From the Lap(top) to the Jungle: Validating the PRIME Network Simulator SimPRIME with Data from the Field

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Abstract—**Many simulation tools for Powerline Communication technologies have been developed during the last years with the aim of evaluating and improving their performance, as an alternative to more expensive, less flexible, and more complex-to-manage physical testbeds. However, how significant are the results coming from such simulation tools? Answering to this question by analyzing how well the model behind the simulations fits reality is especially complicated for such harsh communication scenarios as Powerline Communication networks. Hence, this paper proposes a methodology for doing so experimentally. In addition, the proposed methodology is applied to assess the well-known simulator SimPRIME by comparing statistically the results of simulating a real Powerline Communication network belonging to an operational Spanish Advanced Metering Infrastructure with measurements taken during the operation of such a network. Since the computed confidence intervals overlap, it can be concluded that the results coming from the simulator fit this specific real scenario under the conditions of the considered time period. Although the obtained results contribute to legitimate the research work that have been conducted with SimPRIME throughout the last years, the conclusions of this study cannot be generalized to any scenario without performing more experiments, which opens an opportunity to future research work.**

Keywords— ***Advanced Metering Infrastructure, Narrowband-Power Line Communications, PoweRline Intelligent Metering Evolution, SimPRIME, Smart Grid, Validation***

I. INTRODUCTION

Power Line Communication (PLC) has been an active research area for so many years and it is still so, as some recent special issues and surveys on the topic published in top journals prove [1]-[3]. Why? On the one side, because they present economic and technical advantages for such a wide range of applications, spanning from in-home multimedia networks to manufacturing or power distribution industries. On the other side, because they represent such a harsh communications medium, which suffers from frequency selectivity, continuous altered loads, Electro Magnetic Interference (EMI), and, above all, noise coming both from traditional appliances, such as TVs or boilers, and from more novel equipment, such as Distributed Generation (DG), Electric Vehicles (EVs), or storage [4],[5].

A good part of the research conducted throughout these years in this topic has been oriented to develop simulation tools due to the benefits they bring, such as agility, flexibility, and cost-effectiveness. However, one of the main drawbacks of simulation tools is that the relevance of the results obtained from them depends on how well the model behind them fits reality [6].

This issue is in many occasions addressed under a bottom-up approach, i.e., trying to include in the model all the physical phenomena as accurately as possible. However, applying this approach to PLC is extremely difficult. In addition, assuming that developing a model that absolutely fits reality is not feasible, this approach does not unequivocally ensure better results, well-known principles such as the Occam's razor principle or the KISS principle suggesting even the opposite.

In 2006, in full hype of Wireless Sensor Networks (WSN), Prof. Tanenbaum published a paper that discussed issues that might actually prevent WSN from becoming a reality and appealed the research community to not only focus on academic problems, but also tackle such operational difficulties [7]. That "classical" paper has served as inspiration not only for the title of this paper, but also, together with the aforementioned principles, for approaching the problem of the relevance of the results from PLC network simulators under a top-down approach.

Thus, in this paper measurements are taken from an actual PLC network belonging to an operational Spanish Advanced Metering Infrastructure (AMI), such a network is simulated, both results are statistically compared, and conclusions are drawn based on such a comparison. In particular:

- From the many different PLC "flavors" available in the market, the paper focuses on PoweRline Intelligent Metering Evolution (PRIME) [8], [9]: a Narrowband Powerline Communication (NB-PLC) technology, led by industry leaders such as Spanish Distribution System Operators (DSOs) Iberdrola and Unión Fenosa, and chipset manufacturers such as Texas Instruments or Microchip, which is being widely deployed in the last-mile of AMI both in Europe and overseas [10], [11].
- The PRIME network simulator assessed in the paper is SimPRIME [12], which has been widely used in previous research work [13]-[20].
- The scenario considered in the paper is a real and operational residential PRIME network deployed for AMI purposes.
- The metric that is used for the comparison is the so-called Time-To-Read (TTR), which is the time the data concentrator needs to retrieve a consumption report from a given smart meter after requesting it.

The remainder of the paper is structured as follows. Section II summarizes the basics of the simulator SimPRIME in order to make the paper self-contained. Section III goes through previous related research work. Section IV presents the main contribution of the paper: the methodology used to carry out the study and the obtained results. Finally, section V draws conclusions and proposes future research lines.

II. SIMPRIME IN A NUTSHELL

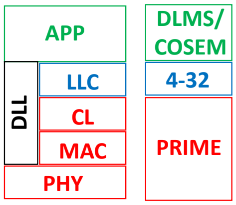

Fig. 1. Protocol stack

Fig.1 shows the protocol stack in the "last-mile" of an AMI which takes advantage of the low voltage cables to transmit data using NB-PLC PRIME technology. It can be seen that is composed of PRIME, which specifies the Physical (PHY), Medium Access Control (MAC), and Convergence (CL) layers, and Device Language Message Specification/COmpanion Specification for Energy Metering (DLMS/COSEM), at the application layer. In the case considered in this paper, the metering legacy protocol IEC 61334-4-32 is used at the Logical Link Control (LLC) layer, which is an optional component of the Data Link Layer (DLL).

This protocol stack is implemented in SimPRIME by combining MATLAB and OMNeT++, which is a widely used event-driven open-source network simulator [21]. As Fig.2 shows, SimPRIME allows performing two types of simulations: (1) simulations where the logical topology of the PRIME network dynamically evolves (i.e., terminals may be promoted/demoted to/from switches or they may register/deregister) based on the regular mechanisms defined in PRIME; or (2) simulations where the logical topology of the PRIME network is fixed, typically based on a standard topology file which is stored and updated by the concentrator (the so-called "S11 report").

In both cases, an attenuation matrix which specifies the attenuation between any pair of nodes is obtained. The difference is that, in case (1), such a matrix is obtained based on transmission line theory as explained in [22]. This procedure depends basically on the impedances that represent a chunk of cable of a given length and a termination (e.g., customer premises), as modelled in [23]. As it can be seen in Fig.2, the physical topology may be specified either through the OMNeT++ configuration file (i.e., the ".ini" file), where several branches can be defined and the smart meters of each branch are equally separated, or by means of a map of an actual power distribution infrastructure in Shapefile format (which is indeed a novelty developed for this work and is going to be used in section IV). It should be noted that in this case the attenuation matrix does not have to be symmetric.

So in the case (1), once the attenuation matrix is obtained, assuming the maximum transmission power allowed by the standard, the Signal-to-Noise Ratio (SNR) at any other node of the network can be computed based on eq. (1), where P_N represents the baseline noise, which is assumed to be the same at every node of the network:

$$\text{SNR}(\text{N}\rightarrow\text{M})\ [\text{dB}] = \text{Ptx}(@\ \text{node N}) - \text{Att}_{\text{NM}} - \text{P}_{\text{N}} \quad (1)$$

As Fig.2 also shows, once the SNR is known, the Bit Error Rate (BER), associated to such a SNR and the constellation in use, can be obtained from the BER vs SNR curves which are pre-computed for each constellation using MATLAB. Once the BER is known, the Packet Error Rate (PER) is computed based on eq. (2), which assumes independency between the probability of error of each bit:

$$\text{PER} = 1 - (1\text{-BER})^{\text{packet\_length}} \quad (2)$$

In the case (2), however, a given level of attenuation is assumed between nodes at the same logical level; a higher level is assumed between nodes at contiguous logical levels; and the maximum attenuation level is set for the rest of the cases. This in turn translates into a given BER between nodes at the same logical level (typically low or even 0); a higher BER between nodes at contiguous logical levels; and a BER of 1 in the rest of the cases. This approach allows simulating how a given logical topology behaves under certain scenarios (e.g., no noise scenario, low noise scenario, very noisy scenario [18]).

The PER is the input to the upper layers, which are modelled in OMNeT++. It should be noted that, although we only considered communication between the concentrator and the smart meters, all the nodes must be able to "see" if there is signal in the channel, so that, if there is a collision, the CSMA/CA mechanism implemented in OMNeT++ is triggered.

Regarding DLMS, it is worth to mention that the functionality of the protocol itself is not implemented, but it is modeled just as the data payload of PRIME. Regarding this, it should be also noted that PRIME defines a Maximum Transmission Unit (MTU). Thus, if the data payload is bigger than such a maximum value, PRIME Convergence Layer fragments the message coming from the application into several PRIME MAC layer Service Data Unit (MSDU), each one no longer than the MTU.

III. RELATED WORK

As a token of the importance of simulation tools for NB-PLC, during the last years much research has been conducted in this specific topic and a bunch of papers have been published.

Reference [24] is one the pioneering works in this topic. It presents an interesting analysis on the performance of multi-hope PLC networks. However, the paper focuses on the MAC layer, noise is not considered in the channel modeling, and so there are no errors in the communications.

Reference [25] is also a pioneering work in proposing a method to abstract the PHY layer from the upper layers by means of PER vs SNR curves (as it is also the case in SimPRIME). However, such curves are computed for a fixed packet length, which is an assumption that most likely affects the "goodness" of the obtained results compared to real scenarios.

References [26] and [27] present two PRIME network simulators also based on OMNeT++ which were developed almost at the same time as SimPRIME. The work presented

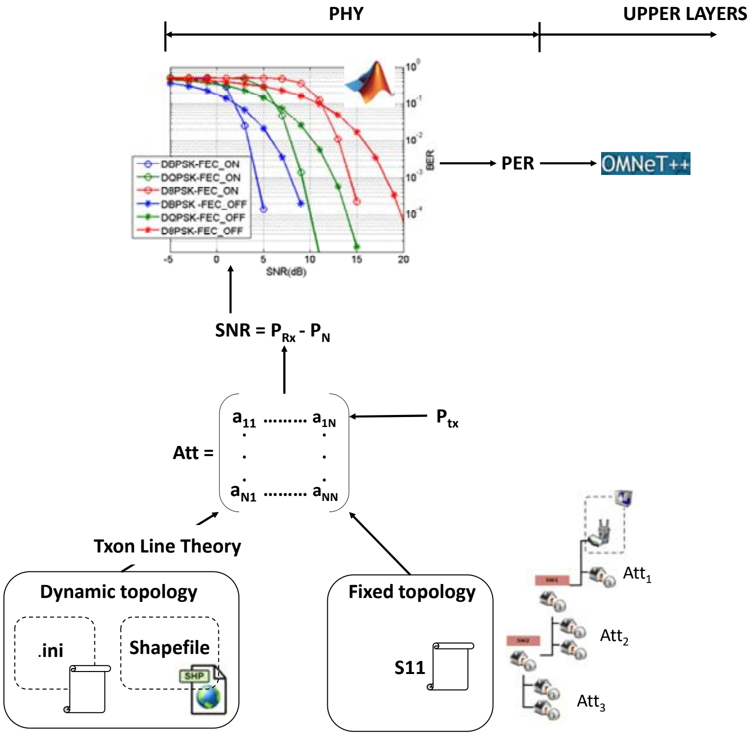

Fig. 2. SimPRIME in a nutshell

in [26] focuses very much on the PHY layer, notably on the probability of error. Although this kind of studies are interesting, the DSOs typically look for other parameters which are more representative of the network performance, such as the latency or the TTR.

The work presented in [27] focuses on a very specific and relevant practical scenario: the remote and massive upgrade of firmware in PRIME networks. In this work, the PHY layer is also abstracted to upper layers by means of PER vs SNR curves. The main drawback of this implementation is that the PER is not only computed for a fixed packet length, but that such a packet length is the maximum. This penalizes the control traffic, which entails typically small packets, and is critical for the proper operation of any communication network.

Some of the assumptions made in SimPRIME, already covered in section II, are that the attenuation is flat in the whole band, does not change with time, and that the baseline noise level is the same in all the smart meters of the network. However, the BER depends on the selected coding scheme, the PER depends on the BER and on the length of the packet, and DLL mechanisms are accurately implemented.

There are also research works where actual PRIME networks are analyzed, based on PHY measurements [28] or on traffic traces [29], with the aim of characterizing relevant communications parameters, e.g., to fine-tune simulation tools. Moreover, there are also recent works that evaluate the performance of PRIME networks under certain conditions based on lab experiments[30], [31], [5].

However, to the best of the authors' knowledge, SimPRIME is the first simulator that allows taking as input actual physical topologies (in Shapefile format) and this paper is the first work where measurements taken from a real operational PRIME network are compared with results obtained from a network simulator.

IV. VALIDATING SIMPRIME WITH DATA FROM THE FIELD

Fig.3 graphically sketches the methodology proposed in this paper to experimentally validate the "goodness" of the results obtained from SimPRIME (and so of the underlying model).

The real scenario which is considered in this work is shown in Fig.4. The lines represent the low voltage cables and the dots represent the smart meters. It is a residential power distribution network which comprises 65 houses, each of them equipped with a type-5 smart meter (i.e., the contracted power is less or equal to 15 KW). Thus, the PRIME network formed by the smart meters and the concentrator can be seen as a communications overlay on top of such a physical infrastructure.

Right before starting gathering data, the administrator of the actual PRIME network under study, which belongs to an operational AMI, launches a task at the concentrator to retrieve the hourly meter read report (also known as "S02 Report") from each smart meter. The data gathered in the field is basically the traffic traces recorded by the concentrator. The concentrator used in the considered PRIME network is from the manufacturer Circutor. This concentrator records the traffic traces in a log in Comma Separated Value (CSV) format, where each entry is associated to a given message and all the PRIME fields are decoded and separated by commas. The PRIME payload (i.e., the DLSM messages), however, appears as a chunk of bytes in hexadecimal.

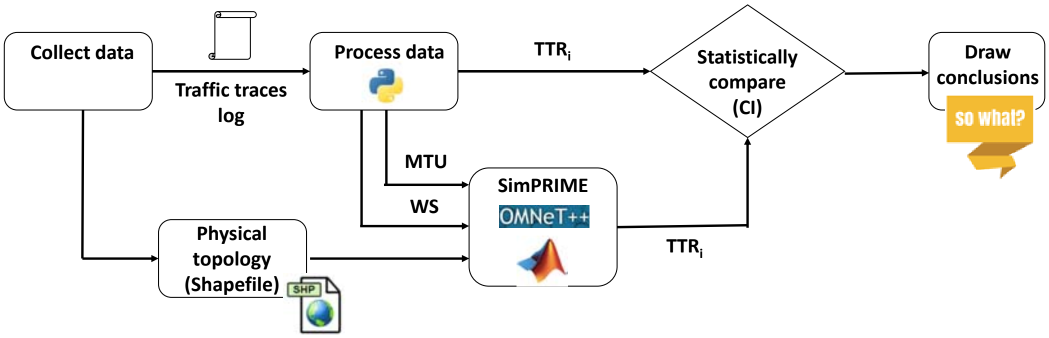

Fig. 3. Proposed methodology

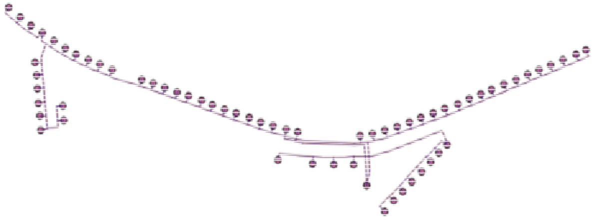

Fig. 4. Physical topology of the considered scenario

As Fig.3 shows, the information that needs to be extracted from such a log is: (1) the TTRi (i.e., the time the concentrator needs to retrieve a “S02 report” from each smart meter after requesting it), which will be used as metric to compare the results of the simulations with the actual procedure; and (2) the MTU and Window Size (WS) used in the PRIME network, which will be input to SimPRIME.

The first step to extract such information is to figure out how to identify the message where the concentrator requests a “S02 report” from a smart meter and the last message of the answer to such a request coming from the smart meter.

Since the DLMS messages are in hexadecimal, the following free tools are used to achieve this first goal: (1) the XML Translator [32], which allows translating DLMS Application Protocol Data Units (APDU) specified as strings of hexadecimal characters into eXtensible Markup Language (XML), and vice versa (this tool will allow identifying the DLMS request and response messages); (2) and the OBIS Helper [33], which allows "decoding" and "encoding" OBIS codes to and from their text description (this tool will allow identifying the OBIS code associated to a S02 report).

As Fig.5 shows, using these tools it is found that:

- The target request (coming from the concentrator) codes are:
    - *Service.request*: “c001c1”.
    - *Service.requestS02*: “c001c10007**0100630100ff**”, “0100630100ff” being the OBIS code of the S02 report.
    - *Service.request.NextBlock*: “c002c1”.
- And the target response (coming from the smart meters) codes are:
    - *Service.response.lastblock_false:* “c402c100” (the next 4 bytes represent the sequence number).

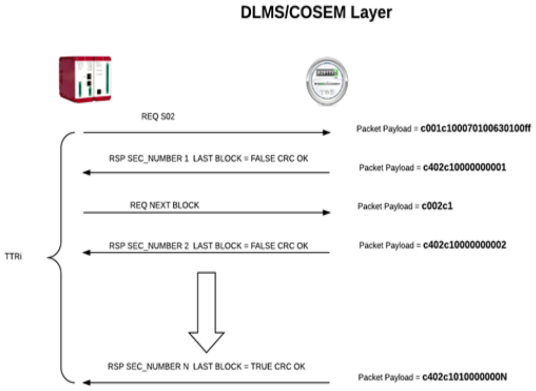

Fig. 5. DLMS exchanged messages and hexadecimal codes

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    - *Service.response.lastblock_true*: “c402c10**1**” (the next 4 bytes represent the sequence number).

Once this is known, a script in Python is used to find, using regular expressions, the hexadecimal code of the Service.requestS02 (to store its associated timestamp as starting time) and the hexadecimal code of the Service.response.lastblock_true (to store its associated timestamp as ending time). The TTRi is computed by subtracting the starting time from the ending time. Nevertheless, the developed script also takes into account that the sequence of exchanged messages is correct in order to avoid fake values. E.g., let imagine that smart meter “N” does not receive the acknowledgment (ACK) associated to its Service.response.lastblock_true message from the concentrator because it gets lost, so it transmits its Service.response.lastblock_true message again while the concentrator has starting polling smart meter “M”; if the aforementioned procedure were not implemented, the script would drop a fake TTRi (smaller than the actual one), since it would end up as soon as Service.response.lastblock_true message from smart meter “N” were logged.

As Fig.6 illustrates, the used MTU is obtained by counting down the maximum number of bytes of all the DLMS messages. The WS is obtained by counting down the PRIME MSDU which are sent without receiving ACK plus 1 (since the last MSDU is indeed ACKed). Hence, in the actual scenario under study, the PRIME MTU is 64 bytes and the WS is 4 MSDU.

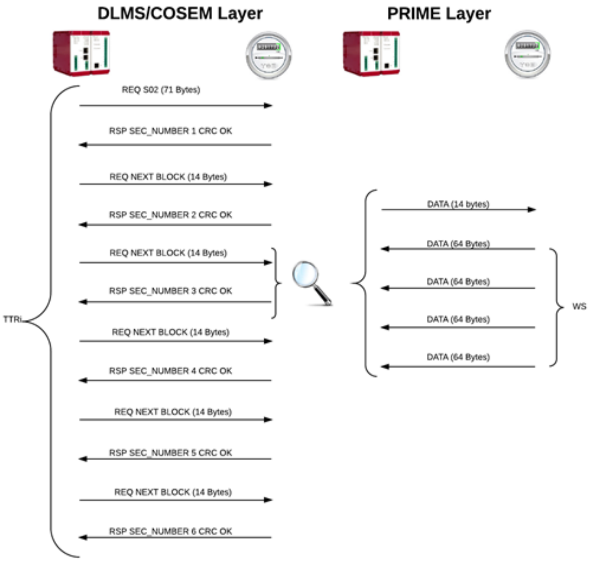

Fig. 6. Mapping of DLMS messages onto PRIME frames in order to obtain MTU and WS

As Fig.3 also shows, once these values are obtained, the simulations are configured using them as input, along with the map of the physical infrastructure in Shapefile format.

Finally, as it is also indicated in Fig. 3, 95% confidence intervals are computed for both the measurements taken from the field and the results obtained from the simulations using eq. (3), being μ the mean of the data, σ the standard deviation of the data, and n the length of the data:

$$(\mu - 1.96 \cdot \frac{\sigma}{\sqrt{n}}, \mu + 1.96 \cdot \frac{\sigma}{\sqrt{n}}) \qquad (3)$$

The obtained results are summarized in Table I. It can be seen that the confidence interval related to the TTRi obtained from the traffic traces includes the confidence interval related to the TTRi obtained from the simulations. As a result, although the number of TTRi obtained from the gathered traffic traces might be too tight for applying eq. (3), due to the fact that the concentrator was not configured to retrieve the S02 reports repeatedly and it did not even manage to receive S02 reports from all the smart meters in the network[1], it can be concluded that SimPRIME results fit this specific real scenario under the conditions of the considered time slot. Thus, it can be concluded that the results of the simulations are significant for this specific scenario despite the assumptions made in the underlying model.

TABLE I. RESULTS

	Traffic traces analysis	**SimPRIME**
n	62	4374
Mean (μ) (seconds)	13.5668709677	13.39230382
Std. dev. (σ) (seconds)	4.208939684	1.479523905
Confidence Interval (seconds)	[12.5192 , 14.6146]	[13.3485 , 13.4362]

Nevertheless, it should be also noted that the statistical dispersion of SimPRIME results is smaller than the statistical dispersion of the results obtained in real life. This may invite to think that there are some phenomena that are not considered in the network simulator. These phenomena may be modeled as a random variable which could be added whenever a packet is received in order to make the results coming from SimPRIME more similar to real life networks, although more experiments would be required to investigate the relationship of such a random variable to the specific scenarios.

V. Conclusions and Future work

As the popularity of NB-PLC technologies increases due to their wide adoption, mainly, for the last-mile of AMI deployments worldwide, more and more simulation tools have been developed for them in the recent years with the aim of allowing solving operational issues and improving their performance as an alternative to more expensive, less flexible, and more complex-to-manage physical testbeds. However, how significant are the results coming from such simulation tools?

As it is very difficult (and may be even inconclusive) to try to answer this question by analyzing how well the model behind the simulations fits reality (especially for such harsh communications scenarios as PLC networks), this paper proposes a methodology for doing so experimentally.

Furthermore, this methodology is applied to assess whether the results obtained from simulating a real and operational PRIME network using the well-known simulator SimPRIME are similar to the measurement taken from the field. Thus, as the title of the paper suggests, SimPRIME is somehow taken for the very first time from the laptop to the jungle.

The considered scenario is a residential power distribution network composed of 65 houses and the comparison is based on 95% confidence intervals computed for all the TTR obtained either from the data gathered in the field or from the simulations. Since such confidence intervals overlap, it can be concluded that the results obtained from the simulations are statistically similar to the measurements taken from the field. Thus, the results of SimPRIME can be considered significant in this specific scenario despite the assumptions made in the underlying model.

Although this result is promising, it cannot be generalized, i.e., in a different scenario, or even in the same scenario but in a different moment in time, the result may be different. Hence, the proposed methodology needs to be applied to different types of power distribution networks (e.g., high density residential area and low density residential areas [34]) under different conditions (e.g., with or without impulsive noise or with the presence of other well-known sources of noise [4], [5]) in order to be able to draw more general conclusions, thus opening an opportunity for future research work.

Having said that, the obtained results brings value and contributes to legitimate the research studies that have been conducted with SimPRIME throughout the last years.

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