Broadband PLC for Smart Grid Applications in LV Grid

Bandwidth extension for NB-PLC technologies

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Abstract— **Although there is no one single internationally recognized smart grid architecture, it is widely accepted that smart metering applications in the low voltage (LV) grid are provided by either PLC or radio technologies. In the case of narrowband PLC, several technologies are available in the market, all of them providing bandwidths between several kbps and tens of kbps. For the applications required up to now, this is enough; however, looking for the future needs of the smart grid, an increase in the bandwidth will be needed in certain scenarios.**

The objective of this paper is to demonstrate the possibility of extending the bandwidth in the LV part of the grid, through the combination of Broadband PLC (BPL) and narrowband PLC (NB-PLC) technologies, generating several advantages such as the increase of the performance for metering, protecting already made investments, and the introduction of additional smart grid applications in the LV grid, such as distribution automation, distributed energy resources (DER) integration and grid sensing.

Keywords- BPL; PLC; PRIME; Smart Grid; metering; LV distribution automation

I. INTRODUCTION

BPL (Broadband Power Line) refers to a set of broadband power line communications (PLC) technologies developed for different applications, such as in-home networking, grid automation, etc. In particular, the OPERA project (in its second phase) [1] investigated the way to apply BPL in the electrical grid to provide services for distribution system operators (DSO), developing an open protocol stack (Physical and MAC layer) and chipsets proven to be valid for the electrical grid. Based on this open technology, several manufacturers developed devices able to provide bandwidths of up to 100 Mbps.

These devices, extensively proven in MV applications [2], are now projecting their use into the LV part of the distribution grid, when the increasing need of bandwidth of the coming smart grid applications reach the limits of narrowband solutions in certain scenarios. For example, in secondary substations with high number of points of supply, in the order of a thousand, relatively common in urban areas across Europe, a unique NB-PLC subnetwork is created, formed by one thousand nodes. Such big networks are already a challenge for a NB-PLC technology and introducing additional services apart from metering becomes virtually impossible.

This paper will analyze the benefits of introducing BPL in the LV grid, through a progressive deployment, taking advantage of the already made investments in smart metering (e.g. recently made AMI deployments based in NB-PLC technologies) and focusing in other smart grid applications such as distribution automation. For such analysis, a test bench simulating a real LV grid will be used, performing several tests to compare results with different combinations (scenarios) of the use of NB-PLC and BPL.

The content of this paper is organized in different sections. Section II provides an overview of the test bench used for the tests and Section III explains the different scenarios tested in this facility. Section IV covers the detailed results, demonstrating the bandwidth increase obtained in metering, while section V shows the possibility to introduce additional smart grid services, such as distribution automation, over the same telecommunications network, utilizing also cybersecurity feature set of BPL system. Finally, section VI summarizes the conclusions derived from the results observed and gives recommendations on the way to apply this solution in the real field.

II. TEST BENCH

The test scenarios described in section III were performed in a laboratory which reproduces a LV segment of a representative distribution grid.

This "*Interoperability Test Platform*" [3] is placed in ITE ("*Instituto Tecnológico de la Energía*"), and is used to test different PLC technologies in a variety of LV scenarios, such as rural, urban, semi-urban, etc. In this facility different configurations can be selected, depending on the number of meter rooms or cabinets, the number of meters in each of these rooms and the distance among them and the power substation. Apart from this, artificial attenuations and electromagnetic disturbances can also be introduces in any part of the grid, simulating those two real-field commonly found phenomena.

This installation is normally used to validate PLC technologies simulating real field conditions, as well as to improve the implementations of these technologies to perform better in these conditions. The complete test bench allows the installation of up to 352 points of supply, distributed in 16 meter rooms connected to 2 different LV lines, being 2 kilometers of real cable the longest distance from the secondary substation.

For smart metering tests, the platform is also equipped with a Data Concentrator (DC) and PLC sniffers in each meter room to collect all the information needed to completely understand the data flow and explain the results.

With these characteristics, the facility allows defining controlled, repeatable and automated scenarios in order to check the effects of combining BPL with NB-PLC. With this purpose, BPL devices are installed in different points of the facility to analyze its effects.

Regarding the technologies used for the tests, the NB-PLC technology is ITU-T G.9904, also known as PRIME [4], which is an OFDM technology with several modulation schemes. It defines up to 8 different channels from 42 to 488 kHz, each of them with 96 carriers. In this particular case, the first channel (in CENELEC-A band) has been used.

For the BPL technology, a system based on ITU-T G.9960 [5] baseband frequency range has been used. It transmits symbols over 1,500 carriers, between 2 and 30 MHz, adaptively modulated in predefined channels, using channel estimation and Forward Error Correction. As a result, it creates robust OSI Layer 2 transparent communication channel that provides advanced dynamic TDMA and manageable IP-based communication platform for various services, with the possibility to isolate and prioritize them, as well as to support cybersecurity features.

III. TEST SCENARIOS

Several scenarios are proposed to compare the performance and the bandwidth increase obtained combining BPL and NB-PLC, as well as the possibility to simultaneously provide several smart grid services over the same multiservice telecommunication infrastructure.

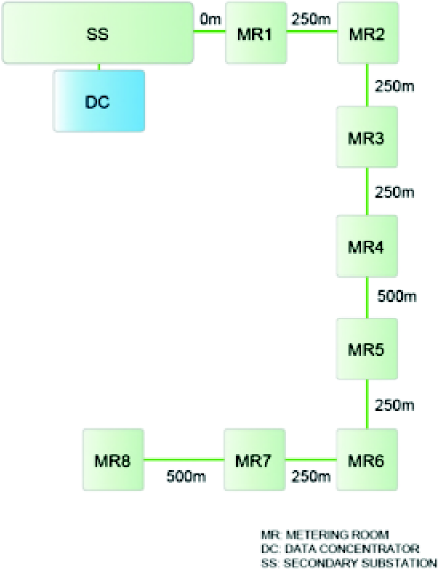

Figure 1. Base Scenario

First of all, a base scenario was tested. It is NB-PLC based and it is needed as a benchmark for the comparison with the scenarios including BPL. The configuration (see Figure 1) includes a DC, integrating a PRIME Base Node. It is located in the Secondary Substation (SS), and all the meters in the different metering rooms are connected to this Base Node using PRIME. With this configuration, all the meters are integrating a single PRIME subnetwork and thus, they are all sharing the bandwidth provided by this technology.

Following this base scenario, BPL in the LV Network was introduced, coexisting with PRIME. For all the scenarios, the BPL system built over the test bench is comprised of a single master unit capacitive coupled at the SS and several units acting as repeaters placed at three selected metering rooms. Additionally, two end-point devices were connected to simulate DER/LVA applications. Figure 2 shows a diagram of this overlaid BPL network, where:

- LAB1 is the master BPL device.
- LAB2, LAB3 and LAB4 are configured as BPL repeaters, even when LAB4 is not acting as such.
- EP1 and EP2 are end-point BPL devices.

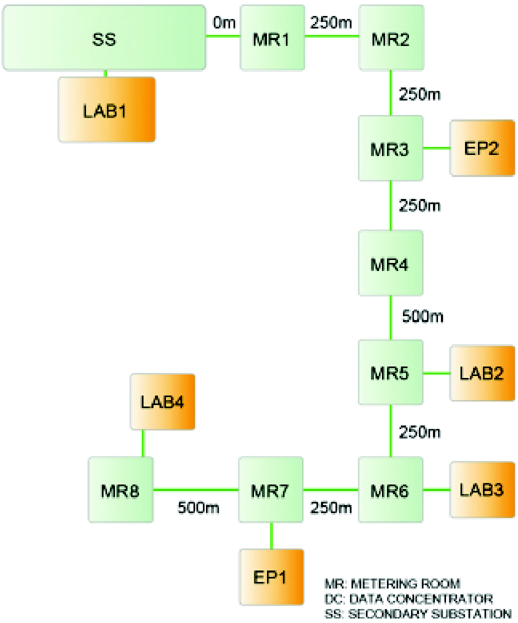

Figure 2. BPL System

The performance of this BPL network was evaluated before the main tests were conducted with the results shown in Table I. The application level testing performed, using IPERF3 for its IPv6 features, showed that the bottleneck of the first hop between LAB1 and LAB2 (substation and MR5, 1.5 km distance), limits the maximum achievable throughput to 15Mbps at IP level, while providing 0% packet loss and a RTT of 10 milliseconds maximum. These results were confirmed in both secured and non-secured configurations of BPL devices.

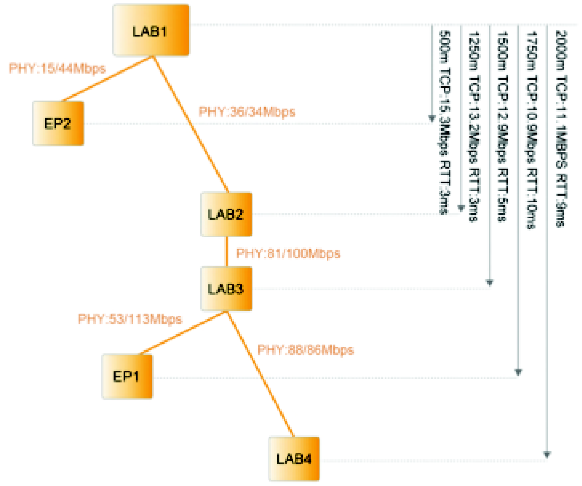

Figure 3. BPL Network topology with results

The reason for this limited bandwidth, in comparison with the maximum available in the technology, around 100 Mbps, was found to be the characteristics of the channel, with high attenuation and low CFR in the highest part of the spectrum and an average SNR of 19.4dB (see Figure 4).

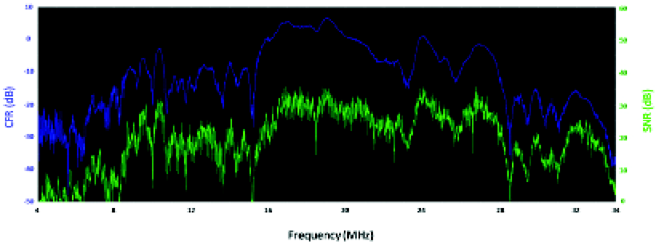

Figure 4. SNR and CFR of the channel between SS and MR5

For each Scenario, the metering application performance was tested, simulating meter readings, which is the main operation required in any smart metering project. Long cycles request (continuous requests of 13 values of the hourly load profile) were executed from the DC to the meters. For this operation, success rate and average time are compared in section IV.

Four different scenarios were tested:

- Scenario A (see Figure 5): A DC is placed at the SS, but it is connected through BPL with a PRIME Base Node installed in MR8. This base node connects with the 20 meters of this room using PRIME, while the base node integrated in the DC connects with the rest of the meters. The DC installed in the substation manages the remote base node through a TCP/IP based protocol [6] over BPL.
- Scenario B (see Figure 6): It is similar to scenario A, but replacing the base node in MR8 by a DC. This DC connects through PRIME with the 20 meters of this room and performs metering operations for these meters, while the main DC manages the rest of the meters. The DC installed in MR8 connects directly with the Meter Data Management System (MDMS) through a TCP/IP based protocol over BPL.

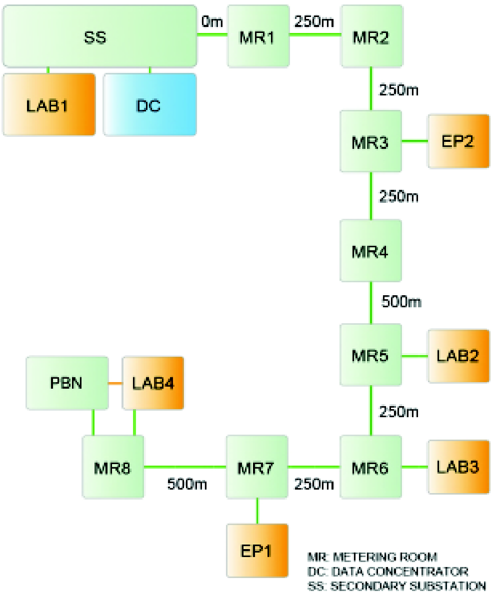

Figure 5. Scenario A

- Scenario C (see Figure 7): in order to use the extra bandwidth of the BPL network for additional services, based in Scenario B, two devices connected to EP2 and LAB2 were added to the scheme, simulating LV distribution automation devices based on IEC 60870-5-104 [7] protocol. The objective of this test was to demonstrate no effects in the metering application while using BPL for additional Smart Grids applications.

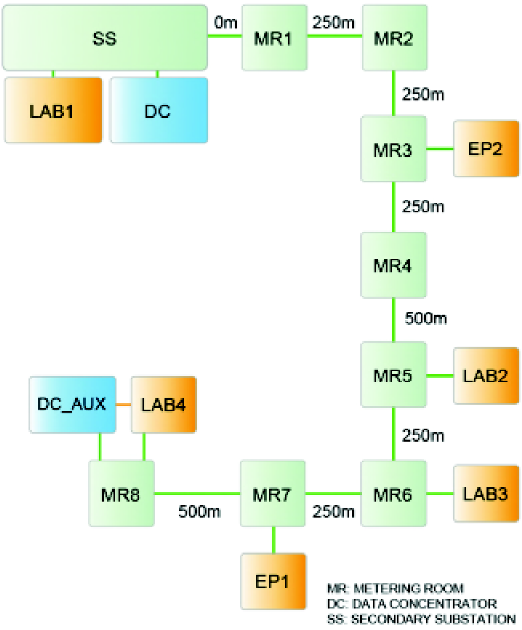

Figure 6. Scenario B

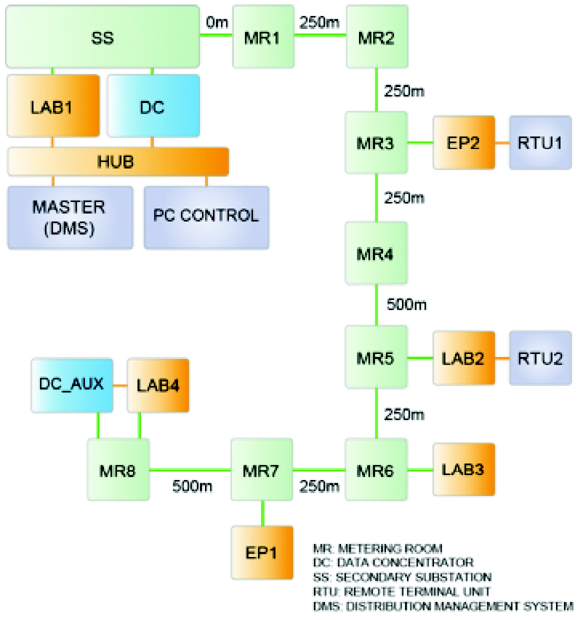

Figure 7. Scenario C

- Scenario D: same as scenario C (see Figure 7), introducing cybersecurity features in the BPL devices, that implement hardware-based security to protect the telecommunications infrastructure and ensure its secure management. The core features introduced were AES128 CBC encryption of the BPL channel, as recommended mode of encryption over public channels [8], VLANs for management and service traffic isolation, RADIUS authentication of the connecting nodes to ensure only authorized access to the resources, IPv6 with SLAAC communication of management traffic, SSH and SNMPv3 for secure manageability of the nodes using both authorization and encryption as per RFC3413 [9].

IV. METERING RESULTS

Performance results presented in this paper make use of indicators from two different perspectives [9]. First, the telecommunications availability of each meter (service node in PRIME) is used to analyze the network stability. This availability is provided by the base node, which registers any change occurred in the topology of the grid. Second, meter readings success is checked through the execution of reading cycles, requesting 13 values of the hourly load profile to every meter in the subnetwork [2].

In all the scenarios, two independent PRIME subnetworks are created, reducing the size of both. As a consequence, PRIME bandwidth is shared by a smaller number of meters and the topology (number of switches and switching levels) of the network is simpler. In particular, the network created by the remote base node in MR8, which consists of twenty nodes.

In Scenario A, the metering requests to the meters in MR8 and the rest of the meters are managed by the main DC. As these requests are not performed in parallel, but sequentially meter by meter, the time to perform one cycle is similar in Scenario A than in the base scenario. Only 3% time reduction is obtained (see Table II). In Scenario B, as each DC manages its requests independently and the auxiliary DC only has to read 20 meters, it reduces the time per cycle up to 96%, being able to execute thirty times more cycles to the twenty meters in its network.

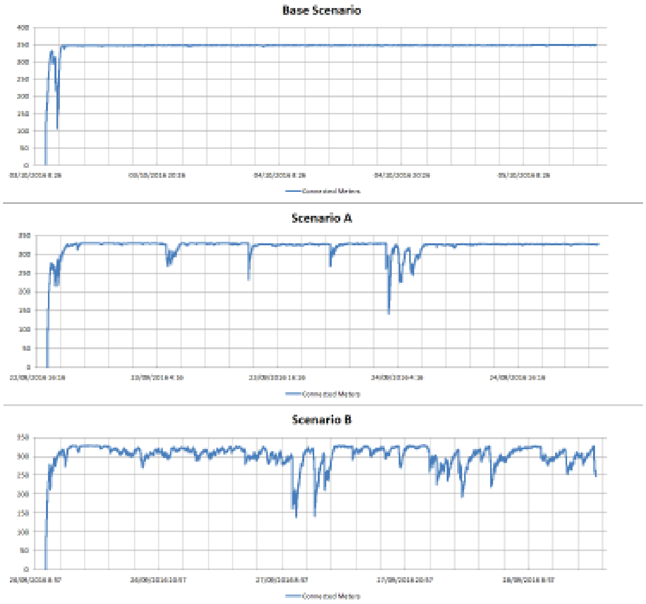

Figure 8. Topology stability comparison

However, in both Scenarios, the stability of the subnetworks is not optimal, as it is shown in Figure 8, where the graphs represent the number of nodes connected to the main PRIME subnetwork along the time for each scenario. X axis represents the date (each graph contains data from two days) and Y axis is the number of nodes. Scenario A presents several events in which some devices, from some tens of them to more than one hundred, disconnect from the subnetwork and connect again later, reducing the overall stability. Scenario B shows even lower stability, with several devices, more than one hundred in some cases, connecting and disconnecting during the whole test and not only in particular moments. Due to the reduced stability of these scenarios, the cycles' success rate (see Table II) is lower in Scenario A than in base scenario and even lower in Scenario B.

The reason for this behavior is that both PRIME subnetworks created, independently managed by each base node, share most of the physical layer, generating collisions among them. This is due to the particular characteristics of the LV grid of the laboratory, which is a single line without branches, virtually a single communication domain. The effect mainly affects the metering rooms close to 8A (from 4 to 8), as it is shown in Table III. The situation in Scenario B is more unstable compared to Scenario A, as each data concentrator is executing cycles without coordination with the other and thus, there is more simultaneous traffic (metering traffic, and not only control traffic as in Scenario A) and more collisions. To check this hypothesis, the tests were repeated disabling the cycles in the main concentrator, obtaining the results in Table II, Scenario B', where the success rate for the meters in MR8 improves four points, closer to Scenario A.

TABLE I. CYCLES RESULTS COMPARISON

Scenario	***Success Rate***		***Average Time per cycle for all meters (seconds)***		***Number of cycles***	
	Main Subnet	***Auxiliary Subnet***	***Main Subnet***	***Auxiliary Subnet***	***Main Subnet***	***Auxiliary Subnet***
Base	97.62%		8,391.33		21	
A	90.74%	97.05%	8,160.59		22	
B	73.22%	90.31%	8,356.76	266.95	21	648
B’	-	94.36%	-	239.71	-	726
C	75.85%	88.19%	8,979.85	258.01	20	670

TABLE II. PRIME TOPOLOGY AVAILABILITY COMPARISON

	Base	***A***	***B***	***C***
MR1	100.00%	100.00%	99.99%	100.00%
MR2	99.99%	99.98%	99.99%	100.00%
MR3	99.03%	99.14%	99.13%	99.86%
MR4	99.58%	99.19%	97.60%	99.28%
MR5	97.41%	98.06%	92.58%	95.54%
MR6	99.39%	96.78%	89.11%	91.12%
MR7	99.20%	93.05%	79.99%	77.15%
MR8	98.97%	90.56%	75.34%	75.16%

V. LV AUTOMATION

This section describes the results of the test involving both smart metering and LV automation applications, sharing the bandwidth of the BPL link at the same time. To simulate LV automation, an IEC-60870-5-104 [7] traffic simulator has been used, in order to reproduce the typical pattern of this kind of applications. One laptop running the server was connected to the substation, while two laptops running remote units simulating LV RTU were connected in MR2 and MR5 respectively. Each RTU was configured with four digital inputs which are sent to the server every 20 seconds.

The results confirm that, as the bandwidth provided by the BPL is high enough, the applications are not exhausting the channel and the performance of metering (see Figure 9 and Tables I and II) is not affected by the introduction of the LV automation and vice versa.

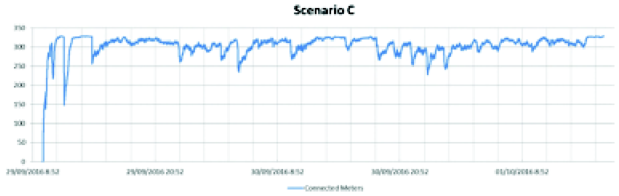

Figure 9. Scenario C: Topology Evolution

The test were repeated enabling the cybersecurity at BPL link level, as explained in section II, scenario D. Results are exactly the same, both for the LV automation and for the metering, demonstrating that the inclusion of cybersecurity features has no impact in the performance of the applications running over the BPL link.

VI. CONCLUSIONS

This paper demonstrates how it is possible to extend the bandwidth of a NB-PLC technology installed in the LV section of the grid, through the use of BPL. The combination of PRIME and the high performance IP-based communication channel created by BPL, ensure scalability in terms of bandwidth, both for Smart Metering and for additional smart grid applications in the LV network, such as LV distribution automation, integration of DER and grid-sensing. As it has been demonstrated, installing additional DC connected to the MDMS through BPL creates several NB-PLC subnetworks of small size and allows each concentrator to perform more operations in the same time. In the case of the load profile readings tested, the operation is performed more than thirty times faster.

However, to obtain this increase of bandwidth without impacting the stability, the installation of additional base nodes or DC should be made taking care of the places where they are installed, respecting the communication domains isolation and trying to avoid collisions among the different NB-PLC subnetworks created. As a general rule, connecting these additional devices separated from each other on different LV feeder of the same transformer should be enough to reduce the collisions and obtain the gain of bandwidth demonstrated in this paper keeping the topology stability.

REFERENCES

[1] J. Simon, P. Sancho, M. Martínez and L.M. Torres “White paper: OPERA Technology”, 2007

[2] A. Sendin, I. Urrutia, J. Simon, I. Berganza and M. Sanchez-Fornie “Smart Grid in Iberdrola: Architecture, Results and Discussion,” IEEE International Conference on Smart Grid Communications (SmartGridComm), Venice, Italy, Nov. 3-6, 2014.

[3] J. Fernández, A. Sendín, A. Soria, M.L. Soriano and I. Urrutia “Communications Benchmark and Interoperability Test Platform for Smart Meters”, 13th Spanish-Portuguese Conference on Electrical Engineering (XIII CHLIE) Valencia (Spain), 3rd to 5th July, 2013

[4] http://www.prime-alliance.org/

[5] ITU-T G.9960 (2015) Unified high-speed wireline-based home networking transceivers - System architecture and physical layer specification.

[6] http://prime-members.org/public/index.php?path_info=projects%2F26%2Ftickets%2F67

[7] IEC 60870-5-104:2006 Telecontrol equipment and systems – Part 5-104: Transmission protocols – Network access for IEC 60870-5-101 using standard transport profiles.

[8] ENISA (2012) The use of cryptographic techniques in Europe. Source: http://www.enisa.europa.eu/activities/identity-and-trust/library/the-use-of-cryptographic-techniques-in-europe

[9] IEFT RFC3413 https://www.ietf.org/rfc/rfc3411.txt

[10] A. Fernandez, A. Sendin, I. Urrutia, J. Mateo, P. Angueira and JJ. Ferro “Analysis of PRIME PLC Smart Metering Networks Performance”, International Conference on Renewable Energies and Power Quality (ICREPQ’13) Bilbao (Spain), 20th to 22th March, 2013