PRIME on-field deployment

First summary of results and discussion

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Abstract— **PRIME (PoweRline Intelligent Metering Evolution) is a narrowband power line communications (PLC) technology targeted for use in smart metering applications. From its initial conception back in 2006, it was designed considering utility needs for a reliable, open PHY/MAC specification which could become a globally recognized industry standard. The use of OFDM techniques and well-known forward error correction mechanisms, along with novel discovery and network-building MAC procedures, allow for cost-effective, seamless integration with recognized standard metering protocols such as DLMS/COSEM.**

This paper presents results obtained from real-field multi-vendor deployments with PRIME-compliant interoperable implementations at Iberdrola network in Spain. The focus is on the definition of "availability rates", how to approach a systematic testing laboratory scenario and obtained results, and sample performances measured at field locations. Finally several considerations on noise sources and impedance, coming from real experience, will be discussed.

Keywords- PRIME; PLC; deployment; results

I. Introduction

The Smart Metering solution which Iberdrola is currently deploying in its Spanish electricity distribution network is based on PLC over the low voltage (LV) grid. This means every MV/LV substation will be equipped with a Data Concentrator which communicates via Low Frequency signals over the grid with all meters which depend on the substation. The way substations communicate to utility central systems is out of the scope of this paper.

From a protocol architecture perspective, the full stack is shown in Figure 1. Basically two sets of protocols are integrated to form a coherent communications solution: PRIME [1] and DLMS/COSEM [2]. These are described in Sections II and III.

The definition of performance statistics which were employed during laboratory testing and field trials is given in Section IV, along with explanation of the benchmark laboratory tests in Section V.

Sections VI and VII give examples of real numbers for measured performance rates for two different meter vendors. These further elaborate results in [3], and are a novelty both from the literature review point of view, and from the PRIME perspective. There is an important lack of references to field results in technical literature, and this is especially true for non proprietary, multivendor technologies such as PRIME.

Section VIII discusses findings on different noise situations at the Castellon trial which comprises tens of thousands of meters, with Section IX concluding some final remarks for this paper.

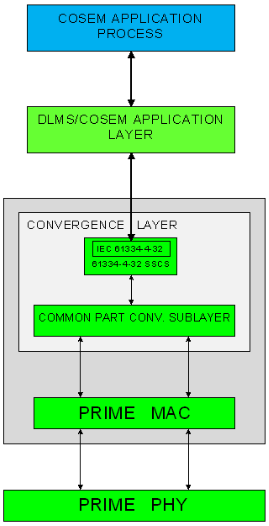

Figure 1. DLMS/COSEM over PRIME stack

II. DLMS / COSEM

Device Language Message Specification/COmpanion Specification for Energy Metering (DLMS/COSEM) has its origins in the car-manufacturing industry at the end of the seventies. It was in 1980 that General Motors officially started an initiative called Manufacturing Automation Protocol (MAP) to design a network standard for interconnecting different electronic devices and machines at its manufacturing plants [4]. This effort involved different industry partners and crystallized in the publication of a full 7-layer communications suite which used the OSI model [5]. At the Application layer, MAP defined a thoroughly comprehensive protocol known as Manufacturing Message Specification (MMS) which is standardized as [6] and [7].

Although MMS did not have the expected success in the automotive industry, it became a reference for utilities when the American Electric Power Research Institute (EPRI) started considering it in 1986 as part of its Integrated Utility Communications Project. The well-known IEC 61850 series for electrical substation automation [8] is a result of that initial work.

During the first half of the nineties, some European utilities and manufacturers started work on adapting MMS to the electricity distribution environment [9]. This resulted in a simplified version of the protocol, then called Distribution Line Message Specification (DLMS) to explain the fact that it was basically a subset of MMS for low-speed PLC. IEC TC57 published standards [10] and [11] in 1996.

Some European manufacturers joined forces in 1996 to promote DLMS, creating the DLMS User Association. A specific profile was created for smart metering, while a whole new "abstract object" model was introduced based on the German Energy Data Identification System (EDIS, see [12]). DLMS was renamed as "Device Language Message Specification" to underline that additional non-PLC media could be used for DLMS-based smart metering, and a new Companion Specification for Energy Metering (COSEM) issued. COSEM defines an object-oriented structure, based on interface classes which represent different types of information inside electricity, heat/cooling, gas and water metering devices. Objects are specific instantiations of interface classes with a certain format, and are identified by means of an Object Identification System (OBIS) based on numeric codes.

The basic transaction in DLMS/COSEM implies the query for a specific attribute of a certain object inside the meter, using its OBIS code and attribute id. The answer containing actual data (e.g. the value of a register containing imported active energy in units of watt-hours) is encoded using the A-XDR encoding rules [13] which are a simplification of the Basic Encoding Rules (BER) defined for ASN.1 [14][15].

DLMS/COSEM data units are usually transported over a simplified LLC layer protocol: IEC 61334-4-32 [16] which is loosely based on IEEE 802.2 [17] and implements both acknowledged and unacknowledged connectionless services.

As a reference, IEC 61334-4-32 adds 24 bits of overhead to each correctly formed DLMS/COSEM "message", also called Application Protocol Data Unit (APDU). On the other hand, the option to use UDP/IP along with the defined DLMS/COSEM wrapper [18] would imply 160+64+64=288 bits, which could be reduced to around 104 bits by means of IP header compression. MAC or other adaptation layer overheads are excluded in the numbers above. This is why Iberdrola currently deploys the simplified architecture shown in Figure 1 in order to remotely access low-cost, low-complexity digital residential meters over power lines.

The equipment installed on-field is compliant to the most recent versions of DLMS/COSEM [19][20] in which strong authentication and encryption algorithms are optionally available. DLMS/COSEM is becoming a de facto standard in Europe (and elsewhere) as a result of M/441 [21] and the maturity acquired for the last 15 years.

III. PRIME

PRIME was already introduced in [3]. IEC 61334-4-32 protocol uses the services of the Common Part Convergence Sublayer, which only performs Segmentation and Reassembly to adapt DLMS APDU sizes to PRIME MAC and handles (possibly) segmented frames to the MAC layer.

Based on extensive measurements which have been taking place since 2007, several utilities mainly in Europe are now in the process of developing PRIME-based systems and networks for smart metering services.

In the case of Iberdrola in Spain, the currently on-going deployment implies the replacement of 100,000+ electromechanical Ferraris meters for intelligent digital meters (which according to law must be remotely managed) in the city of Castellon. Based on the satisfactory results already obtained, the next phase of deployment will be comprised of another 300,000+ PRIME-based meters.

The step-by-step approach followed from the initial stages up to the real deployment of a DLMS/COSEM metering system based on OFDM narrowband PLC over LV networks will be described in the following sections.

IV. PERFORMANCE QUALIFICATION PROCESS

Performance results, as presented elsewhere in this paper, are derived at application level in order to truly reflect the use-case in real life deployment scenarios. Application functions (i.e. COSEM processes) in Data Concentrators trigger readings of COSEM objects which go over the DLMS client into PRIME protocol stack and out on the power line channel. At the other end, these requests are relayed by PRIME Service Nodes to DLMS servers inside meters to respond to.

Such end-to-end generic benchmarking gives confidence that results obtained in initial tests match expected on-field actual performances.

A key objective of tests was to keep the communication media continuously busy in order to better benchmark it. This is accomplished by keeping the meter reads running continuously over the entire PRIME subnetwork. Data Concentrators pick one meter from their registered list, read its relevant COSEM objects, pick a second meter to read, then third and so forth until the last registered meter is read. One meter is exclusively read at a time and after the last available meter has been read, the read cycle starts over from the first meter again.

Interaction with each individual meter is comprised of four steps listed below:

- Open DLMS association with relevant meter. This implies the exchange of Application Association Request (AARQ) from client to server and an Application Association Response (AARE) from server to client.
- Read one simple attribute of the meter (e.g. date and time, or one simple register value). This implies the exchange of one Get-Request and one Get-Response APDU.

- Read a relevant COSEM object again with ‘Get’ APDUs.
- Close DLMS association with the meter. This implies the exchange of Release Request (RLRQ) and Release Response (RLRE).

With the above described methodology, two types of generic tests are defined:

- Short-cycle tests: These are tests in which the COSEM object relevant to instant energy (comprising a total of 7 values) is read.
- Long-cycle tests: In these reads, hourly energy load profile for the last 13 hours is read. This is comprised of 13 arrays (readings) of 8 values each.

PRIME statistics discussed in the following sections contain two different types of availability:

- When we speak of ‘PRIME level’ availability, we refer to a measure of the amount of time during which meters are actually registered to the PRIME subnetwork (either in ‘terminal’ or ‘switch’ functional states), compared to periods in which it has been actually unregistered or not being part of the PRIME subnetwork (functional states such as ‘disconnected’, ‘registering’ etc.)
- PRIME statistics refer to ‘application data availability’ when they calculate the ratio of successful short/long-cycle read tests over total number of tries. The number of tries of a continuously running cycle test per meter ranges from hundreds to thousands a day, depending on the size (number of registered meters) of the PRIME subnetwork.

V. Test Deployment Process

This section describes the steps defined by PRIME Alliance and followed by typical PRIME chipset providers, in the process of transitioning from just a paper-based technical specification to the ongoing field deployments.

One aspect of the process was the development of a detailed interoperability specification, and tests done in certification laboratories. Two international, independent certification laboratories qualify conformance of vendor implementations to PRIME specifications. More than one dozen products from equal number of vendors have already been qualified for compliance. In order to enable certification tests, the support of some diagnostic and control primitives (enabled through the so-called PRIME Information Base which is a small database with relevant attributes residing inside every PRIME Node), and a host control interface, was mandated for all PRIME implementations. These standardized interfaces greatly simplified the certification process. Indeed, host communication was one of the main challenges during the certification process, and the primitives and the test tools were continually refined.

While interoperability tests guaranteed multi-vendor solutions, the performance of PRIME still needed to be verified. Physical layer performance benchmarking was left to individual vendors. Typically, semiconductor vendors benchmarked performance first by simulation under known channel conditions, and then by creating a test setup where the performance of the actual hardware could be verified. This is done by loading test vectors onto equipment that can play it back with a controlled amount of distortion and noise being added. To make this effort comprehensive, it is necessary to draw up realistic models of channel distortion and noise. Some simplified models used were:

- No channel distortion, with Additive White Gaussian Noise (AWGN).
- Frequency-selective channel modeled by a deep in-band notch.
- Cyclostationary bursts of impulsive noise occurring every AC-mains cycle.

The PRIME technical working group has recently aligned simulation results for the above channels across multiple vendors.

While simulations of the MAC are also possible, it was deemed difficult to replicate the unique characteristics of the power line channel and noise. Consequently, the tests for the MAC performance were actually carried out in a neutral, controlled laboratory setup (see Figure 2).

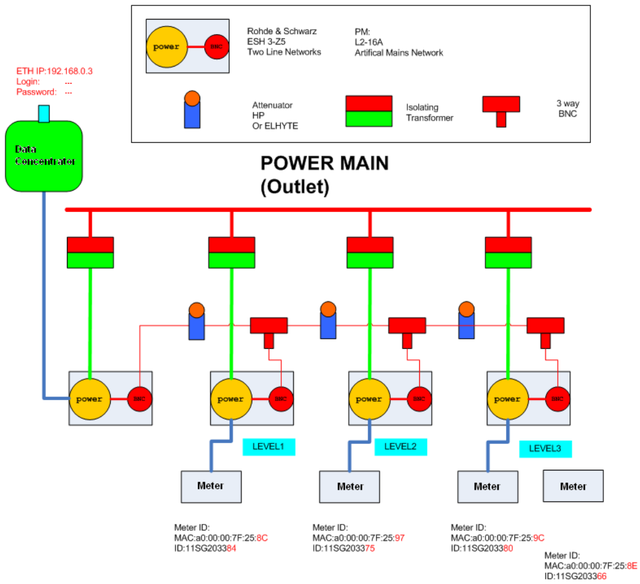

Figure 2. Laboratory schematic setup

The test setup comprised a Data Concentrator, connected to 12 meters through a series of attenuators. The attenuators were asymmetric, as often happens in real power lines. One interesting observation from this setup was that each meter needed to account for the case that its transmit signal may not reach the Data Concentrator, even if the Data Concentrator’s signal itself is received quite strongly by the meter. The test in this case was to ensure that all meters were able to register to the Data Concentrator (through meters that appropriately and dynamically auto-configure themselves as switch nodes), and could maintain a stable connection.

For example, for a meter vendor we will generically call A, it was found all twelve meters were able to register and maintain stable communication for multiple hours, in multiple tests done on different days.

The PRIME availability rate (i.e. percentage of overall test time a specific meter has been registered to the Data Concentrator) is plotted below, and indicates that all but one meter were registered on the subnetwork 100% of the time.

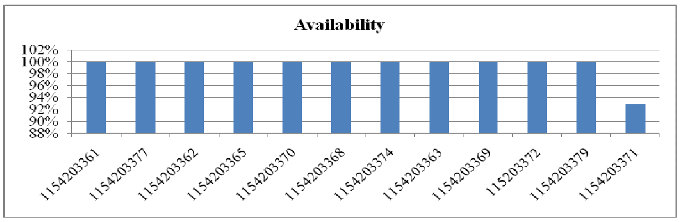

Figure 3. PRIME availability along 5 hours, vendor A

The long-cycle success rate (i.e. number of correctly executed long-cycle read-tests over total long-cycle tries for each meter) varied from 96.05% to 100% over this time, with an average "application availability" of 99.48%.

Further tests with two other vendors (B and C) showed very similar results to the ones above. A total of three more vendors are already at the final stages of the development phase, undergoing similar tests on laboratory setups.

The combination of the above tests successively enabled PRIME Alliance to gain confidence in the performance of the PRIME specification and in the compliance of solutions offered by individual PRIME vendors.

VI. SAMPLE FIELD TEST RESULT FROM VENDOR A

Here a real example is reported of on-field results from the first time PRIME meter vendor A went to actual installations. 52 meters provided by vendor A were installed for the respective LV customers of an MV/LV substation in Burriana, a small town located near Castellon.

All 52 meters were deployed at four different buildings on four feeder lines connected to the LV busbar (in which the Data Concentrator located at the substation injects the PLC signal). It is interesting to note that the Data Concentrator used a PRIME PHY/MAC implementation provided by a different vendor than that of the meters, thus furnishing a test of real-world interoperability.

The results from these tests were found to be quite good, as described below. First, all meters were able to register with the Data Concentrator. For long-cycle tests, the average success rate of the meters for a three-day testing period was 99.1%. An overwhelming majority of the meters succeeded 99.4% or more of the long-cycle tests, and the worst two performing meters had a 92.5% success rate.

It is useful to mention one issue here. Traditionally, narrowband PLC smart metering systems have been using the concept of 'availability' in terms of number of meters read after incremental attempts during a period of days or weeks. This is the case because, formerly, narrowband PLC technologies did not have the "real time" nature typical of telecommunications networks, usually due to the intermittent availability of PLC channels by nature of their changing noise characteristics. PRIME, on the contrary, acts as "real time" telecommunications technology, capable of keeping "real time" topologies and being able to cope with the characteristics of different PLC media, so as to achieve always-on communications with its nodes (meters).

When statistics discussed here deliver data referred to the concept of availability, these are related to data extracted from real availabilities checked in the tens or hundreds of milliseconds, rather than to successful reads after days of attempting to read a meter.

VII. SAMPLE FIELD TEST RESULT FROM VENDOR B

Results from three different representative locations where vendor B is installed allowed assessing readiness of PRIME for large scale rollouts. The three install locations are described below, and obtained results for several days of measurements summarized in Table 1:

- Location X: typical MV/LV substation with one underground transformer serving 95 customer premises with equal number of meters.
- Location Y: country location as shown in Figure 4, which has overhead cables and outdoor transformer serving only 15 customers in a disperse environment. The low number of meters is particularly interesting to qualify performance in a subnetwork where there may not be too many "helper devices" capable of acting as switches.

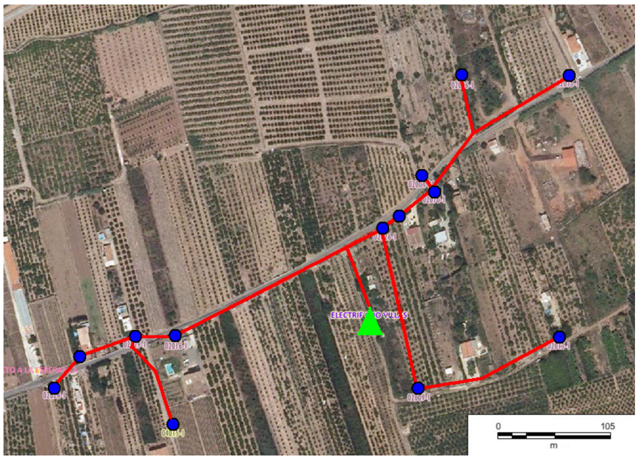

Figure 4. Google GIS view of substation (triangle), with disperse meters (circles) at location Y

- Location Z: dense urban population location where a substation has 2 transformers serving a total of 293 households with roughly equal distribution across the two transformers. The substation was underground.

TABLE I. SAMPLE PERFORMANCE RATES, VENDOR B

Location	*Overhead / underground*	*Meter count*	*Meter visibility*	*Short cycle success*
X	Underground	95	100%	93.5%
Y	Overhead	15	100%	96.6%
Z	Underground	293	100%	97.6%

VIII. FIELD ISSUES RELATED TO NOISE AND SIGNAL QUALITY

In this section we will analyze some issues related with noise and signal quality in real PRIME systems which have been observed and analyzed in the field deployment of tens of thousands of meters in Castellon, and where useful lessons have been learnt. Although obviously not feasible for future deployments, extra time and resources were employed during this first large field experience to identify, investigate, isolate, analyze and record all possible cases in which meters have been understood not to work properly due to abnormal physical PRIME situations. This actually allowed vendors to improve e.g. injection mechanisms, fine-tune transceiver parameters (e.g. sensitivity), or to change certain PHY/MAC algorithms to more efficiently face tough channels on-field.

The list of issues which have been analyzed has been classified and is discussed as follows.

A. Wideband interfering noise sources

Wideband noise is the single most common and serious issue found at PRIME deployments, with a statistic of hundreds of MV/LV substations. Usually the problem arises when a very powerful noise source is tied to the AC mains and generates a very high-level wideband noise (sometimes accounting for tens of watts of injected noise) which results several dB above the PRIME signal and thus makes PRIME- (and any other LV PLC technology) based communications impossible, completely denying meter readings. The main issue in these cases is how to chase the source, and what is the impact of the source in the subnetwork. For instance, if communications are halted for an hour, it could have not that big relevance from a system point of view, as metering data can be retrieved during some other time of the day by the Data Concentrator. These noise sources can be further classified in two different categories due to its occurrence profile:

- Fixed time-of-day noise, where the noise source appears at fixed times of the day, and as a result of this it can be easily tracked down to its source: usually ancillary services (such as e.g. garage ventilation systems) which are connected daily at pre-programmed intervals. Situations of this kind could be corrected by the addition of filters at customer's premises. It could even be investigated if interferer's emission levels might be above regulatory limits.

- Random occurrence noise, where apparently at random times the communication is halted (even when some general patterns can be traced). This noise is more usually linked to customer premises or appliances, and it is much more difficult to isolate. However, using the technique mentioned in the following section it can be somehow debugged. In some cases, it has led the operations crew down to a severely defective TV set or lighting system which was causing the problem.

B. Ability to detect the interfering noise source with a non-invasive CENELEC-A band sniffer

Due to the nature of the LV grid and its topology (full of many branches and derivations) there is a natural consequence: any kind of conducted signal injected to the grid, be it a LV PLC signal or interfering noise, quickly loses amplitude (attenuates) as we put more branches between the source and the point of measurement. As a result of this, it is relatively easy to detect quantitatively where the source of a noise distortion lays. This can be easily detected just by clamping non-invasive magnetic core-type probes (attached to a PRIME sniffer) in the wires coming out from the meter up to the end customer, and by repeating the measurement at different points of the LV distribution grid. Using this procedure, some tricky noise sources were selectively traced down to the originating customer without disconnecting any point of supply.

C. Signal interference due to misconfigurations

In order to maximize the bandwidth in densely populated MV/LV substations where more than one transformer is present, a separate PRIME device is installed at each of the transformers, just one of them acting as the Base Node (Data Concentrator) and the others acting as switches (this is always done a priori because in most situations the two or more LV networks, although depending on the same substation, have totally 'isolated' transformers with no signal coupling whatsoever between them). In a particular location with two transformers of this type, severe problems of subnetwork instability were reported. After debugging, it was discovered that due to a misconfiguration there were actually two configured PRIME Base Nodes with beacons colliding in the time domain, one attached to each transformer, and thus some Service Nodes were 'jumping' between both subnetworks. In spite of this, it is noticeable that the performance level of the two subnetworks was enough to read most of the meters on a daily basis and to remotely debug and detect the issue.

D. Impedance issues

PRIME PHY specification requires every transmitter to be able to inject a 1 Vrms signal over a 2 Ohm line impedance (phase to neutral), in order to have an acceptable signal level under reasonably low line impedances, as opposed to line impedances defined in EN 50065-1. In the case of vendor C, impedance has been checked at many MV/LV substations as the Base Node is able to measure the transmitted signal it injects, and thus characterize the LV network it is connected to. Impedances in Castellon are above 2 Ohm in the verified locations, so transmitted signal levels are satisfactory (above 120 dBuV). In some meter rooms the impedance has been validated as well, and here the impedances are quite diverse. In general, due to the concentration of many meters in one specific location at the basement of buildings (i.e. meter rooms) the total impedance equals the parallel input impedance of all the meters at the same point, lowering the effective impedance of the LV network.

E. Unreliable communication results when MV/LV substations are not completely populated with meters

In hostile Error Vector Magnitude (EVM as defined per the PRIME specification, reciprocal of the signal-to-noise ratio) scenarios, the network is very sensitive to a sudden rise in the noise floor. The received signal level in any point of the grid is more or less stable, as it is determined by grid impedance and signal propagation (grid structure), which do not change significantly in the short term. However, the noise floor is subject to heavy fluctuations. As a result of this, whenever the EVM of received PRIME frames is in the low side of the range, a sudden increase of 2-3 dB in the noise floor may significantly degrade or inhibit PRIME communications. This happens typically when the EVM is around 5 dB or worse, and is a typical symptom of MV/LV substations where not all the meters have been populated (i.e. old mechanical meters substituted by PRIME meters) In this case, the subnetwork topology is not as good as it might be with a completely populated scenario, distances are larger and EVM figures are lower.

In the following figure the minimum SNR (calculated from EVM) for the robust modulation schemes in PRIME is shown (those with convolutional coding enabled).

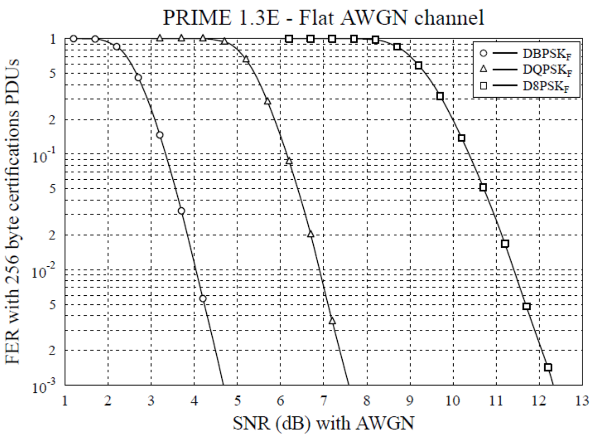

Figure 5. FER against SNR, AWGN case

As a result, when receiving frames with an SNR below 5 dB, error probability can change one order of magnitude per dB of variation of the noise floor. An important learnt lesson is not to extract conclusions on communications reliability tests until all the meters in the MV/LV substation have been deployed.

IX. CONCLUSIONS

We reviewed some background on Iberdrola selection of protocols for its DLMS/COSEM over PRIME smart metering deployment in the city of Castellon (Spain).

The definitions employed for an initial benchmarking have been shown, and repeatable, relevant associated results in a test bed scenario shown. It has been demonstrated that expected performances are actually achieved in very diverse field scenarios with different vendors.

Some conclusions were extracted on the analysis performed to a high number of deployed PRIME subnetworks which were analyzed in detail, with respect to noise levels, expected performance, impedance scenario and subnetwork density.

Additional sets of measurements are currently being gathered over the growing base of installed meters and vendors, and will be complementing the measurements shown to ensure an ever-increasing performance of the whole PRIME PLC solution in a multivendor environment.

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