usage of broader frequency band and data transmission at higher rates [10]. Nevertheless, NB PLC communication systems provide lower data rates in comparison with BB PLC and higher robustness against impulsive noise. There are four available high data rate (HDR) NB PLC standards founded on the multicarrier modulation OFDM (Orthogonal Frequency-Division Multiplexing), with commercially available products for NB PLC communications: PRIME (PoweRline Intelligent Metering Evolution), G3-PLC, ITU-T G.hnem and IEEE 1901.2.

Basic AMI applications require throughput up to 100 kbps and the message latency not exceeding 15 s. All above listed NB PLC standards could fulfil these requirements. However, their performance will vary in different power grids, due to topology, consumption patterns and quality of cables and connections. Some other AMI applications, such as real-time metering, require higher data rates and latency bellow 20 ms [1]. For such applications, priority should be given to BB PLC systems.

The research presented in this paper makes two major contributions: firstly, measurement methodology necessary for comprehensive performance analysis of NB PLC system is proposed. Secondly, performance analysis of PRIME-based NB PLC system is performed for the rural distribution grid and results are presented in the paper. DSOs have a strong incentive to monitor rural distribution grids, for many reasons such as: distributed generation presence is often in rural areas, the grid strengthening is costly due to long lines, faults are more common than in urban areas because of overhead lines, and some areas are not frequently visited. The error performance is correlated with the measured PLC channel frequency response and noise characteristics. These results are benchmark for further theoretical investigation based on numerical simulations and laboratory measurements.

II. NB PLC TECHNOLOGY: A BRIEF OVERVIEW

PRIME and G3-PLC are the most widely used HDR NB PLC standards in AMI systems. Both standards implement OFDM, which is robust modulation technique, with an ability to cope with the frequency-selective fading and impulsive noise. The main difference between these two standards is in the utilized frequency range, available data rates and used routing approaches at the media access control (MAC) layer. Originally, PRIME operates in the frequency band from 42 kHz to 89 kHz (CENELEC A band) and ensures low data rates, up to 128 kbps at PHY layer. Standard G3-PLC defines wider frequency range, from 10 kHz to 490 kHz, but also reaches higher data rates (up to 4 Mbps) [11], [12].

PRIME uses 96 equally spaced subcarriers, which are modulated using differential phase-shift keying (DPSK), in particular DBPSK, DQPSK and D8PSK [11]. Modulation scheme is adaptive, with arbitrary application of forward error correction (FEC) (1/2 convolutional encoder with an interleaver). DBPSK with FEC is the most robust and ensures data rates up to 21.4 kbps.

PRIME-based NB PLC system is organized in subnetworks, with a tree topology. All terminals in a network can be either a base node or a service node. There is only one base node in the network, usually located at the transformer (root of the tree topology). The base node registers service nodes in the network and manages their connections. Network is configured automatically. Service nodes can take one of three possible modes: disabled, terminal or switch. In the terminal mode, service node communicates with the base node. However, the base node can't communicate directly with all nodes in the subnetwork [11]. Service nodes are dynamically self-configured as switches after reception of required permission from the base node, when is necessary to extend the network. A switch serves as a repeater and forwards messages in order to ensure connectivity of all service nodes. The traffic forwarding is done in a selective manner, according to its control hierarchy. A switch node maintains the table of the serving terminal nodes and discards all other traffic. As a result, traffic flow is reduced, while connectivity of all service nodes is maintained.

Research reports on the performance of NB PLC systems in the available literature mostly include analytical considerations and numerical simulations. The performance of PRIME standard based on simulation model of the real low voltage network is presented in [13]. This paper gives insight into bit error rate simulated for three modulation techniques with and without FEC, for different distances between PLC modems. In general, there is lack of relevant literature that investigates NB PLC system behaviour at physical (PHY) layer using field test results. Performance analysis of a PLC system assuming DBPSK modulation, under Nakagami-*m* background and impulsive noise in the presence of Rayleigh fading, is investigated and reported in [14]. The paper derives expressions for analytical average bit error rate and compares analytical results with numerical simulations. Authors in [9] propose a noise model appropriate for OFDM PLC channels and use this model to test performance in the terms of BER versus E_b/N_0. In [15], end-to-end performance analysis of smart metering system using heterogeneous network combining radio and PLC communication technologies is studied in the terms of loss rate and data rate, for three grid topology sizes. Simulation results were verified by laboratory measurements. Performance analysis of the narrow-band PLC communication system with realistic channel conditions is presented in [16]. Authors used measurements to develop emulator, which is further utilized to predict the performance of PLC communication systems.

III. MEASUREMENT METHODOLOGY

The measurement methodology describes procedures for collecting and processing data necessary for the performance analysis of the PRIME system deployed in the rural area. Performance analysis contains:

1. PLC channel frequency and noise characteristics, in the frequency range devoted to the NB PLC communication systems.
2. Registration time of the PRIME service node at the base node.
3. Plots describing bit error rate (BER) versus SNR class, a measure of PRIME error performance.
4. Promotion of service nodes into a switch mode.

A. Measurement of the High-Frequency Characteristics of the Low Voltage PLC Channel

The high-frequency characteristics of a communication channel, such amplitude and phase characteristics, return loss, are incorporated in S parameters. S parameters, that characterize PLC channel between the transformer and a power meter at the consumer premises, are measured using vector network analyser Agilent E5061B (Fig. 1). Two ports of the vector network analyser are connected to the low voltage (LV) grid via capacitive coupling devices. High-frequency signal generated by the network analyser is injected at the transformer, while received signal is extracted at the power meter and returned through the coaxial cable. Two identical coupling devices are used at the both ends, and their aggregated amplitude characteristic (magnitude of the measured parameter S_{21}) is given in Fig. 2. The utilized coupling device is optimized for the CENELEC A band, and introduces higher attenuation outside of this band.

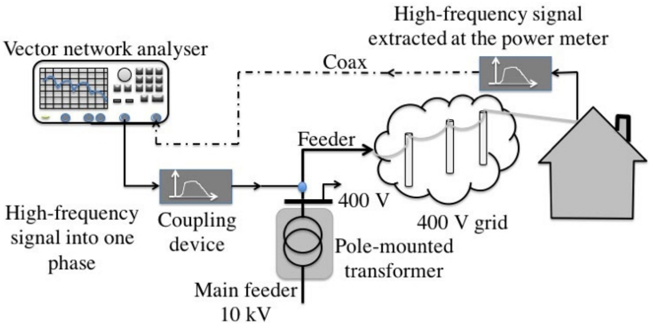

Fig. 1. Channel characteristics measurement setup.

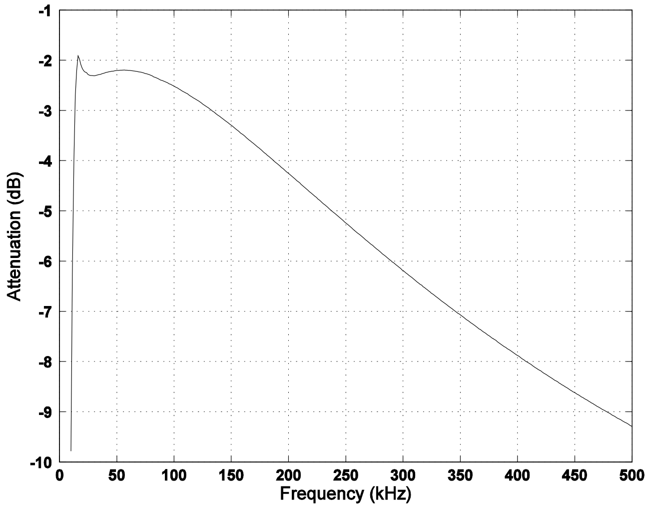

Fig. 2. Coupling amplitude characteristic.

For the complete characterization of the PLC channel, S parameters should be accompanied by the noise description. Power spectrum of the noise is captured using Rohde & Schwartz FSL spectrum analyser at the transformer site as well as at the customer premises behind the same coupling that blocks 50 Hz component.

Impedance mismatch between coupling device and the low-voltage grid influences the measurement accuracy. This mismatch appears due to intensive fluctuations of the grid impedance and manifests as the additional attenuation.

B. PRIME Modem Measurements

Atmel evaluation boards SAM4SP32AMB with integrated PRIME PLC System on Chip (SoC) modem and the coupling device are used for the modem measurement. The evaluation boards can be configured as a service node or as a base node. The base node, installed at the substation, is programmed to broadcast messages addressing all service nodes located at power meters (Fig. 3). The used software implements primitives defined in the PRIME standard [11], which allows collection of performance data reading out of the registers inside the SoC [17].

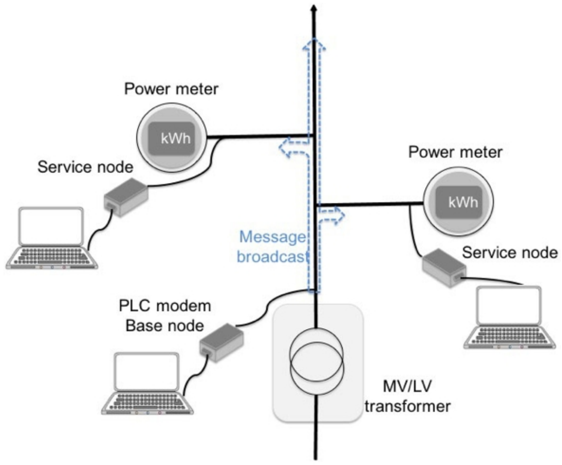

Fig. 3. PRIME modem measurements.

1) Registration Procedure of the PRIME Service Node

When a service node is switched on, PRIME procedure automatically tempts to register a service node at the base node. The service node registration time is estimated reading parameter *Local Node Identifier* (LNI) that differs for registered and disabled nodes, during the registration procedure. We provoke unregister procedure and save the instant when the procedure is initiated. When the service node becomes disabled, it automatically initiates registration procedure. After a successful registration, LNI is switched to the different value. That moment is detected and the registration time is calculated.

2) Error Performance Analysis

Error performance is a quality measure of digital communication links. Bit error rate (BER), that equals the number of bits received in error divided by the total number of bits transferred, is the most common parameter in the evaluation of the error performance. Errors in the LV PLC system occur in bursts, since the channel introduces impulsive noise and FEC is applied.

BER is calculated using *VtbBerHard* register readings synchronized with the SNR class. *VtbBerHard* register “stores the number of errors accumulated in a message reception using Viterbi hard decision” [17]. This value is cleared with every new message received. According to the vendor's guidelines [17], BER can be calculated as a quality parameter using

$$BER = \frac{10^{\frac{VtbBerHard}{40}} - 1}{100}. \tag{1}$$

PRIME implementation guidelines specify that SNR is expressed and recorded in classes from 0 to 7. In other words, detected SNR values are classified into one of eight classes with 3 dB steps as follows: 0:≤ 0 dB; 1:≤ 3 dB; 2:≤ 6 dB; … 7:> 18 dB. During the measurements, a pair (*VtbBerHard, SNR class*) is stored for every received message. *VtbBerHard* values are further grouped according to the *SNR class* and BER values for all SNR classes are calculated using (1). A plot BER vs SNR class presents error performance.

BER calculated using (1) is measured quality parameter rather than long-term BER. Long-term BER can be estimated from the measurements using error model based on Neyman Type A contagious distribution [18], [19]. This model is valid when errors appear in bursts (clusters), as is the case with LV PLC channel. The model assumes that error clusters have Poisson distribution, and that errors in a cluster also appear with Poisson distribution.

Let's denote a mean number of clusters with errors as M_1 and a mean number of errors in a cluster with M_2. The probability that cluster will contain r errors is equal to [18]

$$P(r) = \frac{M_2^r}{r!} e^{-M_1} \sum_{j=0}^{\infty} \frac{z^j j^r}{j!}, \tag{2}$$

where $z = M_1 e^{M_2}$. The mean of this distribution is M_1 M_2, and it equals to n BER. Value of n equals to the number of transmitted bits, while BER corresponds to the long-term bit error ratio. Means M_1 and M_2 can be calculated from the recorded values of *VtbBerHard* registers and SNR classes, for a given number of transmitted bits n. After M_1 and M_2 are estimated from the measurements for n transmitted bits, the long-term BER is calculated for each SNR class as

$$BER = \frac{M_1 M_2}{n}. \tag{3}$$

Base node consecutively sends messages (in our use case 120 bytes long at the convergence layer) and each message is treated as a cluster in the error performance analysis. Calculation of the total number of bits sent at PHY layer must incorporate headers in message formats at convergence, MAC and PHY layers [11].

It is necessary to send a certain number of messages to get some confidence that true BER is lower than obtained BER with required confidence level (CL). In other words, CL is the percentage confidence that true BER is less than measured BER. Since high SNR occurs rarely in the LV PLC channels, capturing a large number of messages received with the SNR class 7 requires long measurement time. The proposed measurement methodology includes evaluation boards connected to computers, with restricted access to the power grid (Fig. 3). This means that BER should be estimated also with a limited number of transmitted messages. If we specify bit error ratio (BER_S) value, the number of transmitted bits without an error should be at least $3/BER_S$ to have 95 % confidence interval [18]. This relation is further used for the estimation of true BER when a small number of messages are transferred with no errors at high SNR level that occurs rarely.

3) *Promotion of Service Nodes*

Operation mode of a service node is registered at the base station. This data is collected in order to get the detailed topology of the PRIME network.

IV. MEASUREMENT RESULTS

Performance assessment of the PRIME-based NB PLC system was conducted in the rural distribution grid with the topology outlined in Fig. 4 using measurements obtained with the proposed methodology (Section III). The grid consists of three-phase and mono-phase overhead lines, with different cross-sections and characteristic impedances. The PLC channel is considered as a channel between the pole-mounted transformer and the entrance of a house, where a power meter was installed. There were no disruptions in power supply service during the measurements, with measurement equipment connected using crocodile clips.

This section provides results of the PRIME-based NB PLC system performance together with the measured PLC channel characteristics of the LV distribution grid in which the system was installed.

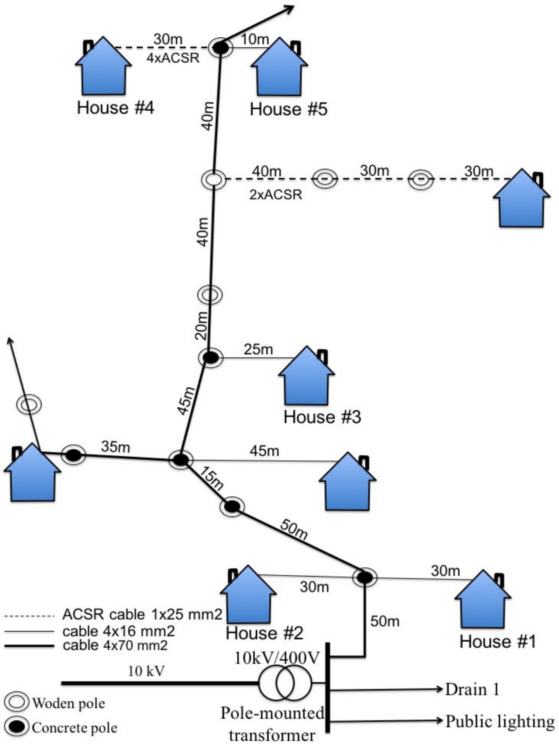

Fig. 4. Topology of the measured rural distribution grid.

A. *PLC Channel Characteristics*

A large number of branches in the network, as well as mismatched impedances cause significant attenuation and signal reflection. Network topology, line lengths and impedance values are stochastic in nature, what is confirmed with the attenuation (magnitude of parameter S_{21}) measurements. Figure 5 presents measured attenuation between the pole-mounted transformer and entrance at houses #1, #2 and #3, respectively. PLC channel is obviously frequency selective and characterized by high attenuation, up to 50 dB. In the frequency band used for PRIME (from 42 kHz to 89 kHz), attenuation varies in 15 dB range. The measurement results are compliant with the measured NB PLC characteristics presented in [16], [20]. Usage of the wider frequency band (up to 500 kHz) would be justified to utilize OFDM subcarriers at the frequencies with lower attenuation.

A notable crosstalk between phases at PLC frequencies has been observed. When a communication signal is injected into one phase only, it is also transmitted over other two phases. Figure 6 shows attenuation for the case when high-frequency signal is injected into the phase A at the transformer and captured at phases A, B and C at house #2, respectively. Such crosstalk may be considered useful when service nodes are connected to different phases at different locations but still can be promoted from a service node into a switch to serve remote nodes.

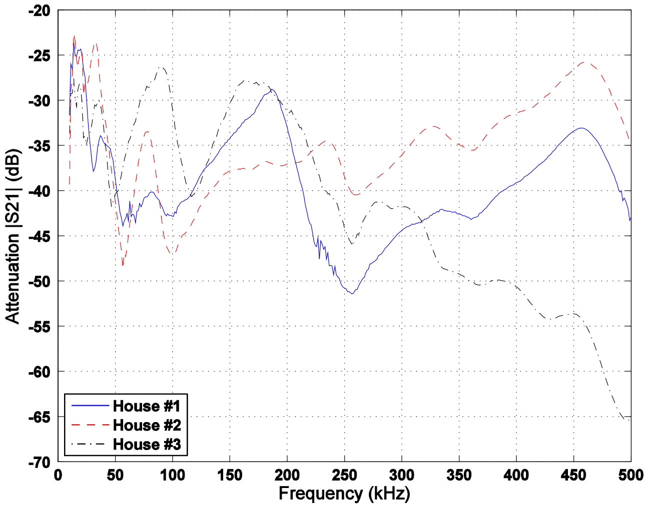

Fig. 5. Measured attenuation between transformer and customer premises.

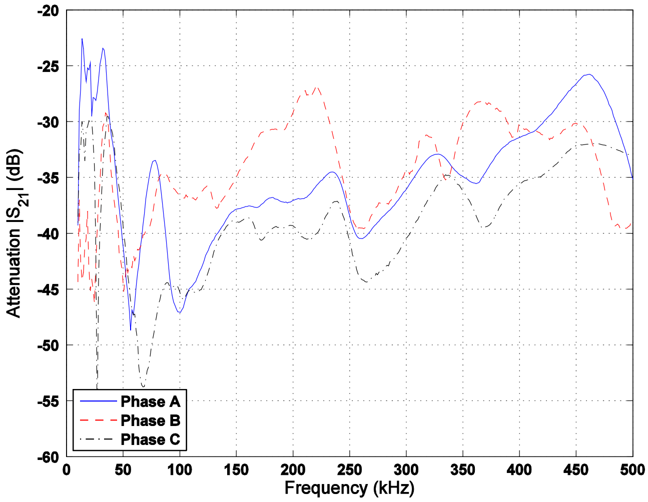

Fig. 6. Measured attenuation between transformer and House #2 for all three phases.

In order to determine noise level in the NB PLC channel, power spectrum of noise was measured at the transformer and customer premises. The noise level, measured after the coupling device, at the transformer and at the house #2 entrance is presented in Fig. 7. The noise power spectrum is similar at houses #1 and #3.

Atmel PRIME evaluation boards (receivers) detect SNR level and record quantized value as SNR class. For every received message, SNR class is stored. Figure 8 represents the frequency of occurrence of the recorded SNR classes during the measurement period, for houses #1, #2 and #3, respectively.

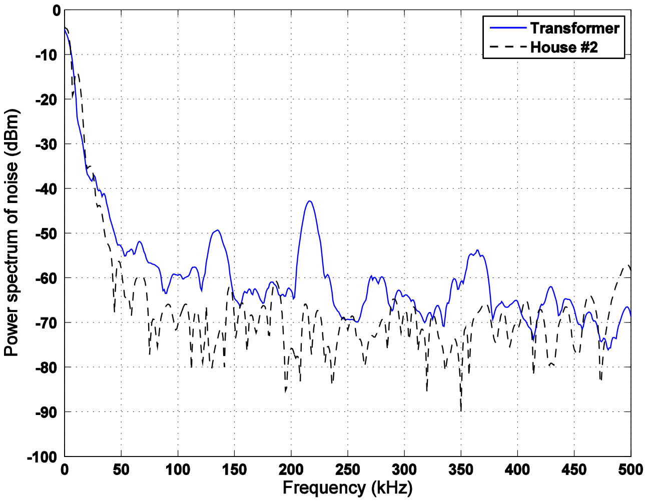

Fig. 7. Measured power spectrum of noise at the transformer and House #2.

We observe that messages are dominantly received with SNR classes 4, 5 and 6. Taking into account relation between SNR classes and SNR expressed in dB, we conclude that SNR level mostly varied in the range from 12 dB to 18 dB.

B. PRIME PLC System Performance Analysis

Performance analysis was done using data collected with PRIME nodes (evaluation boards) placed at the transformer (base node) and houses #1, #2 and #3, respectively (Fig. 4), using measurement methodology from Section III. PRIME modems are locked by the vendor to use DBPSK technique for OFDM sub-carrier modulation with the FEC on, providing bit rate 21.4 kbps.

After a service node is connected to the grid, it automatically initiates a registration procedure. Registration time is influenced by the state of the PLC channel and depends on whether a service node is connected to the base node directly or via a switch. In this scenario, all three service nodes are directly connected to the base node. 95 % confidence interval (CI) for the mean value of the registration time is calculated and given in Table I. The number of registration time samples is small and CI was calculated for inverse *t*-distribution.

TABLE I. THE REGISTRATION TIME.

PLC link from TS to	**95 % Confidence Interval (s)**
House #1	(1.2028, 9.8081)
House #2	(3.4580, 12.0633)
House #3	(1.1075, 7.4724)

BER vs. SNR class plots were obtained using data recorded at the service nodes. Base node communicates directly with the service nodes, without any switches in between. This fact is important for the error performance determination using proposed methodology. BER was calculated from *VtbBerHard* register recordings using (1).

We treated these calculated BER values as measured and determined 95 % confidence interval with this assumption. In the second step, long-term BER was estimated using *VtbBerHard* register recordings and the error model described in Section III. Results are compared for all three PLC channels used in this case scenario and showed in Fig. 9, Fig. 10 and Fig. 11, respectively.

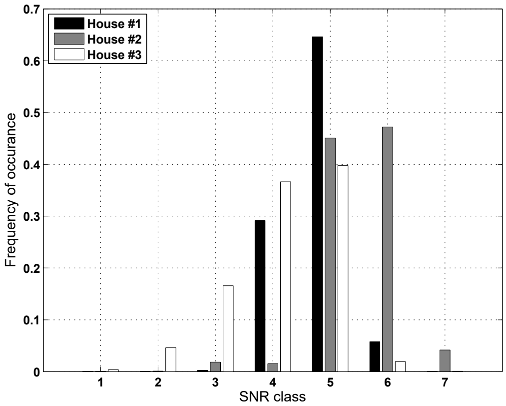

Fig. 8. Frequency of occurrence of the SNR level during the measurement period.

The BER vs SNR class plots contain 95 % confidence intervals for the bit error rates calculated using (1) and the long-term bit error rates (denoted with black asterisks) estimated with the error model based on Neyman Type A contagious distribution. We can see that estimated long-term BER is bellow the averaged BER calculated using (1) and in the most cases falls inside the computed confidence interval. There were no detected errors in the collected data for the messages received at the SNR class 7. Calculated BER values for SNR class 7 that appear in Fig. 9, Fig. 10 and Fig. 11 guarantee with 95 % confidence level that the true BER is bellow the estimated long-term BER. Obtained BER value is high since it depends on the number of transmitted bits while the number of received messages at SNR class 7 is small. The presented plots are matched with the PLC channel characteristics given in the previous subsection.

V. DISCUSSION

Performance evaluation, presented in this paper, is founded on three aspects that are integrally considered: attenuation of the NB PLC channel, frequency of the SNR class occurrence and error performance analysis. Attenuation measurements refer to the communication channel between transformer and customer premises utilizing the same phase A at both sides (Fig. 5). Similar measurements are obtained for the PLC channel between phase A at the transformer and phases A, B and C at the customer premises (Fig. 6). Measurement results show very high attenuation of the PLC links and articulated frequency variations, even at small distances and in such narrow band. It is known fact that longer line length in NB PLC channel does not necessarily introduce higher attenuation, what is evident from Fig. 5.

Performance analysis is founded on the limited communication measurements, in which PLC modems utilize OFDM with DBPSK subcarrier modulation with FEC on and bit rate 21.4 kbps. Error performance analysis provides BERs for every SNR class, determined using two distinctive approaches. Firstly, BER is calculated using (1) for each received message and treated as a random variable to calculate 95 % confidence interval. This result provides information about the interval of values that BER will take with a 95 % confidence, for a given SNR class.

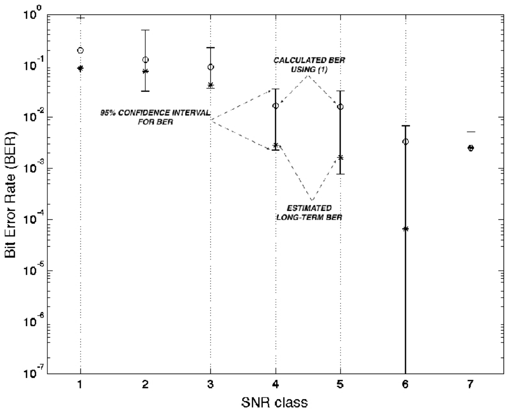

Fig. 9. BER vs SNR class for the PLC link between the transformer and the House #1.

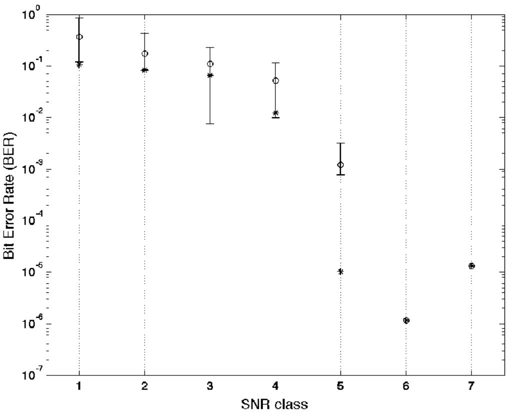

Fig. 10. BER vs SNR class for the PLC link between the transformer and the House #2.

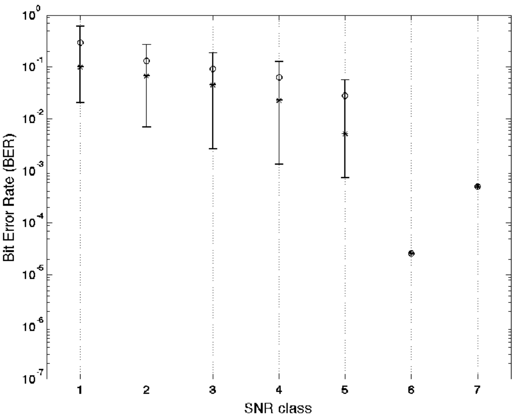

Fig. 11. BER vs SNR class for the PLC link between the transformer and the House #3.

In the second approach, the long-term BERs have been estimated using recorded values of “errors accumulated in a message reception using Viterbi hard decision” and Nayman Type A contagious distribution error model. Result is a value that long-term BER will not likely to exceed. Motivation for this approach is the fact that number of transmitted bits is relatively low due to the limited access to the distribution grid and inability to leave the measurement equipment unattended.

It should be kept in mind, however, that PLC channel characteristics strongly depend on the loads present in the grid and vary with the time. Noise characteristics are incorporated in the analysis through the frequency of SNR class occurrence, recorded at the service nodes for each received message during the measurement period. We observe in Fig. 8, that SNR class is dominantly between 4 and 6, that is SNR is in the range between 9 dB and 18 dB. Impulsive character of noise, however, causes high level of BER what can be seen in Fig. 9, Fig. 10 and Fig. 11.

Measurement results, presented in the paper, show lower performance of PRIME-based NB PLC system in comparison with the simulation results available in the literature. The presented analysis is, however, compliant with the analysis and measurement results for NB PLC system reported in [16].

VI. CONCLUSIONS

Advance metering infrastructure (AMI) has been recognized as one of key enablers for smart grids. Even though AMI relies on different wired and wireless communication systems, NB PLC plays a crucial role in the AMI deployment as a technology that is naturally integrated in the distribution grid and fully operated by a power utility, providing data rates that meet smart metering requirements.

Performance of PRIME-based NB PLC system is evaluated using actual measurements in the rural overhead low-voltage grid under operation from DSO perspective and findings are presented in the paper. Performance analysis is based on the methodology that uses limited amount of PLC modem measurements in order to determine BER vs SNR class relation, as dominant characteristic for the performance analysis of the NB PLC system at the PHY layer. These results are correlated with the measured PLC channel characteristics (frequency response and noise level).

Two different approaches are used to calculate BER. In the first approach, BER is calculated for every received message using vendor's guidelines. Such BER represents a random variable and 95 % confidence interval is determined. The second approach estimates the long-term BER using recorded number of bit errors in received messages and error model based on Neyman Type A contagious distribution appropriate for channels with impulsive noise. Methodology presented in the paper leads to the results providing information about interval that will contain BER with 95 % confidence for each SNR class but also determines a value that long-term BER will not likely to exceed.

Overview of the findings from measurements indicate that PRIME-based NB PLC links show satisfactory BER performance, respecting high attenuation of the utilized PLC channels and impulsive character of noise. On the other hand, revealed performance is significantly lower in comparison with simulation results found in the relevant literature.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the power utility Elektroprivreda B&H for the permission to access the power grid for the measurement and testing purposes.

REFERENCES

[1] Y. Yan, Y. Qian, H. Sharif, D. Tipper, "A survey on smart grid communication infrastructures: motivations, requirements and challenges", *IEEE Comm. Surveys & Tutorials*, vol. 15, pp. 5–20, 2013. DOI: 10.1109/SURV. 2012.021312.00034.

[2] K. Sharma, L. M. Saini, "Performance analysis of smart metering for smart grid: An overview", *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 720–735, 2015. DOI: 10.1016/j.rser.2015.04.170.

[3] H. Sui, H. Wang, M. Lu, W. Lee, "An AMI system for the deregulated electricity markets", *IEEE Trans. Industry Applications*, vol. 45, no. 6, pp. 2104–2108, 2009. DOI: 10.1109/TIA.2009.2031848.

[4] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, "Smart grid technologies: communication technologies and standards", *IEEE Trans. Industrial Informatics*, vol. 7, no. 4, pp. 529–539, 2011. DOI: 10.1109/TII.2011.2166794.

[5] C. Lo, N. Ansari, "The progressive smart grid system from both power and communications aspects", *IEEE Comm. Surveys & Tutorials*, vol. 14, no. 3, pp. 799–821, 2014. DOI: 10.1109/SURV.2011.072811.00089.

[6] M. Yigit, V. C. Gungor, G. Yuna, M. Rangoussi, E. Fadel, "Power line communication technologies for smart grid applications: A review of advances and challenges", *Computer Networks*, vol. 70, pp. 366–383, 2014. DOI: 10.1016/ j.comnet.2014.06.005.

[7] M. Zimmermann, K. Dostert, "A multipath model for the powerline channel", *IEEE Trans. Communications*, vol. 50, no. 4, pp. 553–559, 2002. DOI: 10.1109/26.996069.

[8] G. Laguna-Sanchez, M. Lopez-Guerrero, "On the use of alpha-stable distributions in noise modeling for PLC", *IEEE Trans. Power Del*, vol. 30, pp. 1863–1870, 2015. DOI: 10.1109/TPWRD.2015.2390134.

[9] M. Antoniali, F. Versolatto, A. M. Tonello, "An experimental characterization of the PLC noise at the source", *IEEE Trans. Power Del*, vol. 31, no. 3, pp. 1068–1075, 2016. DOI: 10.1109/TPWRD.2015.2452939.

[10] S. Galli, A. Scaglione, Z. Wang, "For the grid and through the grid: the role of power line communications in the smart grid", in *Proc. IEEE*, vol. 99, no. 6, 2011, pp. 998–1027. DOI: 10.1109/JPROC.2011.2109670.

[11] *ITU-T G.904 Narrowband orthogonal frequency division multiplexing power line communication transceivers for PRIME networks,* International Telecommunication Union, 2012.

[12] *ITU-T G.903 Narrowband orthogonal frequency division multiplexing power line communication transceivers for G3-PLC networks,* International Telecommunication Union, 2014.

[13] R. Smolenski, J. Bojarski, A. Kempski, P. Lezynski, "Time-domain-based assessment of data transmission error probability in smart grids with electromagnetic interference", *IEEE Trans. Industrial Electronics,* vol. 61, no. 4, pp. 1882–1890, 2014. DOI: 10.1109/TIE.2013.2263772.

[14] A. Mathur, M. R. Bhatnagar, B. K. Panigrahi, "On the performance of a PLC system assuming differential binary phase shift keying", *IEEE Comm. Lett.*, vol. 20, no. 4, pp. 668–671, 2016. DOI: 10.1109/LCOMM.2016.2527002.

[15] P. Wang, A. Marshell, K. A. Noordin, Huo Xufeng, G. Markarian, "Hybrid network combining PLC and IEEE802.16 for hospital environment", in *Proc. of IEEE Int. Symposium on Power Line Communications and Its Applications (ISPLC),* 2010, pp. 267–272. DOI: 10.1109/ISPLC.2010.5479883.

[16] W. Liu, M. Sigle, K. Dostert, "Channel characterization and system verification for narrowband power line communication in smart grid applications", *IEEE Comm. Mag.,* vol. 49, no. 12, pp. 28–35, 2011. DOI: 10.1109/MCOM.2011.6094003.

[17] *ARM Cortex-M4 PRIME SoC Datasheet,* Atmel SAM4SP User Guide, 2014.

[18] D. R. Smith, *Digital Transmission Systems*. Springer Science Business Media, LLC, 2004, p. 47.

[19] J. Neyman, "On a new class of contagious distribution, applicable in entomology and bacteriology", *The Annals of Mathematical Statistics,* vol. 10, pp. 35–57, 1939. DOI: 10.1214/aoms/1177732245.

[20] M. Zhai, "Transmission characteristics of low-voltage distribution networks in china under the smart grids environment", *IEEE Trans. Power Del*, vol. 26, pp. 173–180, 2011. DOI: 10.1109/TPWRD.2010.2067228.