

Analysis and Preparation of the Deployment of PRIME 1.4 Smart Meters in an Interoperable Field Environment for 15,000 Meters

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Abstract— Narrowband Power Line Communications (NB-PLC) is one of the preferred solutions used by utilities for smart metering applications, being PRIME (PowerLine Intelligent Metering Evolution) the technology standard implemented by Iberdrola in its low voltage grid. The latest version of the protocol, PRIME v1.4, includes many additional features at both PHY and MAC layers which will enable the development of future Smart Grid (SG) services and applications.

This paper presents the strategy followed to structure Iberdrola's first massive PRIME v1.4 smart meter deployment, including the methodology applied, the made analysis and the main results obtained in the process.

Keywords—Deployment strategy, PLC, PRIME v1.4, Secondary substation, Smart Grid, Smart meters.

I. INTRODUCTION

Smart metering deployments are considered as one of the foundations for the development of the Smart Grid (SG), enhancing the operation and supervision capabilities of the low voltage (LV) grid.

Among the different existing telecommunication technologies, Narrowband Power Line Communication (NB-PLC) is one of the most popular for smart metering due to its cost effectiveness, having reasonable installation, operation and maintenance costs. PRIME (PowerLine Intelligent Metering Evolution) is the ITU-T G.9904 standard [1] developed within the PRIME Alliance [2] and currently deployed in Iberdrola's LV grid.

PRIME connects the concentrator, located at the secondary substation (SS), and the smart meters, located at the customers' homes, enabling two-way communications between the central systems of the utility and the smart meters (Fig. 1).

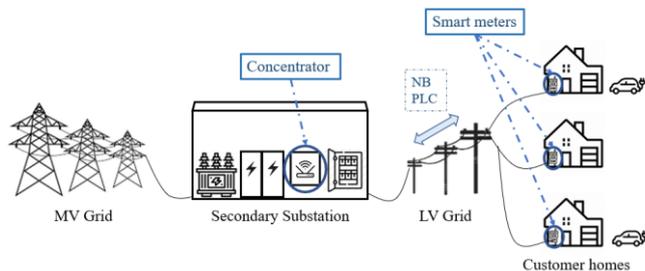


Fig. 1. NB-PLC in the LV power grid

During the last decade, Iberdrola has extensively and successfully deployed PRIME v1.3.6 in the Spanish LV grid. Nonetheless, the necessity to improve the current capabilities

to support the new SG services and applications has led to the development of PRIME v1.4 [3]. The latest version of the standard includes many improvements, being the increase of bandwidth from 3-95 kHz to 3-500 kHz, providing flexibility and increased throughput, and the addition of new robust modes to increase reliability the most relevant ones [4].

When facing a smart meter deployment, even if they are not unusual at all, a lot of uncertainty is faced due to the lack of literature and guidelines applicable to all or most cases. The reasons for this reality are mainly related to the difficult access to real grids by academics, the lack of data available to the public and the heterogeneity of the electric power grid, two equal grids not existing anywhere in the world. Besides, on contrary to any other telecommunication technology deployment, the location of the equipment is already predetermined, as the smart meters must be located at the customers premises and the concentrators at the SSs, not being those the optimal places in most cases [5].

Consequently, ex-ante planning efforts are almost worthless for PLC deployments, and thus the strategy traditionally followed by Iberdrola for its deployments is a post-deployment monitoring of the PLC performance and analysis of the obtained results to solve the issues present [5]-[7].

II. PRIME TECHNOLOGY

Basic knowledge about the functioning of the PRIME MAC layer is essential to fully understand the project.

Firstly, PRIME is a hierarchical tree-like structure with two types of nodes [3]:

- **Base Node (BN):** It is the master node that manages the PRIME subnetwork. There is a single BN per subnetwork, one per SS, and it is responsible of managing the resources and connections. The concentrator acts as the BN and it is the root of the tree.
- **Service Node (SN):** They are the remaining elements of the subnetwork. The smart meters register into the PRIME subnetwork to become SNs by communicating with the BN and getting permission.

Secondly, the SNs can have three different functional states (Fig. 2), which change automatically during operation depending on the conditions [3]:

- **Disconnected:** While on this state, the smart meter cannot transmit data to the BN and its only goal is to search for a PRIME subnetwork and register on it.

- **Terminal:** It is the most common state, which allows the SN to establish new connections and transmit data to the BN.
- **Switch:** It is the most complex state and it behaves as a terminal but with the additional ability to switch data from other terminals to the BN. This state allows some terminals to switch data so that the SNs that otherwise cannot communicate with the BN can register in the subnetwork. For a terminal to become a switch, it must ask the BN for a promotion, once an isolated SN that cannot register has requested a switch.

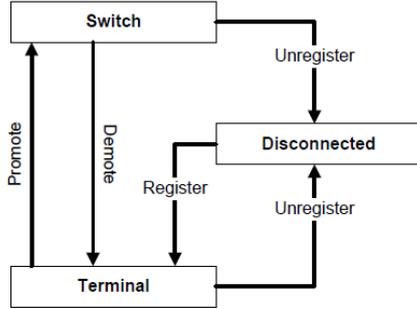


Fig. 2. PRIME service node states

Finally, it is worth remarking that PRIME is a plug-and-play technology, and once deployed the topological relations between the BN and the SNs are automatically configured in the most optimal way. Besides, this topology changes dynamically during operation with the objective of always having as many SNs connected as possible.

Fig. 3 displays an example of a PRIME topology, where its tree-like structural nature can be easily observed:

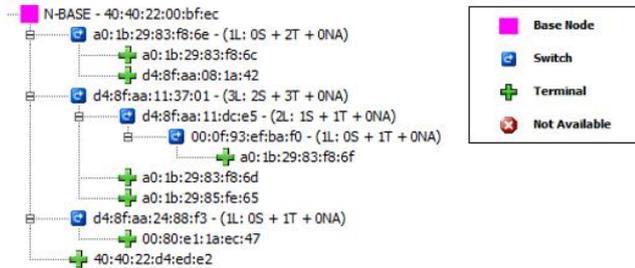


Fig. 3. PRIME subnetwork topology

III. PROJECT DEFINITION

This project faces the task of structuring Iberdrola’s first massive PRIME v.1.4 deployment, improving the methodology developed by Iberdrola for its previous deployments [6] and adapting it to the newest version of PRIME.

The main motivation is the interest of the utility to perform its first massive PRIME v.1.4 deployment successfully, guaranteeing a smooth transition from PRIME v.1.3.6, achieving improved performance as soon as possible. Besides, the advantage of having PRIME v.1.3.6 already deployed on the field, allowing the analysis of the current performance of the SSs and not planning the deployment blindly is present.

Three Spanish municipalities, which will be referred as North, Central and East (Fig. 4), have been selected for the deployment due to their appropriate characteristics for this first on the field “test bed”.



Fig. 4. First PRIME v.1.4 deployment municipalities

IV. PROJECT DEVELOPMENT

Five different project stages can be distinguished, presented in chronological order:

A. Grid topology study

A thorough research of the electric topology of the SSs was performed. The data is available in the utility’s databases and the difficulty lies in finding the useful one.

From hundreds of variables, a selection of 29 was done, i.e. the number of customers, the contracted power, the feeder length, etc. Afterwards, a statistical analysis was done to see the differences between municipalities and the correlation between variables was also studied.

Finally, three variables were selected to create a first draft classification of SSs with similar topological characteristics and thus probably similar PLC behaviour. A simple PLC performance variable that can be directly downloaded from the databases, the average daily meter reading success, was used to check the validity of the groups formed with this first classification.

B. Power Line Communications performance monitoring

A complete monitoring of the 159 SSs was performed to understand their current PRIME v.1.3.6 performance. The results are essential to serve as a benchmark when PRIME v.1.4 is deployed, comparing the performance results, and to structure the deployment stages, identifying the easiest and most difficult SSs.

The monitoring methodology had been previously developed by Iberdrola [6], but the required tools were outdated, and they had to be adapted and tested until they functioned correctly. Monitoring a single SSs is a tedious process which consists of 10 tasks and takes a whole week to be completed, so task automation is compulsory. During monitoring, these three aspects are registered (Fig. 5):

- **Topology:** It registers how the PRIME topology evolves for one week. SN dependencies, functional states (switch, terminal, etc.) and the durations and times of this states are recorded. It analyses PRIME from the communications perspective.
- **Short polling cycles:** Repeated cycles asking all the smart meters for a low-load data transaction (reading). The success and duration of these cycles are measured for two days. It analyses PRIME from the application data perspective.
- **Long polling cycles:** The same as the short cycles but high-load data transactions are requested.

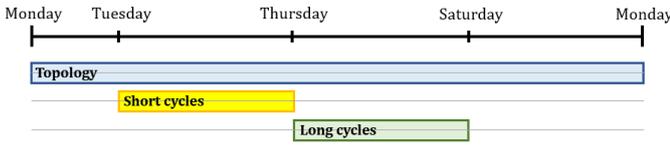


Fig. 5. Secondary substation monitoring chronogram

C. Post-processing and new variable design

The raw data obtained after the monitoring consists of hundreds of csv files per SS. To produce humanly understandable results, data post-processing is needed to calculate high level variables that show the PLC performance of the SS.

The post-processing of the data had been previously developed by Iberdrola, but once again, an adaptation was needed. Moreover, a new set of PLC performance variables were designed to improve the existing ones and consider PRIME v1.4 specific aspects, so an additional processing step using Python was included to calculate these new variables. In total, accounting for the new and old variables, 48 PLC performance variables were calculated per SS. These variables can be of different types (single value, set of values or a graph) and are organized into different topics, each providing a different PLC performance perspective [7].

The most relevant PLC performance metrics, related with some of the previously mentioned PLC variables, are the following [6]:

- **Availability:** If referred to the topology (PRIME availability), it measures the percentage of time that the smart meters are connected to the subnetwork, and if referred to the cycles (short/long availability), it measures the average meter reading success of the subnetwork.
- **Stability:** Ability to maintain a constant number of nodes connected, and if possible, with the same functional states.

D. Secondary substation categorizing

From the 48 PLC performance variables, five were selected to group the SSs into categories with similar PLC performance: connected nodes (avg. and SD), PRIME availability (avg. and SD), short cycles availability (avg. and SD), long cycles availability (avg. and SD) and a stability histogram (Fig. 6), a promising newly designed variable.

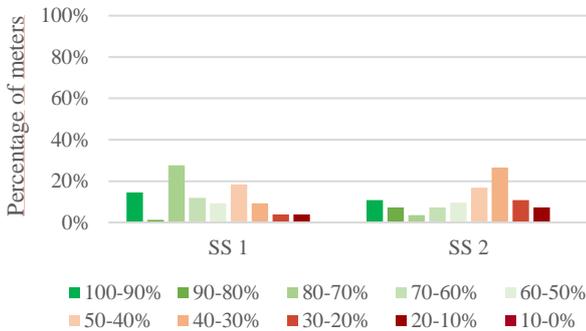


Fig. 6. Stability histogram example

During operation, meters can change their functional states and topological dependencies. This histogram registers the percentage of time each meter of the SS stays in its most

common state, and then separates them into stability ranges (100-90%, 90-80%, ..., 10-0%), creating a ten-value variable. Finally, the data is normalized by dividing it by the total number of meters of the SS to be able to compare SSs of different sizes, obtaining the percentage of meters present on each range. For instance, SS1 of Figure 2 is more stable than SS2 because it has more meters in the most stable ranges (peak on the left side). The most stable and thus desirable situation would be to have all the meters in the 100-90% range.

The SS categorizing was performed using the k-means unsupervised clustering Machine Learning technique [8]. Five different options, consisting on different combinations of the input variables, were tried and the most adequate for deployment purposes was chosen. Different cluster size alternatives were also tried for each option, selecting the one that produced the best results. Additionally, Principal Component Analysis (PCA) [9] was applied to the clustering results to be able to visualize the clusters in 2D (Fig. 7) or 3D plots.

The five input variable combinations for the k-means algorithm were the following:

- **Option 1:** Stability histogram.
- **Option 2:** Availabilities (PRIME, short cycles and long cycles).
- **Option 3:** Connected nodes + Availabilities (PRIME, short cycles and long cycles).
- **Option 4:** Stability histogram + Availabilities (PRIME, short cycles and long cycles).
- **Option 5:** All the variables.

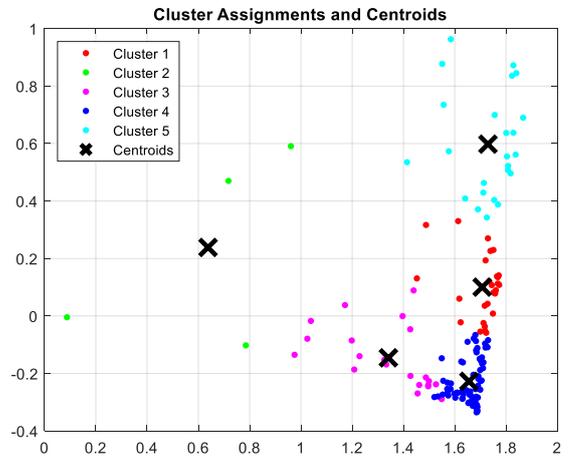


Fig. 7. Clustering example (2D) – Cluster assignments and centroids

E. Deployment strategy

The deployment was structured in different stages to ensure a smooth transition and optimize the knowledge gained, increasing the complexity in an incremental way. The specific deployment dates for each stage, the chosen SSs and the brand/s of smart meters and concentrator to install on each SS were the aspects to be decided. The factors affecting the deployment were the equipment arrival dates for each manufacturer, the designed SS categories, time constraints and specific aspects of each SS.

TABLE III. SELECTED CLUSTERING OPTION – AVERAGE RESULTS AND NUMBER OF SECONDARY SUBSTATIONS PER CLUSTER

Option 5	Connected Nodes		PRIME avail (%)		Short cycle avail (%)		Long cycle avail (%)		Stability histogram										N° SS
	Avg.	SD	Avg.	SD	Avg.	SD	Avg.	SD	100-90%	90-80%	80-70%	70-60%	60-50%	50-40%	40-30%	30-20%	20-10%	10-0%	
1	27	6	98.4%	4.2%	98.9%	3.3%	96.1%	9.5%	59.2%	6.3%	9.0%	5.7%	6.4%	6.0%	3.0%	0.9%	0.0%	3.5%	23
2	101	17	98.7%	3.9%	96.9%	7.8%	96.4%	8.9%	27.8%	11.3%	9.7%	12.8%	13.7%	11.1%	7.0%	4.4%	0.8%	1.5%	39
3	25	3	94.9%	9.5%	91.4%	15.6%	88.4%	18.2%	9.6%	9.0%	10.8%	14.5%	13.7%	15.2%	16.2%	7.9%	2.6%	0.3%	36
4	301	51	95.4%	8.7%	88.7%	13.0%	87.4%	14.0%	15.6%	7.2%	10.5%	11.3%	12.3%	15.0%	13.2%	10.3%	4.0%	0.5%	29
5	50	11	78.8%	21.2%	63.5%	30.3%	66.1%	28.6%	5.6%	7.1%	8.0%	10.4%	13.9%	12.2%	14.0%	19.1%	9.4%	0.5%	14
6	91	25	60.8%	9.1%	15.9%	5.1%	20.9%	10.9%	23.4%	6.6%	2.7%	5.0%	5.6%	4.9%	6.4%	20.7%	24.2%	0.5%	4

V. RESULTS

A. Grid topology study

Central and East municipalities looked more favourable for PLC, having shorter overhead feeder lengths, more customers, less fuse boxes per feeder and more concentrated meters. In general, the three municipalities are not densely populated, and the main loads are customer homes with a few industrial areas also present.

Moreover, the presence of highly correlated variables, i.e. the contracted power, the number of customers and the number of fuse boxes, allowed for the detection of redundant variables and the proposal of a draft classification using only three of them, which are relevant for PLC and not correlated. These three variables were selected:

- **N° of customers:** It indicates how many devices share the same medium (electric power cable).
- **Customers per fuse box:** It indicates how concentrated the smart meters are in specific locations (meter rooms or similar), affecting the probability of data collisions.
- **Length per fuse box:** It indicates how separated the smart meters belonging to different fuse boxes are on average. A greater separation implies more difficulty to find a switch, increasing the probability of having isolated meters.

The results of this first classification (Table I) were not good enough, as some categories (A and B) contained SSs with a very different average daily meter reading success (high SD) and others showed very similar global results both in average and SD (D, E and F) and could not be distinguished. For that reason, the monitoring of the SSs was necessary to obtain more detailed information about PLC performance and achieve a better classification.

TABLE I. SS DRAFT CLASSIFICATION

		N°. of customers			
		<25		25 ≤ x ≤ 100	>100
		Length per fuse box ≥ 100m	Length per fuse box < 100m		
Customers per fuse box	<3	A 20 SSs Avg.: 89.08% SD: 24.82%	B 41 SSs Avg.: 97.85% SD: 5.80%	C 33 SSs Avg.: 97.28% SD: 3.62%	D 15 SSs Avg.: 98.93% SD: 1.15%
	≥3			E 17 SSs Avg.: 99.47% SD: 0.91%	F 36 SSs Avg.: 98.60% SD: 2.28%

B. Power Line Communications performance monitoring

The monitoring results proved the performance of PRIME v.1.3.6 on the field, showing the following figures (Table II):

TABLE II. AVERAGE AVAILABILITY RESULTS BY MUNICIPALITY

Municipality	PRIME avail. (%)	Short cycle avail. (%)	Long cycle avail. (%)
North	92.2%	84.6%	82.0%
Central	97.0%	94.5%	93.4%
East	92.7%	86.3%	87.0%
Global	94.1%	88.7%	87.5%

In general, superior performance is observed in the Central municipality indicating that it is more favourable for PLC. Be that as it may, all of them show very respectable results. Additionally, the results were also segregated by concentrator manufacturer, predominant consumption, etc. trying to extract additional conclusions.

C. Secondary substation categorizing

Some of the options tried gave excessive importance to the availabilities or the stability to form the groups, while others did not consider the SS size (connected nodes), something essential for deployment purposes. In the end, option 5, which used all the five variables as inputs, was the best trade-off between size, stability and availability. Besides, the stability histogram, the only new variable used in the clustering, was determining to achieve a good classification, becoming a new reference to measure stability and the key to distinguish the SSs better and form the clusters.

Table III shows the complete clustering results for option 5, showing the average values of all the variables for the SSs belonging to each cluster. Furthermore, Table IV summarizes the information of Table III, indicating the characteristics of the SSs belonging to each of the six clusters, something crucial to plan the deployment:

TABLE IV. CLUSTERING RESULTS - SUMMARY

Cluster	SS Size	Availability	Stability	N° SS
1	Small	Excellent	Excellent	23
2	Medium - small	Excellent	Very good	39
3	Small	Very good	Good	36
4	Big	Very good	Good	29
5	Medium - small	Bad	Bad	14
6	Any	Very bad	Very bad	4

D. Deployment strategy

The deployment was structured to be performed with incremental difficulty, selecting the clusters with best performance for the initial stages, guaranteeing that more knowledge is accumulated before facing the worst SSs:

1. **Individual manufacturer trials:** Their main objective is to check that the smart meters of each manufacturer work well independently, so a single manufacturer is installed on each SS. SSs from clusters 1 and 2 are selected and only three or four SSs are deployed per manufacturer.
2. **First incremental interoperability trial:** A single SSs from the best performing clusters, 1 or 2, is selected and initially only smart meters from two different manufacturers are installed. When decent performance is achieved, a new manufacturer is added incrementally until every PRIME v1.4 manufacturer has been installed.
3. **Small and medium SS size interoperability trials:** Full manufacturer mixes on SSs of clusters 1, 2, 3, 5 or 6.
4. **Big SS size interoperability trials:** Full manufacturer mixes on SSs of cluster 4.

It is important to succeed before continuing with the next stage, but the contrary could also happen if the project needs to continue advancing due to time constraints.

VI. CONCLUSIONS

Smart meter deployments have always been characterized by their uncertainty, due to the heterogeneity of the LV grid and the difficulty to predict the results until the deployment has been performed. For that reason, this first massive PRIME v1.4 deployment, even if it is the first of its kind, relies on the advantage that PRIME v1.3.6 is already deployed on the field, allowing to identify the current performance on the field and structure the deployment optimally.

With respect to the electric grid study, the main conclusion is that it is very difficult to reach a good enough SS classification by only using electric variables, as there are externalities that are not reflected in the data. Anyways, this information is essential to structure the deployment, as even if it is not used to categorize the SSs, it is needed to select between SSs belonging to the same category and identify the most convenient ones for each deployment stage.

With respect to the monitoring of the SSs and the data post-processing, it would be recommendable to achieve a higher degree of automation, as the process is still tedious.

With respect to the newly designed PLC performance variables, they will surely be useful to analyse the performance of PRIME v1.4 and compare it with PRIME v1.3.6, ensuring that an improvement is achieved with the latest version of the PLC standard.

With respect to the SS categorizing, the possibility of classifying the SSs using Machine Learning techniques with the chosen variables, achieving groups with homogeneous stability, availability and size, which are appropriate to structure the deployment has been proven. Furthermore, the most remarkable aspect is the success of the only newly designed variable used for this end, the stability histogram. This variable has been crucial to categorize the SSs and has become a new reference to measure PRIME stability, also showing high correlation with the availability. Consequently, Iberdrola has shown its interest to continue studying this variable, using past monitoring data from hundreds of SSs to analyse if the conclusions extracted from this project can be generalized.

Finally, with respect to the structuring of the deployment, the deployment stages arranged with incremental difficulty together with the previously designed SS categories, containing SSs with adequate characteristics for each of stage, has facilitated the task enormously. This strategy is in fact the culmination of the project, structuring the first massive PRIME v1.4 pilot with the least uncertainty possible and gaining as much knowledge as possible, becoming an initial step towards the Smart Grid.

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