Performance Evaluation of AMR Simultaneous Polling Strategies in a PRIME PLC Network

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***Abstract*—PLC is gaining prominence as a solution for Smart Grid developments. However, several aspects still require further research and analysis. Among the different solutions, PRIME (PoweRline Intelligent Metering Evolution) standard is one of the most popular and extended implementations.**

This paper analyses the performance of an Auto Meter Reading (AMR) process for a PRIME PLC network regarding two aspects. Firstly, the impact caused by the polling strategy utilized. In particular, the number of connections that the Master Node manages simultaneously is studied. Secondly, the influence of the positions of the Switch Nodes in the network is examined. The time required to read all the meters in the network is utilized as performance metric.

In order to replicate the performance of a PRIME network, a co-simulation framework that combines Matlab and OMNeT++ has been used. This architecture allows to take into account both physical phenomena and control and application message management. Simulated topologies represent a general European low-voltage network. Results highlight the importance of selecting an adequate number of simultaneous connections in order to optimize the use of the channel, as well as the impact of the logical structure of the network.

Keywords—Power Line Communication; automatic meter reading; PRIME; polling strategy; switch; OMNeT++; European LV Distribution Network; time to read meters.

I. Introduction

In general, a Smart Grid (SG) is the combination of a traditional distribution network and a two-way communication network for sensing, monitoring, and dispersion of information on energy generations and consumptions [1].

The Smart Grid makes the power system to use all available information, providing computational intelligence in an integrated fashion over generation, transmission, distribution and loads, to achieve a system that would be much more clean, safe, secure, reliable, efficient and sustainable [2].

Although there are several technologies that can be used to comply with the SG purposes ([3], [4]), utility companies have increased their interest in Power Line Communication (PLC) in the last decades. Nowadays, PLC technology presents a mature state and deployment background in structures where SG are present, like transmission and distribution in the electric grid. This technology is seen like a tool to reduce operating costs, improve reading measurements and efficiency and enable demand management.

As a result, designers have attempted to offer different solutions for communication via power lines. Mainly, these technologies can be grouped into two categories: Broadband-PLC (BB-PLC), more inclined towards end user entertainment and Internet, and Narrowband PLC (NB-PLC), more suited to metering and communication purposes in Smart Grid environments.

NB-PLC offers several characteristics that make it suitable for Smart Grid applications, such as the Automatic Meter Reading (AMR), Advanced Meter Infrastructure (AMI) or Demand Response (DR). Indeed, this technology provides low bit rates between smart meters and data concentrators as well as a low cost infrastructure [1].

One of the first specifications for NB-PLC was PRIME, appeared in 2007, that implements multi-carrier modulation in a low voltage network. Since then, a number of standards have been released such as G3- PLC, G.hnem, and IEEE1901.2.

The present paper aims to obtain, by means of simulation, some conclusions on PRIME networks' performance with regard to two aspects that are not defined in the standard.

On the one hand, PRIME standard specifies a MAC layer that is connection-oriented, implying that data exchange is necessarily preceded by a connection establishment between communicating peers. Nevertheless, the connection and polling strategy to be followed by the Master Node is not defined.

On the other hand, this study focuses on the way the positions of the Switch Nodes in a PRIME network affect the overall system's performance. Again, no promotion strategies are provided by the standard.

In this work, the time required to gather the information from all the nodes in an AMR process is used as a performance metric. The availability of all the nodes in the network has also been considered in the simulations.

The structure of this paper is as follows. In Section II, a literature review of the different approaches to study the performance of a PLC network can be found. Section III offers a general description of PRIME's mechanisms that are of interest for the study. The way that the different polling strategies affect the performance of a PLC network is depicted in Section IV. Section V encompasses the description of the effect caused by the positions of the Switch Nodes over the network performance. In Section VI, the description of the case study can be found. Results obtained from the simulations are shown in Section VII. Finally, the paper concludes with a discussion of the significance of the main findings.

II. Performance of a PLC network

Several works in the literature provide an analysis of the performance of a PLC network. Commonly, a simulation framework is used to compare different parameters or standards.

Although [5] highlights that discrete event simulators do not permit the simulation of the continuous behavior of signal propagation, currently, industry and academia are showing growing interest in having available simulation tools. Some of the models found converge to a similar solution, that consists on modeling the physical channel characteristics through Matlab, and the telematic events and standard upper layers in a network simulator tool (OMNeT++, OPNET, ns-3).

In this line, a PRIME dual simulation framework is presented in [6]. In this work, the model of the channel is based in the work presented in [7], where the physical behavior of an OFDM-based communication system is abstracted in terms of Bit Error Rate (BER) vs. Signal to Noise Ratio (SNR) curves. This analysis is very helpful for the computation of the physical layer within the simulation framework. On the other hand, the physical effects of the transmitting medium are modeled as an attenuation affecting the transmitted signal based on [8]. This study provides a methodology to calculate the transfer function of the PLC network utilizing a bottom-up approach and Transmission Line Theory, taking into account the topology and cable characteristics.

The effects of the topological configuration of the network over the error rate are analyzed in [9], where the performance of an OFDM BB-PLC system with respect to number of branches, line length and load is studied. Similarly, [10] evaluates the telemetering performance of a PRIME system with respect to the number of branches. In [11] the capacity of a Broadband over Power Line network is evaluated with respect to the physical position of up to two repeaters. In this reference, several topological scenarios are proposed. However, the aforementioned study does not take into account aspects like telematic events and connection management, imposed by a specific communication standard.

With respect to other PLC standards, [10] and [12] compare the behavior of PRIME and G3-PLC, concluding that G3-PLC is more robust due to the use of redundancy and error correction techniques, with the drawback of slower bit rates. In [13], a G3-PLC simulation model is presented. In this work, the physical layer of the standard is implemented in Matlab, and the data link/adaptation layer (with IPv6) in OMNeT++.

Other lines of work emphasize the need of analyzing the performance of a PLC system at network level. In case of AMR scenarios, an interesting metric is the time required for the Data Concentrator to read the information from all (or one of) the smart meters in the network. [14] provides a maximum value for the time required to read all meters in a Low Voltage (LV) network, and suggests a threshold of 15 minutes.

In this line, [15] employs the time required to read 100 meters to compare different standards for upper layers of PLC technologies. In this study, DLMS/COSEM is highlighted as the best option. Additionally, and in line with [16], a comparative analysis is carried out taking into account the possible polling strategies to be followed in a data exchange process for a system of this nature. However, these strategies are analyzed without going deep into the number of connections that are managed simultaneously by the master of the network.

This high-level metric is also used in [10] and [16], where the simulation framework presented in [6] is utilized to evaluate the performance of a network when the channel is impaired with background or impulsive noise. Noise suppression techniques effects, number of branches in the LV network and PLC standards are compared.

Optimization techniques for communication networks are also addressed in the literature, and some of these mechanisms should be prone to be applicable in PLC networks. [17] describes a collection of routing algorithms based on the assignment of a weight (transmission cost) to each possible path. Taking advantage of this, [13] presents a routing algorithm applicable to G3-PLC, which adequacy has been proved by simulation in terms of throughput.

The work presented in this paper utilizes the simulation framework presented in [6] in order to analyze the performance of a PRIME PLC network. The structure of this tool is schematically represented in Fig. 1. As can be seen, all effects related to the physical layer (PHY) of the communication stack have been taken into account via Matlab simulations. In order to model the telematic effects of the PLC network, OMNeT++ is used. Matlab and OMNeT++ are linked by the bit error rate, signal to noise ratio and the communication mode values. In this case, DLMS/COSEM is used in the upper layer of the stack, as common practice in the AMR field.

III. PRIME SPECIFICATION

PRIME standard [18] defines the Physical (PHY), Medium Access Control (MAC) and Logical Link Control (LLC) layers of the PLC transceiver. The PHY manages all mechanisms related with the signal modulation, whereas the other two layers take care of the correct way of using the channel, implementing some functions related with logical connections. Although the standard specifies different modulations, it is a common practice in industry to use only BPSK for robustness reasons.

With respect to the MAC layer, PRIME defines two kinds of nodes: Base Node and Service Node. The role of the Base Node (BN) is to manage the network resources and connections as master node. Only one BN should exist per network and the rest of the nodes must register to it in order to be able to transmit data. By contrast, Service Nodes (SN) act as leaves or branch points of the logical tree-structured network.

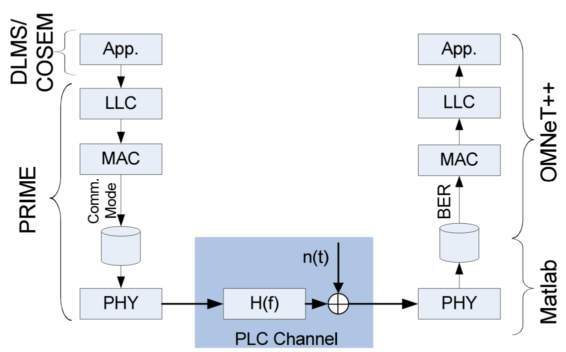

Fig. 1. Structure of the simulation framework [6].

As can be seen in Fig. 2, the initial state of the SN is Disconnected Node (DN). It may change to Terminal Node (TN) by registering to the network's BN and, only when it is already at terminal state, it can be promoted to Switch Node (SW). It is worth highlighting that Terminal, Switch and Disconnected are three possible states of a Service Node. While the objective of a node in Terminal state is to provide connectivity between PHY layer and upper layers, Switch nodes are also responsible for forwarding PHY traffic between BN and other nodes.

Additionally, PRIME standard specifies the mechanisms to exchange data packets between nodes for AMR purposes, among others. This process works end-to-end, and the connection between application layers of communicating peers is required.

This mechanism operates at two levels: firstly between Converge Layer (CL) and Medium Access Control Layer (MAC), and secondly between the MAC layers of the connecting nodes. In order to communicate between upper and lower layers, the standard defines a set of primitives to provide request, indication, response and confirmation of the different processes. PRIME defines two types of packets. The first type is **control packet**, which is used to manage the connection, and the second one is the **data packet**, dedicated to contain the requests and responses of the measured information from the smart meter.

Making use of these tools, PRIME specifies the process to poll the measured data from the different nodes in the network. In the analysis proposed in this paper, all the data requests are started by the BN and responded by each SN. This process consists of four phases, which are schematically presented in Fig. 3.

First of all, the application layer of the BN decides to poll one of the registered nodes. Once the CL receives the order of sending the data request, an **establish request primitive** is pushed down to the MAC layer. This layer is in charge of accessing the channel and sending the control packet required to establish the connection. Later, this control packet is received by the MAC layer of the SN. As a result an **establish indication primitive** is passed to the CL, that is in charge of deciding whether the connection will be accepted or rejected by means of an **establish response primitive**. Then, the MAC layer of the SN sends back the response to the connection request with the corresponding control message. This packet is received by the MAC layer of the BN and an **establish confirm primitive** is then passed to the CL, who is in charge of opening the connection and delivering the data request primitive. This primitive will, in its turn, command the MAC layer to send the data request message addressed to the polled node. The following steps of the process are similar: The data request message is received by the SN and a response is sent to the BN. Finally, when the data response has been received by the upper layer of the master node, the release connection negotiation is started in the same way.

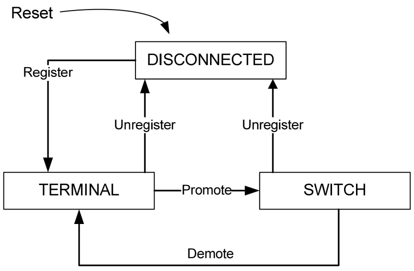

Fig. 2. Different states for a PRIME's Service Node. Obtained from [18].

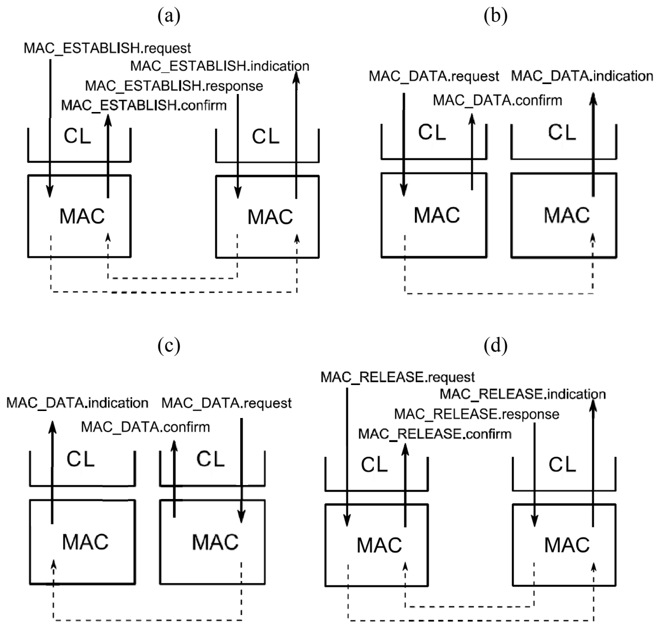

Fig. 3. (a) Connection establihsment, (b) data request (from BN to SN), (c) data response (from SN to BN) and (d) connection release. Obtanied from [18].

IV. POLLING STRATEGIES

The analysis made in the previous section is a description of the process that has to be followed in a single end-to-end connection. Extending this process to a network with several nodes is more complex.

Moreover, the way that the nodes are polled is a problem that is of interest for the industry, as described in [15] and [16]. Although PRIME standard specifies the mechanisms required for data request and response, the polling strategy to be followed is not imposed, leaving room for analysis and different implementations. Mainly, this process can be carried out in a sequential or simultaneous fashion.

In the first one, every node is polled once the previous one has been successfully read. This implies opening a connection between nodes, sending and receiving the data information, closing it, and afterwards, starting again the process with the next node. Obviously, the main advantage of this polling strategy is the dedication of the channel for each node, which prevents collisions and long waiting times when contending for the channel. On the other hand, there is no overlapping in the auto metering process, which may increase the time required to poll all the members of the network.

By contrast, simultaneous polling permits reading different nodes at the same time, i.e., one node can be polled before receiving the response from the previous one. As it will be seen in the next sections, the time required to read all the meters can be reduced, but the common channel will suffer more access requests, which may increase the latency for each end-to-end dialog, as well as the probability of collisions.

When the number of meters is very large, managing as many connections as nodes in the network requires the dedication of a large volume of resources. Hence, a parameter prone to be taken into consideration is the maximum number of connections that the master node manages simultaneously (K in the analysis presented) optimizing the network performance. As it will be seen later, selecting the right number of simultaneous connections seems important in order to obtain a good balance between resources and bus occupancy. It is worth highlighting that sequential polling is equivalent to a simultaneous polling where the maximum number of simultaneous connections is equal to 1.

Studies like [15] and [16] compare the performance of a PLC network under these schemes considering the impact of the number of branches and nodes or the communication standard utilized.

The following subsections give more insight into two important concepts utilized in the proposed analysis.

A. Time to read one meter (TTR 1 meter)

In the approach presented, the time required for a data message to travel through the channel from the BN to its destination node, plus the time required for the response to travel back to the BN, is used as global metric of the efficiency of the system (i.e. the shorter this period, the more efficient the network is).

The schema in Fig. 4 represents a dialog between BN and a pair of SN in sequential polling that illustrates the concept of TTR 1 meter.

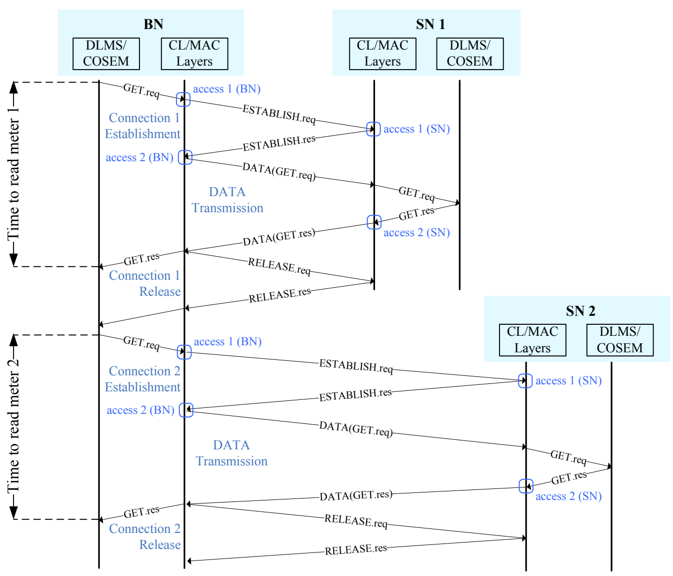

Fig. 4. Data request dialog in sequential polling.

The arrows between DLMS/COSEM and CL layers (GET.xxx) represent primitives as defined in PRIME standard; and the arrows between nodes represent both control and data traffic from node to node through the common bus. Detailed traffic between CL and MAC layers is depicted in Fig. 3, so, in Fig. 4 it has been removed for clarity. Thus, ESTABLISH.xxx and DATA.xxx cover respectively the MAC_ESTABLISH.xxx and MAC_DATA.xxx primitives noted in Fig. 3, as well as the corresponding control and data packets exchanged between the MAC layers of BN and SN.

In this representation, the time required to read one meter is measured as the time elapsed since the application layer releases the send data primitive, until it receives the response primitive to the data request from the corresponding node, following (1). The propagation delay, considering speed of light and distances of hundreds of meters, is neglected.

$$TTR_{1\text{meter}} = t_{\text{prim}} + t_{\text{access 1(BN)}} + t_{\text{CON}} + t_{\text{access 1(SN)}} + t_{\text{CON}} + t_{\text{access 2(BN)}} + t_{\text{DATA}} + 2 \cdot t_{\text{prim}} + t_{\text{access 2(SN)}} + t_{\text{DATA}} + t_{\text{prim}} \quad (1)$$

In (1), t_{prim} is the time required for a primitive to be pushed between layers; t_{CON} is the time elapsed between the beginning of the transmission of a control packet and the end of the reception at the destination node; analogously, t_{DATA} is the time elapsed between the beginning of the transmission of a data packet and the end of the reception at the destination node; and $t_{accessX(YY)}$ is the time required for the node *YY* to process a received message or primitive and accessing the channel with message number *X*, as noted in Fig. 4. As the number of nodes contending for the channel increases, the latter period shall be higher for each transmission, since the access to the channel is less probable according to the CSMA-CA algorithm [18], [19]. Hence, in the case of sequential polling, the value of $t_{accessX(YY)}$ shall be smaller than in simultaneous polling, where several nodes contend for transmitting both control and data packet at the same time. As it will be explained below, an increase in the number of simultaneous connections enlarges this time, harming the total time required to read each meter.

In the example presented in Fig. 4, the time required to read all meters in the network (TTR all meters) encompasses the sum of the time to read each meter, so that it presents a direct relationship with the TTR one single meter. As it will be seen, in the case of simultaneous polling this relation is not so direct, and the number of simultaneous connections available has to be taken into account.

B. Number of simultaneous connections

Fig. 5 shows one example of simultaneous polling using a maximum number of two connections (K=2). The arrows in this figure are analogous to the mechanism expressed in Fig. 4. The tags have been removed for clarity and different line styles have been used for each node.

As can be seen, the time required to read two meters differs from the sum of the TTR one node. Moreover, the TTR meter 3 begins once the first or second node have released its respective connection. Accessing the channel in a simultaneous fashion permits a reduction in the time elapsed between the beginning of consecutive requests.

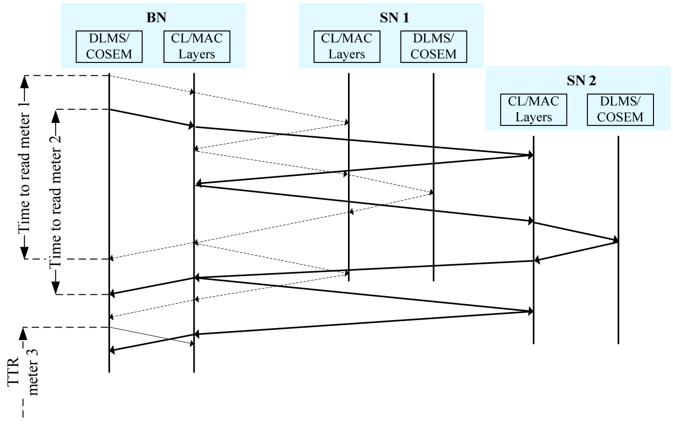

Fig. 5. Data request dialog in simultaneous polling (K=2).

Fig. 6 extends this idea to a number of K simultaneous connections and 4 nodes. In Fig. 6(a), K is equal to 1 (which is equivalent to sequential polling), and each node has to wait until the BN closes the previous connection. In Fig. 6(b) and 6(c), the TTR all meters is shorter, with a value of K equal to 2 and 3, respectively. Finally, Fig. 6(d) shows a different TTR all meters period with a K equal to 4. It is worth highlighting the variation of the periods of time depending on the value of K. On the one hand, larger values of K cause the TTR each meter to increase, due to the concurrent access to the channel. On the other hand, the time elapsed between consecutive requests is reduced as K grows up.

In the light of Fig. 6, managing simultaneous connections appears to be a good option in terms of TTR all meters. Nevertheless, increasing the number of simultaneous connections may cause longer latencies, because of the use of more concurrent control traffic that will enlarge the access time (as defined in (1)) for each node. Hence, it seems reasonable to assume that there has to be a value of K that offers a good balance between latency and connection overlapping, with an optimum occupancy of the channel.

V. Effect of the Position of the Switch Nodes

In addition to the effect previously described, the logical topology of the network also affects its performance. This effect was introduced in [10] and more deeply studied in [20].

In this work, the analysis of the effect of the position of the switch nodes in the network is broaden with the use of TTR all meters as performance metric, as well as the time that each message is retained in the transmission queue of each node (t_{access}).

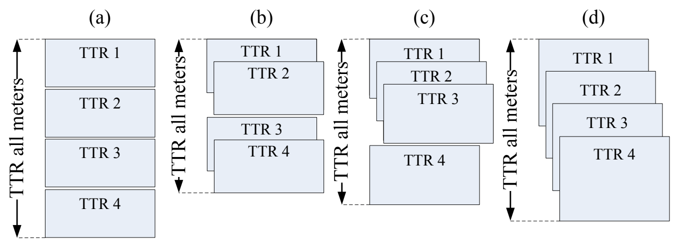

Fig. 6. Schematic representation of the TTR all meters with K = 1, 2, 3 and 4; respectively in (a), (b), (c) and (d).

Following the structure of Fig. 4, Fig. 7 represents a data request dialog between BN and a SN registered through a SW. In this case, the application layer of the SW node has been removed for clarity. The time required to read one meter when the service node is registered through a SW is given by (2).

$$\begin{aligned} TTR_{1\text{meter}} = {} & t_{\text{prim}} + t_{\text{access 1(BN)}} + t_{\text{CON}} + t_{\text{access 1(SW)}} + t_{\text{CON}} + t_{\text{access 1(SN)}} \\ & + t_{\text{CON}} + t_{\text{access 2(SW)}} + t_{\text{CON}} + t_{\text{access 2(BN)}} + t_{\text{DATA}} + t_{\text{access 3(SW)}} \\ & + t_{\text{DATA}} + 2 \cdot t_{\text{prim}} + t_{\text{access 2(SN)}} + t_{\text{DATA}} + t_{\text{access 4(SW)}} + t_{\text{DATA}} + t_{\text{prim}} \end{aligned} \quad (2)$$

The definitions for (1) are also applicable in (2). In this case, the time required for a message to be forwarded by the SW node ($t_{accessX(SW)}$) plays an important role in the equation, harming the total time required to read one meter, thus the whole network.

When a TN is registered through a SW, the latter is in charge of forwarding the traffic exchanged between the former and the BN. Hence, the number of messages transmitted by a node promoted to switch is significantly bigger than in the case of a regular SN. This entails that the time elapsed between the reception by the SW of a message to be forwarded and the beginning of the transmission of the forwarded message is also larger. This increment is proportional to the number of messages that have to be forwarded, and hence, in a regular polling cycle, proportional to the number of nodes that have to be registered through each switch.

In order to analyze the effects described in the previous sections, a set of simulations have been carried out.

VI. Case Study

A. Simulation framework

As mentioned, the study presented in this paper utilizes the simulation framework reported in [6] with the purpose of evaluating the performance of a PLC network. This tool has been briefly described in Section II of this work.

B. Simulation scenario

One of the main problems in the standardization of a global PLC solution for LV networks, along with the unpredictable behavior of the channel, is the topology of the distribution system.

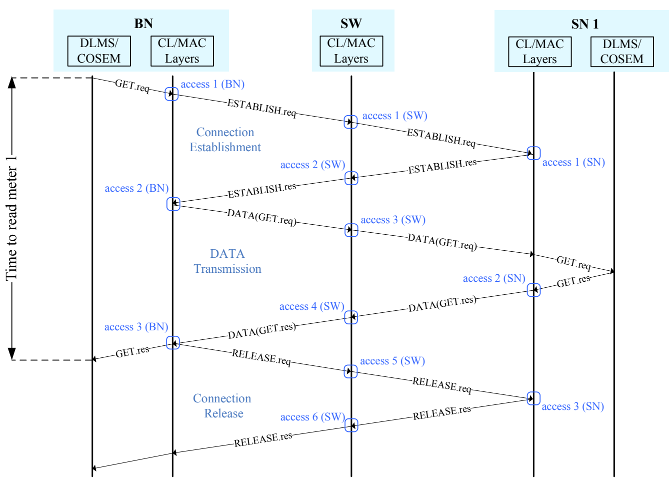

Fig. 7. Data request dialog between BN and a SN registered through a SW.

As assessed in [21], the topology varies from country to country, but several references coincide to point out that there are two main and differentiated schemas [22]. On the one hand, a European LV network typically presents a maximum length of 1000km, with up to 350 households connected to a single transformer station through a maximum of 10 branches. On the other hand, USA and Asian installations present a higher number of smaller transformers served by a MV distribution level, and each of those transformers supply a small number of cells with cable lengths in the order of 100m.

These dissimilarities produce important discrepancies in the suitability of the different PLC technologies. It is worth pointing out that in the work proposed in this paper, only European LV topologies will be considered.

When a simulation scenario is analyzed, it is important to make clear what the topology of said scenario is. Unfortunately, due to the high variability of possible configurations, the literature is very poor in this topic, and the majority of the studies present one single example in line with the typical European or US configurations, or present results of field measurements without detailing the exact configuration ([5], [16], [23]).

Based on [15], [22] and [24], a representative European LV PLC network has been selected for the simulations. This structure, schematically represented in Fig. 8, is formed by a main distribution line that interconnects several household PRIME meters with a Medium to Low Voltage (MV/LV) transformer station (TS), where the BN is located at.

The smart meters present in the network are distributed in different groups equivalent to meter rooms (MR) separated by electrical wiring. Hence, each meter room contains the same number of SN, and the attenuations between consecutive meter rooms are constant and equal to 15dB, compatible with the physical values given in [24]. These attenuations are large enough to make the promotion of two terminal nodes to switch necessary for the registration of all members of the network. In the simulations carried out, different topology patterns have been evaluated, with a total number of nodes of 50, 75, 100, 150 and 200, respectively.

As explained in [20], this physical topology can be configured into different logical structures, depending on the position of the switch nodes in the network. The mentioned study highlights the effect of this selection over the overall performance of the system.

Within this frame, there are two possible configurations that involve a different three-level logical tree structure depending whether the switches are placed in a meter room or another. Respectively, the scenarios 1 and 2 are defined by the position of the switches in meter rooms 2 and 4 and 1 and 3. The logical structure of each scenario is schematized in Fig. 9.

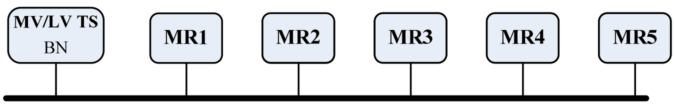

Fig. 8. Topology of the scenario simulated

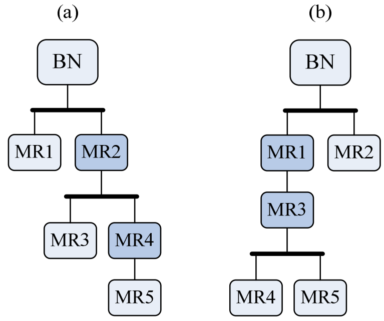

Fig. 9. Logical structure of the scenarios simulated. (a) Scenario 1 and (b) Scenario 2.

For each of these scenarios, a set of different maximum number of open connections (K) has been simulated, with values between 1 and 25. On each simulation, a complete polling cycle is repeated 100 times, and the average value of the time required to poll every node is recorded. A total of 50 simulations have been carried out for each case. The average availability for each node is over 99% in all the scenarios considered. It is also worth mentioning that only BPSK modulation has been utilized. Two variables have been analyzed: TTR 1 meter as noted in Fig. 4, Fig. 5 and Fig. 7; and TTR all meters in the network.

VII. Simulation Results

According to the scenarios described in Section VI, a set of simulations has been carried out in order to analyze the variations of the network performance in terms of time required to read all meters, according to the number of connections open simultaneously and the position of the switch nodes.

The results obtained are analyzed in the following subsections.

A. Effect of the number of maximum connections.

As explained, the effect of the number of simultaneously open connections has been analyzed via simulations.

The results are summarized in Fig. 10, Fig. 11 and Fig. 12. The abscissa axis corresponds to the maximum number of simultaneous connections (K), meanwhile the ordinate value represents the TTR measured in seconds. Each value represented in the charts corresponds to the average within the total number of simulations.

Fig. 10 contains two sets of data, corresponding to each of the scenarios described in Section VI (Fig. 9). This chart encompasses the values obtained as the average of the TTR one meter for all the data messages sent during the simulation. It can be observed that, as the value of the maximum number of connections is increased, the time required to read one single meter increases dramatically, in a direct relationship. It is also noticeable that the results obtained for Scenario 2 is worse than the case of Scenario 1 i.e., the time required to read is longer.

Fig. 11 and Fig. 12 show the values obtained as the average of the TTR all meters in the network. In both cases, there are 5 possible topological patterns, depending on the number of total nodes in the network; respectively, 50, 75, 100, 150 or 200 terminal nodes.

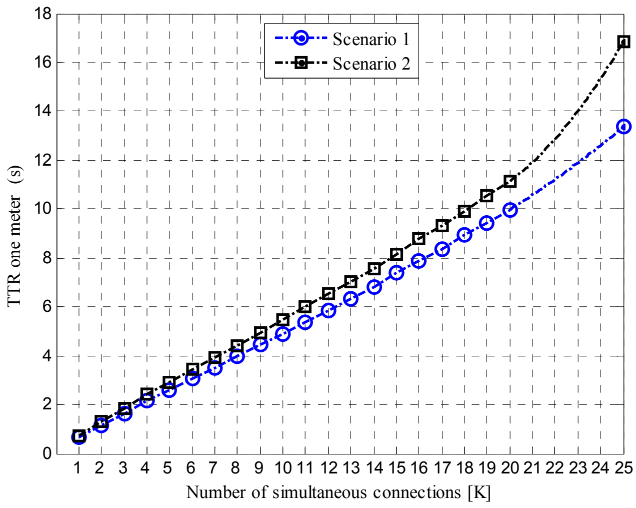

Fig. 10. Time To Read one meter.

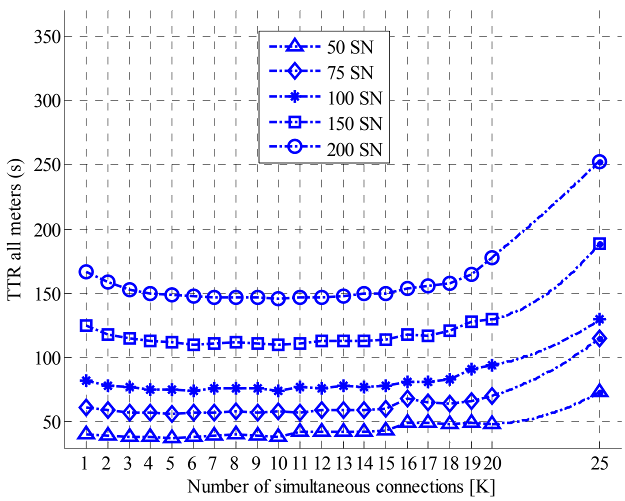

Fig. 11. Time To Read all meters (Scenario 1).

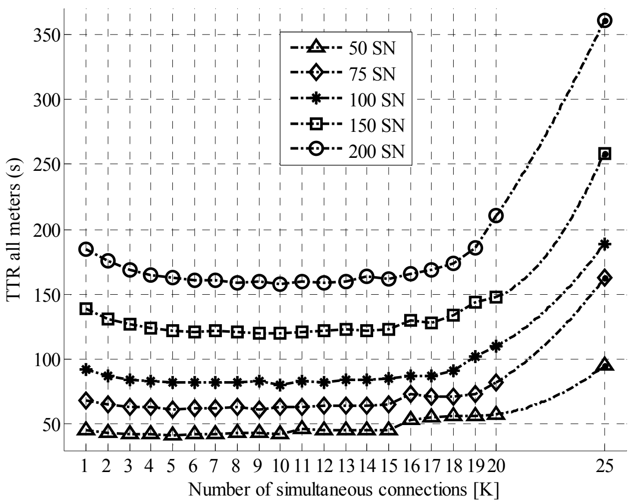

Fig. 12. Time To Read all meters (Scenario 2).

Looking at Fig. 10, it could be inferred that the performance of the network gets worse as the number of simultaneous connections increases. Nevertheless, the results shown in Fig. 11 and Fig. 12 lead to a different conclusion. As it can be seen, the values of the TTR all meters conform a bathtub curve, where the best values can be found between 5 and 10 maximum open connections. For values of K larger than 10, increasing the number of simultaneous connections enlarges also the time required to poll all the nodes.

Tables I and II provide numerical information based on the results shown in the figures. As it can be seen from Table I, the percentage improvement in the TTR all meters when using simultaneous polling with the best value, with respect to sequential polling is in the order of 10%. Moreover, this difference increases along with the number of nodes in the network, with a maximum value of 14% and 17% for Scenario 1 and 2, respectively.

The percentage deviation between the TTR all meters in the range of the recommended maximum number of simultaneous connections (K between 5 and 10), is shown in Table II. As it can be seen, this difference is smaller than 5% except in the case of 50SN for Scenario 1.

These results are in line with what was concluded in Section IV of this work. It can be seen that there is a trade-off between the increase in the time required to read one single meter, caused by an increment of the control traffic in the common transmission channel, and a reduction in the time between consecutive requests, which decreases as the value of K grows up, as explained in previous Sections of this paper.

In addition to the graphical analysis, the results collected have been analyzed statistically. Thus, the correlation coefficients between the TTR obtained and the variables that define the topological features of the scenarios have been computed. In order to eliminate the distortion caused by the variable size of the network, the TTR all meters has been normalized, dividing by the number of nodes. Table III and IV contain these data, which have been obtained independently for each scenario.

TABLE I. IMPROVEMENT IN TTR ALL METERS (%) WITH RESPECT TO SEQUENTIAL POLLING (K=1).

	Scenario 1	Scenario 2
200 SN	14.68	17.10
150 SN	12.98	16.16
100 SN	10.98	13.81
75 SN	9.36	10.81
50 SN	8.31	9.31

TABLE II. DEVIATION IN TTR ALL METERS (%) IN THE INTERVAL K=[5,10].

	Scenario 1	Scenario 2
200 SN	1,89	2,81
150 SN	1,26	2,37
100 SN	2,23	2,53
75 SN	4,29	2,69
50 SN	7,43	4,95

TABLE III. CORRELATION MATRIX. SCENARIO 1

	K	numNodes	TTR 1 meter	TTR all meters (Normalized)	Taccess SW2 (Normalized)
K	1	0	0.97	0.62	0.70
numNodes	0	1	-0.02	0.23	0.09
TTR 1 meter	0.97	-0.02	1	0.75	0.69
TTR all meters (Normalized)	0.62	-0.23	0.75	1	0.57
T_{access} SW2 (Normalized)	0.70	0.09	0.69	0.57	1

TABLE IV. CORRELATION MATRIX. SCENARIO 2

	K	numNodes	TTR 1 meter	TTR all meters (Normalized)	Taccess SW2 (Normalized)
K	1	0	0.93	0.58	0.87
numNodes	0	1	-0.03	-0.14	-0.28
TTR 1 meter	0.93	-0.03	1	0.80	0.85
TTR all meters (Normalized)	0.58	-0.14	0.80	1	0.73
T_{access} SW2 (Normalized)	0.87	-0.28	0.85	0.73	1

As can be seen from the data obtained for both scenarios, there is a strong direct relationship between the value of K and TTR 1 meter. This relationship is graphically represented in Fig. 10. The TTR all meters divided by the number of nodes in the network is also influenced directly by the value of K. Additionally, it can be inferred that none of this TTR is influenced by the size of the network since the correlation coefficient with the number of nodes is very low. These conclusions confirm the dependency between the performance of the network in terms of TTR all meters and the number of maximum open connections.

B. Effect of the position of the SW node.

Along with the effect of the simultaneous connections over the overall performance of the system, the effect of the logical structure can also be appreciated in Fig. 10, Fig. 11 and Fig. 12. As can be seen from the figures, the values of TTR obtained in the case of Scenario 2 are worse than the values obtained for Scenario 1 when the same K is utilized, i.e. the latencies are longer. Table V summarizes this comparative for the interval K=[1,20]. The data presented highlights that the minimum difference is around 5%, with a maximum of 18%, always positive with respect to Scenario 2.

As it was studied in Section V of this paper, the time required to read a meter registered through a switch node is related to the number of messages that the switch has to forward, which presents a direct relationship with the number of nodes registered through it. Taking a look at Fig. 9, it can be observed that the number of nodes registered through SW2 (the switch node in the second logical level, located in MR4 for Scenario 1 and in MR3 for Scenario 2) differs between Scenario 1 and 2. Hence, the time required for a message to be queued before being transmitted by SW2 is analyzed in Fig. 13 and Fig. 14.

TABLE V. MINIMUM AND MAXIMUM DIFFERENCE IN TTR ALL METERS (%) BETWEEN SCENARIO 1 AND 2.

	Minimum	Maximum
200 SN	7,74	18,03
150 SN	7,89	13,72
100 SN	7,01	17,11
75 SN	7,17	16,68
50 SN	4,79	18,71

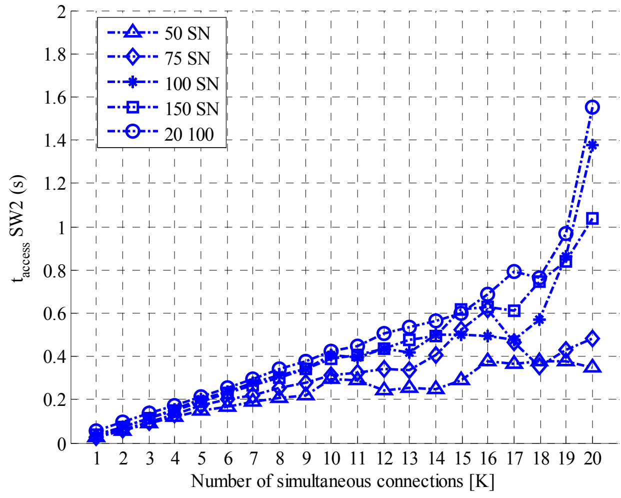

Fig. 13. t_{access} for SW2 (Scenario 1).

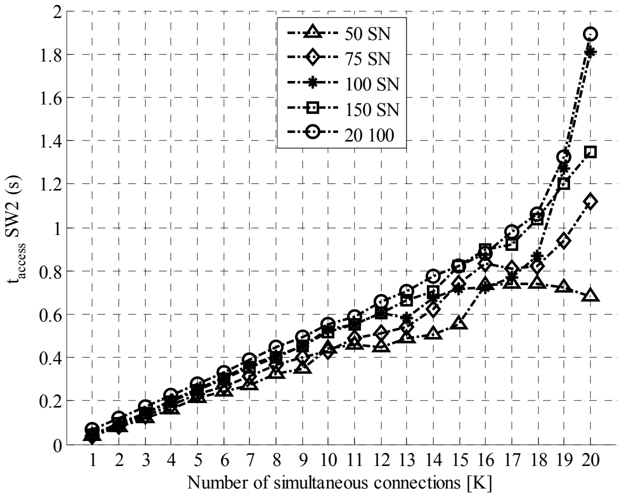

Fig. 14. t_{access} for SW2 (Scenario 2).

Taking a look at the waiting times represented in the figures, it can be observed that the values in the case of the simulations carried out with the topology of Scenario 2 (Fig. 14) exceed the values corresponding to Scenario 1 (Fig. 13). The minimum and maximum percentage difference of these data is summarized in Table VI. It is worth noting that the minimum difference between these values is always larger than 22%.

This relation is consistent with the fact that the number of nodes that are registered through the second level SW are 20% of the total meters in the network in the case of Scenario 1, and 40% in the case of Scenario 2.

TABLE VI. MINIMUM AND MAXIMUM DIFFERENCE IN T_{ACCESS}*SW2* (%) BETWEEN SCENARIO 1 AND 2.

	Minimum	Maximum
200 SN	22,13	38,53
150 SN	26,52	50,46
100 SN	26,52	61,10
75 SN	34,51	131,65
50 SN	36,48	103,93

Additionally, Table III and Table IV show the correlation coefficients of the $t_{access(SW2)}$ with respect to the output metrics. Again, this variable has been normalized in order to prevent the distortion caused by the number of nodes in the network. As it can be seen from the tables, there is a direct relationship in both scenarios between the TTR all meters and the time required for a message to be forwarded, which in turn is affected by the value of K.

VIII. CONCLUSIONS

The contribution of this paper is twofold. On the one hand, the work presented analyzes the impact of the polling strategy utilized in an auto meter reading process in a PRIME PLC network, which is of interest for the industry. On the other hand, the effect of the logical structure of the network established by the position of the switches is studied. These two aspects fulfill a gap left open in PRIME standard. The time required to read all meters is used as a metric of the performance of the network. A typical PLC LV European network in line with industry test scenarios has been simulated with OMNeT++ and Matlab.

The simulations confirm that the selection of a number of maximum simultaneous connections has an impact over the performance of the network when using simultaneous polling. Indeed, there is a trade-off between the latency of the messages exchanged between nodes and the time elapsed between consecutive requests. The former increases as the number of simultaneous connections grow up, due to the concurrent access to the channel. The latter is reduced as the number of simultaneous connections is enlarged. Additionally, the effect of the position of the switches over the system performance is also confirmed, and the scenario with more nodes in the last level of the logical structure is identified as the less favorable.

Furthermore, from the simulations carried out, a recommended number of simultaneous connections can be extracted. Independently of the number of nodes in the network, the performance of the system is enhanced with values between 5 and 10 simultaneously open connections.

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