PRIME interoperability tests and results from field

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Abstract— **PRIME (PoweRline Intelligent Metering Evolution) is one of the prominent upcoming powerline communication technologies, targeted for use in smart metering applications. The PRIME PHY / MAC specifications are open, publicly available and are developed by the PRIME Alliance, an industry consortium that includes utilities, meter vendors and semiconductor suppliers. PRIME employs OFDM modulation in the CENELEC A band (9 – 95 kHz), and achieves data rates from 21 kbps to 128 kbps at the PHY layer. The PRIME MAC is optimized for tree-topology networks, and features a novel node discovery and network building process. PRIME converges to IPv4 and IEC 61334-4-32 at the network layer, and is evolving to support IPv6.**

In this paper, we describe the PRIME Alliance, and review technical details of the PRIME PHY and MAC. We review the certification and interoperability tests defined by the PRIME Alliance, to ensure openness and future-proof technical performance with multi-vendor solutions. We present some initial results from small-scale PRIME field deployments.

I. INTRODUCTION

Smart metering has become a hot topic in the last couple of years in Europe. Recent legislation supports and encourages the use of Automated Metering Infrastructures [1]. In a meter market which is already open to competition, AMI rollouts will result in a non-homogenous metering base with different levels of functionalities within grid areas. A wide range of different actors (distribution network operators, suppliers, retailers) and interests (end customers, regulators, industry) will coexist. Hence there is a renewed and compulsory interest in open standardization that will provide for interoperability between meters to be installed.

From the perspective of the data model, DLMS/COSEM [2] seems a candidate to become the de facto reference for information interchange between meters and data concentrators. However, at the PHY/MAC level, there is a need for new standard(s) that will facilitate cost-effective devices which will at the same time provide enough throughput and robustness to meet future demands.

Power Line Communications in the so-called CENELEC-A Band (3 kHz-95 kHz) [3] is a well proven, low cost alternative to wireless solutions in typical European networks. Devices installed in Medium Voltage to Low Voltage transformers inject signals directly into the LV network to communicate with installed electricity meters (around 120 meters per transformer in average). While some PLC-based AMI systems

have been deployed in Europe, they have been proprietary or region-specific, and further, have not ensured multi-vendor interoperability. One of few exceptions to the above is Spread-FSK technology deployed in a few countries. However, this suffers from a limitation in data rate (at most 2.4 kbps in currently deployed systems).

Deploying either proprietary or low-throughput systems would imply additional risks on the utilities' investment, as the limited data rate and lack of multi-vendor support will impede supporting the evolving functionalities of smart meters and Smart Grids over the next decades.

The above observations prompted the launching of the PRIME Alliance to develop cost-effective, standardized PLC in the CENELEC A band. The structure of the PRIME Alliance and the standardization status are reviewed in Section II. Section III describes one of the unique features of the PRIME specification, namely the self-configuration of PRIME tree networks. PRIME networks have been trialled on the low voltage grid in Spain. Results from the trial are presented in Section IV, which also describes a simple and effective method to evaluate the PHY/MAC modem performance in the field without the development of actual electricity meters. Section V reviews interoperability and certification tests, established by the PRIME Alliance. Section VI summarizes the conclusions from this paper.

II. PRIME TECHNOLOGY

PRIME [4] represents one of the most comprehensive efforts in the European smart metering industry to provide for an interoperable PLC-based AMM solution. The initiative began in December 2006 with the aim of promoting a Physical (PHY) and Medium Access Control (MAC) layer standard definition based on state-of-art concepts, in order to guarantee that future market requirements are met and that utilities' investments are safe.

The goal of the PRIME project was to develop communication systems whose viability could be assessed by tests. After the proof-of-concept phase, the goal was to define suitable specifications and test compliant systems on field. PRIME is open, royalty-and-patent free, and it seeks different vendors' equipment/system interoperability to ensure the growth of a new market so that, at the end of the day, all players will benefit.

PRIME has evolved into an Alliance of 17 members, including utilities CEZ, EDP and Iberdrola, and meter providers such as Circutor, Iskraemeco, Itron, L+G, Orbis, Sagemcom and ZIV. Three different profiles of industry

players contribute to PRIME: meter manufacturers that bring their know-how in metering, telecom equipment providers that bring fresh thinking and their expertise in communications and semiconductor manufacturers that set up the limits of cost-effectiveness to all. All members at the growing Alliance have extensive experience in PLC and metering.

The PRIME specification (currently v1.3) is published and free to download [5][6][7][8]. PRIME is one of the first systems to employ an OFDM PHY (see [9][10][11][12]) in the CENELEC A band, where frequency shift keying and other single-carrier solutions have been applied in the past. It is well know that OFDM offers robustness to attenuated, frequency-selective fading and to colored (frequency-variant) noise; all of which are characteristics of the powerline channel. At the same time, to exploit the fact that low voltage lines can sometimes present good channel conditions, PRIME has a flexible PHY that can adapt to support high data rates, up to 128 kbps. The main characteristics of the PRIME PHY are tabulated below.

Band occupied	42-90 kHz	
Tone spacing	488.28125 Hz (97 tones in band)	
CP length	192 us	
Preamble length & type	2.048 ms, chirp sequence	
Modulation size	DBPSK, DQPSK, D8PSK	
Modulation type	Frequency differential	
Coding	Rate ½ convolutional code (optional for the payload)	
AWGN minimum SNR required	DBPSK + conv. code (21 kbps)	4 dB
	DQPSK + conv. code (42 kbps)	7 dB
	D8PSK + conv. code (64 kbps)	11 dB
	Uncoded D8PSK (128 kbps)	21 dB

PRIME primarily uses contention-based CSMA/CA (carrier sense multiple access with collision avoidance), but also allows for contention free periods in every MAC frame. Frame synchronization is enabled by broadcasting of beacons from the base node and from various switch nodes within a tree-network described further in the Section III.

PRIME MAC layer provides services to a traditional IEC 61334-4-32 LLC layer [13] or directly to IPv4 [14]. A convergence sublayer to IPv6 [15] has recently being developed.

Further details of the PRIME PHY/MAC can be found in the open PRIME specifications, or in review articles [17] and white papers [18].

III. PRIME NETWORKS: STRUCTURE AND AUTOMATIC CONFIGURATION

A. Network building process

A PRIME network consists on the following elements:

1) *A Base Node*, which is the central element in the network. In metering applications, Base Nodes can be located as a separate function within data concentrators, or as separate devices connected to them. They may have single-phase or three-phase coupling capability (maximum output voltage levels are different in both applications as per [3]). The Base Node is usually installed at a secondary substation. It requires a WAN link (usually over GPRS, Medium Voltage BPL, ADSL, Ethernet fibre links…).

2) *Service Nodes,* which are the elements registered with the Base Node. In metering applications the meters embed the PRIME Service Node functionality. Service Nodes can also be dynamically self-configured as repeaters when needed to extend the network, and in this case they act as Switch Nodes.
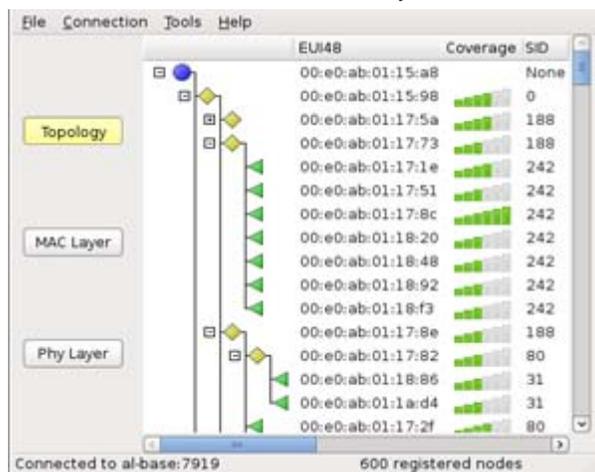

Figure 1 - PRIME subnetwork where the Base Node, Switch Nodes and Service Nodes are represented.

Arguably the main advantage of PRIME devices in the field is that they are able to configure a network automatically, without user intervention or configuration. This was one of the main design goals of the PRIME specification, and is achieved through a special mechanism in PRIME MAC which takes care of network topology configuration and maintenance.

The Base Node broadcasts periodically a special control message, the *Beacon*, advertising its presence. Every unregistered Service Node which successfully receives and decodes *Beacon* messages initiates a registration process in order to establish a link and become active part of this subnetwork. In this way the first level of the subnetwork, comprising service nodes which have a direct link to the base node, is constructed. The connectivity is checked periodically by the interchange of bidirectional *Alive* messages, so both ends of the communication always know immediately whether their link is still valid or not. This aspect is crucial for fast network reconfiguration.

However, some Service Nodes may be located far from the secondary substation or be installed in an environment with a significant noise floor, so they are not able to receive beacons. These nodes, upon checking that there is no *Beacon* receiving activity, begin to transmit a special control message,

PromotionNeeded. This message is intended to inform any Service Node within reach that there is a node which is not receiving beacons.

Upon reception of *PromotionNeeded* messages, a Service Node requests the base node's permission to become a switch node, in order to provide connectivity to the currently unregistered node.

It is the Base Node that assigns promotions to Service Nodes to make them switches. After promotion, switches are able to broadcast their own beacons within specially allocated slots in the PRIME superframe time, so Service Nodes listening to these order-N beacons will be able to register to the Base Nodes through the intermediate switches.

The Base Node also has the responsibility of building a scalable and stable network, so it has the ability to remove switching rights by demoting a node. The maximum number of switches in a network is limited by the superframe timing slot availability, and also the higher the number of switches, the more bandwidth is wasted in control messages.

Also the Base Node will try to maintain the network with a reasonably low level switching hierarchy, as each switching process actually halves the available bandwidth. In real field scenarios it has been verified that in urban areas, with up to 600 customers per secondary substation, the maximum depth of the hierarchy is usually not higher that 4 levels (one phase signal coupling). A topology of this size and complexity can automatically converge to a stable topology within minutes after Base Node power up.

B. Network throughput

PRIME specification currently supports six different combinations of modulation and coding schemes which enable different throughputs. Control messages are always modulated in the most robust (lowest throughput) modulation, DBPSK + Convolutional Coding as highest importance is given to network convergence and maintenance. Data-carrying Protocol Data Units can be modulated in any of the available modulations. It is the nodes in each link who locally decide which modulation to use based on latest SNR and FER data for interchanged control frames. As a result of this, the throughput of each network segment is maximized by decisions taken based on local link data.

As the transmission medium is shared between lots of Service Nodes, collisions may happen. A CSMA/CA mechanism tries to avoid collision situations by assigning a random back off time whenever the channel is busy. As the number of nodes in the network rises, so do switching levels, control messages and collision probability, so the throughput is lowered.

Actual application layer throughputs in field tests with around 500 Service Nodes have been measured at around 50% of the raw PHY data rate for first level nodes, with latencies in the order of 100 ms per link.

IV. PRIME PERFORMANCE ANALYSIS

To benchmark performance of PRIME MAC and PHY in field while PRIME-enabled meters were still in development,

a thin metering simulation application called *AppEmu* (Application Emulation) was defined. The "pass-through" convergence sublayer is also used for *AppEmu*, in a manner conducive to implementation in PHY+MAC modems.

AppEmu was used extensively in interoperability and field tests to quantify throughput and latency. It also furnishes a simple method for interested parties to evaluate PRIME modem operation without having to develop elaborate stacks.

An *AppEmu* running on PRIME MAC in a Service Node opens connections with its peer running on Base Node at the end of a successful registration.

The Base Node periodically scans all open *AppEmu* connections from different Service Nodes in the network and runs a sequence of 9 message exchanges (called transactions) with each of them. Messages in a transaction were defined to match a set of DLMS transaction with a real meter to read standard COSEM objects such as date-and-time and energy-value. Once a Base Node completes a cycle of transaction with all open *AppEmu* connections, it starts a new cycle; therefore emulating a real world metering reading application.

Base Node end of *AppEmu* logs statistical information from every transaction such as round-trip time, number of retransmissions etc. All of these collectively provide a comprehensive view of how PRIME performed during the test time in given network.

Devices enabled with above described *AppEmu* functions were used in several field trials across different geographical locations in Switzerland and Spain in networks of diverse sizes. Given below is the result of an installation in Mägenwil, Switzerland where a set of 36 Service Nodes were connected to a Base Node in a grid topology as shown in figure below where signal was injected on all phases concurrently. For sake of comparative study, devices were installed on all phases in each observation points and no phase related artefacts were discovered for the entire test period.
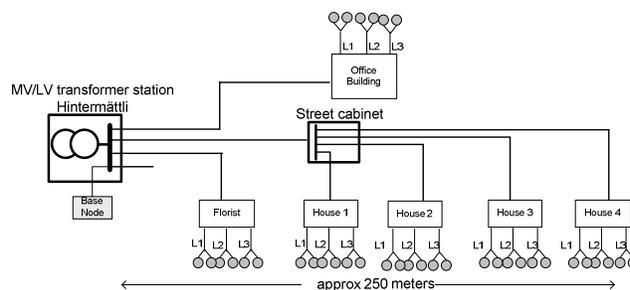

Figure 2 - PRIME test bed used in Switzerland

Results presented below were measured across a 16 hour installation period where the entire network was using DBPSK with convolutional coding enabled, so the lowest possible throughput was tested. *AppEmu* was constantly running and benchmarking was performed on each of the 9 messages in a single *AppEmu* transaction. Results below present a cumulative figure across all 36 Service Nodes during the measurement period.
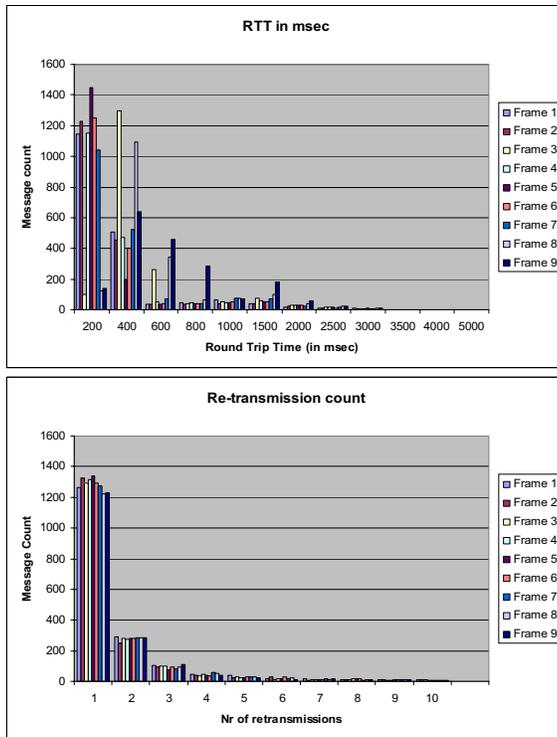
Figure 3 - Round Trip Time and Number of retransmissions statistics measured in Fig. 2 subnetwork

Figure 4 - Round Trip Time and Number of retransmissions statistics for a real network with 613 meters in Madrid, Spain

In a different large-scale interoperability as well as technology test in Madrid, Spain, a Base Node from CURRENT managed a network comprising of 613 Service Nodes. The network auto-scaled to cover the entire installation footprint. The auto-scaling resulted in promotion of 28 Service Nodes to Switch Nodes. The installed network fully converged within 2 levels of repeating hierarchy levels in the case of 3-phase PLC signal injection and continued to exhibit stable conditions across entire test time.

The aforementioned installation has been monitored over several months also with a ZIV Base Node (1-phase PLC signal injection). The following figure shows the results of Round-Trip Time and retransmissions for such a network monitored over a 7-day period. During this period of continuous data interchange with the meters, the percentage of successful data transmissions was 96.47%.
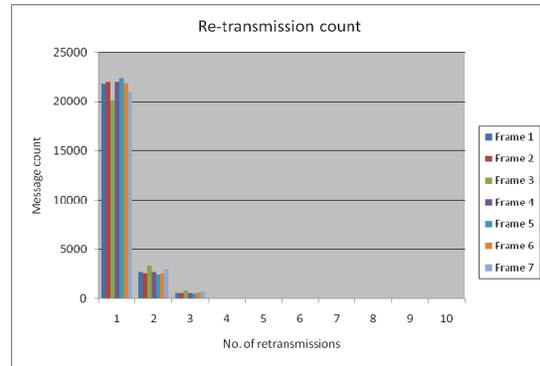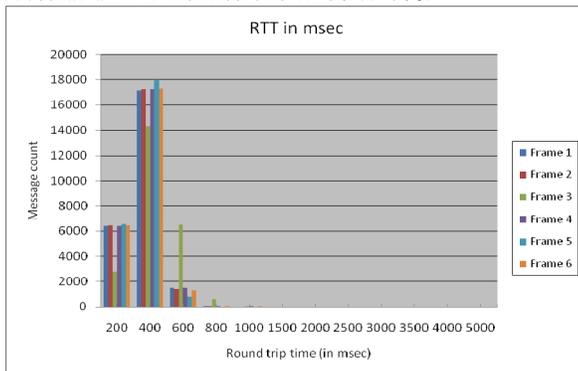

More recently, PRIME-enabled meters are becoming available for from different vendors and some field tests are starting to cover entire metering application test i.e. benchmarking performance of PRIME in reading real electrical meters. One such test continues to run in Bilbao, Spain where devices from different vendors continue to operate without any issues. The network comprises of 191 PRIME enabled meters that are read from a Data Collection application running on the Base Node. The PRIME topology in this network is flat without need of any Switch Nodes. Results from this (DBPSK with Convolutional Coding) network over a 9 day period are shown below. Data Collection was configured to read every meter every hour.

Parameter	Number	As percentage of total meter read attempts
Total Number of Meter Reads	41204	99.9%
No. of successful meter reads	40628	98.6%
No. of failed meter reads	576	1.4%

V. PRIME STANDARDIZATION, INTEROPERABILITY & CERTIFICATION

PRIME standardization progresses in several working groups. The specifications were drawn up, and updated, by the technical working group (TWG) inside the PRIME Alliance. The TWG is now focused on defining a certification process for the PRIME specification.

The foundation for this work was laid by interoperability tests by multiple vendors, which were conducted in two steps:

- PHY interoperability for all modulation and coding schemes was established--first by exchanging time-domain generated by simulation / physical hardware and later by connecting physical hardware together and verifying error-free communication.
- The next level of interoperability testing was with the MAC. Here, Base Nodes manufactured by two different companies were tested against Service Nodes manufactured by various meter vendors. Further,

hardware from at least three silicon manufacturers was involved in these tests.

Experience from multi-vendor interoperability tests (solutions were tested based on FPGA, DSP and integrated silicon platforms) was crucial for the work of the certification task group in the PRIME TWG. In addition to PRIME members, two certification labs, KEMA and Labein, were involved in drawing up the Service Node and Base Node tests, which are already complete and soon to be made public.

With regards to certification tests, all devices connecting to low voltage lines in Europe have to satisfy regulatory requirements. Of particular interest are the [3] requirements on conducted emissions, as measured at the output of a LISN, as defined in [16]. While these limit the *maximum* voltage levels injected by PRIME devices at various frequencies, PRIME also specifies the *minimum* voltage level (equal to 1V rms) to be injected (across the whole PRIME band) on a modified LISN, given in section 3.8 of [5]. The modified LISN has an effective in-band impedance of roughly 2 ohms as seen from the lines, and reflects the low impedances seen on low-voltage power distribution lines. In addition to the above, the PRIME certification tests also specify the ability to transmit and receive packets with the various modulation and coding schemes across the PRIME LISN, transmitter accuracy (as measured by the error vector magnitude) at various temperatures, etc. Performance tests are not included in the first round of certification tests to enable vendor differentiation.

The PRIME MAC tests exercise all the mandatory features in the PRIME specification, including network discovery, registration, (unicast and multicast) connection make and break. Of particular importance are the switching and frame control packet tests, which enable the PRIME Base Node (concentrator) to reach directly unreachable nodes.

One crucial instance of the flexibility enabled by PRIME is the firmware upgrade process. Firmware upgrade has rightly been considered the domain of application layer specifications, beyond the scope of PHY / MAC specifications. However, given that PRIME is the first narrowband OFDM technology to be deployed for smart metering applications, the Alliance found it necessary to define and control procedures for performing firmware upgrades (that allow for future technology enhancement) over the power line. To facilitate firmware upgrade while maintaining industry-standard semantics of the OSI layers, PRIME defined a "pass-through" or null convergence layer, which enables the MAC to pass on firmware upgrade files to a higher layer. Firmware upgrade file transfer is done over the power line using either unicast or multicast connections, with the firmware image being split into pages of smaller lengths. PRIME describes the procedures to be implemented in the upper layer for transmitting and receiving the firmware upgrade file, and requires storage of a "backup" copy of the older image by the upper layer while the new layer is trialed. Higher-layer signaling is defined to set up, control and terminate the firmware upgrade process.

VI. CONCLUSIONS

We reviewed the establishment of the PRIME project, and the methodology used to prototype, test and fine-tune PHY/MAC specifications for smart grid applications. We described the way PRIME creates automatically configured, plug & play meter networks, and how its performance and interoperability was evaluated in labs and on field.

The main strength of PRIME is its structure as a multi-vendor Alliance of various industry players with a wide variety of expertise. The PRIME Alliance standardization process was reviewed. The PRIME technical working group has defined a certification process to ensure interoperability, and a minimum level of performance.

PRIME field tests are underway, confirming PRIME as an effective, technically proven solution for powerline communications to enable smart metering applications.

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