# Signal Injection Strategies for Smart Metering Network Deployment in Multitransformer Secondary Substations

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***Abstract*—This paper analyzes the strategies for injecting power-line communications (PLC) metering signals in secondary substations with multiple distribution transformers. The study is based on real measurements of PLC connectivity across the low-voltage sections of transformers in a representative set of secondary substations. The results show that there is not a general rule indicating the quality of the PLC channel among secondary windings of distribution transformers in a secondary substation and, consequently, there is no general solution based in pre-existing information. Following this conclusion, a strategy is defined to maximize the performance of the PLC system, based on the PRIME PLC specification. This strategy is based in the use of a base node connected to one of the low-voltage panels, together with auxiliary nodes connected to the remaining low-voltage panels, and interconnecting all of the elements (base node and auxiliary devices) by means of non-PLC technologies.**

***Index Terms*—Coupling, distribution transformers, injection, power distribution, power-line communications (PLC), power–line intelligent metering evolution (PRIME), smart grids, smart metering.**

## I. Introduction

SMART metering deployments can be considered as the first step toward smart grids [1]–[4]. Smart metering is more than plain remote metering; smart metering includes the ability to remotely operate over meters (connect/disconnect), and is the door to new services for energy efficiency [5]–[10].

The natural media to connect meters to the central premises is power-line communications (PLC) [11]. Many technologies have been developed through recent history [12], [13] to communicate meters with concentrator devices at secondary substations (SS), where distribution transformers adapt voltage levels for user consumption. PRIME is a recent narrowband PLC specification using frequencies of the Cenelec A band. PRIME defines a novel layer 2 switching concept that is capable of automatically reconfiguring plain meters as repetition devices that will assist other meters in communicating with concentrators (base nodes).

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PLC smart metering performance depends on the architecture and constraints of the electricity grid. The electricity system is a conceptual aggregation of four main elements: 1) generation plants; 2) transmission lines; 3) substations; and 4) distribution system. This last part of the system, the one closer to the points of supply, is the object this paper.

SS are the core of the distribution system. Distribution transformers adapt voltage levels for customer delivery. The connection to customer distribution lines comes out from low-voltage (LV) panels attached to the secondary windings of the transformers. In consequence, these LV panels will be the connection point for PLC base node devices. In a standard SS, there is usually more than one LV panel, associated with one or more distribution transformers. As in many other parts of the electric grid, utilities' databases do not provide information about PLC interconnection across these LV panels, especially in multitransformer environments. The objective of this paper is to propose an optimal signal injection strategy to maximize the performance of a PLC system in a subnetwork inside an SS.

LV panel injection in multitransformer environments has not been addressed so far in the literature. Most references on this topic analyze the nature and structure of PLC automatic meter-reading (AMR) systems [8]–[10]. There are papers that focus on the technical description of PRIME technology [14]–[19]. Other papers deeply analyze the architecture of PLC modems, and their coupling interfaces [20]–[23]. There are papers that focus on the injection of PLC signals in SS mainly in the medium-voltage (MV) grid, in the primary winding of the distribution transformers [24]–[26]. Few papers focus on the characteristics of the communications devices for PLC communications in electricity substations [27], and some other papers discuss the three-phase nature of LV in substations [28]–[30]. Some recent studies deal with single-phase—single transformer PLC injection [31], [32].

The lack of references dealing with LV signal injection may be due to several reasons. The AMR systems have traditionally been proprietary solutions tightly fitted to each specific system provider. Details of the solutions used for these situations remain as the know-how of stakeholders involved in system deployments. The conclusion from the literature survey is a lack of references for PRIME PLC signal injection in multitransformer environments. This paper provides a strategy based on field tests.

The content of this paper is organized as follows. First, an overview of PRIME technology is provided, focusing on the relevant aspects of base node LV injection in SS. Second, the

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structure of SS is described, and PLC signal coupling is introduced. Then, this paper focuses on describing the two field tests performed: the first field test analyzes the communications connectivity across PLC LV panels, and the second field tests cover LV PLC injection in multitransformer environments based on the results from the previous analysis. This paper finishes with the conclusions.

## II. Overview of SS for Smart Metering PRIME PLC Deployment

### A. PRIME Overview

Power–line intelligent metering evolution (PRIME) is a narrowband PLC communication system in the LV electricity grid. PRIME specifications are managed by PRIME Alliance [33].

PRIME consists of physical (PHY) and media-access control (MAC) layers. In addition, PRIME provides convergence layers toward two applications: device language message specification/companion specification for energy metering (DLMS/COSEM), and the IP protocol layer. Convergence layers are the way in which PRIME makes lower layer resources available to applications [34].

One of the main novelties of PRIME is the concept of network autoconfiguration [35]. The PRIME MAC layer defines mechanisms that allow PLC network elements to be dynamically reconfigured at each moment to adapt to electricity network conditions (noises, interferences, etc.). Thus, the necessary switches in the network are created ("promoted" in PRIME terminology) and maintained by the base node, according to the help needed by service nodes of the network that cannot "hear" the base node, and demand assistance from terminal nodes that can reach base nodes. In a way, switches are delegates from the base node, helping it to reach everywhere in the subnetwork.

The PRIME PHY layer [36] works in the Cenelec A band, specifically from 42 to 89 kHz. This Cenelec subband is "restricted to electricity distributors and their licensees," as EN50065-1 states [37]. PRIME uses OFDM multiplexing with different modulation schemes (DBPSK, DQPSK, and D8PSK) and forward error correction (FEC) strategies.

The PRIME MAC layer is in charge of all the procedures to manage subnetwork creation, message exchange, and maintenance [38].

### B. SS Structure and Elements

The electricity distribution system at the SS level is composed of SS, distribution lines, and fuses at the supply end (where energy consumption meters are placed). SS are at the core of the distribution network and from a PLC perspective, they are the head end of the communication system, aggregating upstream data flowing from the meters connected to the secondary winding of the distribution transformers.

Transformers are the main components of a substation, and convert voltages from medium to low voltages. The elements specifically present in the SS, listed in the order in which they appear from the MV, through the LV grid, and to the points of supply are: distribution transformers, LV panels, and LV lines.

### C. PLC Signal Injection at SS with Multiple Transformers

Transformers in SS connect through LV panels (busbars) with different LV lines. These are the LV distribution lines that run through different paths toward all households. From a telecommunications point of view, LV lines are a shared media for PLC signals.

PLC signal injection takes place in SS at LV panels. These panels (there can be more than one at the SS) are a set of busbars acting as the origin of electricity flow from the SS toward the points of supply. The panels are also connected to the secondary winding of the transformer. Inside the panel, several bars are found (three phase and neutral), with blade-type fuses for each output circuit or line. All of these elements are mounted on a metallic framework (old panels) or inside a metallic enclosure (modern panels).

There is usually more than one transformer in an SS. This is the case especially in densely populated areas. In some instances, several LV panels belong to the same transformer in such a way that there is an electrical connection among them and the potential PLC communication channel is very good (without considering noise aspects). In other cases, LV panels are not electrically connected when they belong to different transformers showing practical isolation between them, and in a third scenario, the panels are somehow connected for PRIME communication through a common earthing.

As an example of the relevance of this study, in Europe, most SS in urban and suburban areas have a variable number of distribution transformers, from 1 to 4, with marginal exceptions. The percentage of SS with two or more transformers is about 30%, and this situation is predominant in urban cases where the percentage exceeds 50%. Specifically, when two or more transformers are present, the number of points of supply connected to the group of transformers far exceeds both percentages above, due to the fact that subsequent transformers are placed wherever demand increases. The typical number of lines connecting to the LV panels that interface between the secondary winding of distribution transformers and the point of supply themselves is around 1 to 16. Each LV line consists of four wires, three phases, and neutral (namely, R, S, T, and N).

For practical system deployment, the heterogeneous nature of real cases reveals even further difficulties, because on many occasions, the utilities' network databases do not reflect how LV panels are interconnected (if any connection is to be present).

In summary, there are severe constraints in the way the PLC signal has to be injected in the substations toward all LV points of supply, and the implications of the different topologies must be assessed to come to the most effective solution. This "case-by-case" deployment method approach is unfeasible in real networks, and an effective PLC injection strategy for PLC must be found, independent of the particularities of each substation.

## III. LV PLC Connectivity Tests in SS

From a telecommunications perspective, different situations may appear in a certain SS, where several transformers feed the

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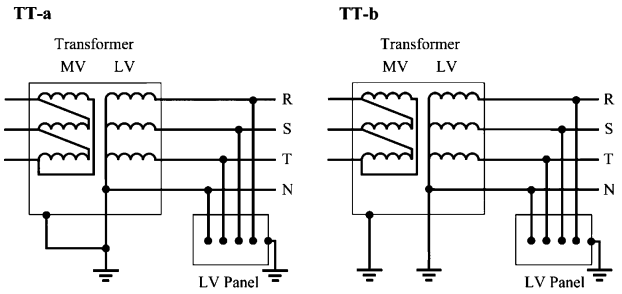



Fig. 1. Some of the different configurations of distribution transformers [39].

LV grid, and independently of electricity connections of the different LV panels. There is not *a priori* knowledge of the existence or quality of the communication channel that could be present among the different LV panels of the SS.

Fig. 1 shows two typical transformer and conductors connections in SS. TT-a and TT-b are sample representations of neutral and earth connectivity situations, but not the only possible ones. In configuration TT-a, it can be seen that in the case where multiple transformers exist in the SS, as the earthing for MV section is shared among them, there is a possible PLC connectivity path in the LV section.

Two approaches for signal coupling can be used depending on the following cases. The first one corresponds to LV panels that do not result in a PLC channel. In this situation, the interaction among PRIME elements is nonexistent, and the selection of a coupling strategy only depends on parameters related to the cost and performance of the resulting network. Several PLC injections must be necessarily made, because several naturally separated subnetworks exist in the SS.

The second case is in reference to LV panels that do result in a PLC channel. The initial apparent advantage of reaching certain meters belonging to bars where the PRIME signal is not directly coupled is soon replaced by the need to control the injection to achieve full communications with all meters. Thus PRIME signal must be fed to the different panels, to guarantee full PRIME "coverage," and the interference created due to this multicoupling will affect performance.

### A. Field Test

Ten different SS have been chosen to carry out a field test, selecting them with the conditions as will be stated and obtaining a representative sample of the SS of the utility: dense urban situations, two or more transformers present in the SS, different transformer combinations (B1, B2, and B2A in Table II are different transformer types) inside the SS, SS extracted from the most prevalent types of SS with several transformers in dense urban areas, and a number of points of supply served greater that a few hundreds. The first four columns of Table II summarize the characteristics of the 10 SS selected. This selection covers a representative group of relevant situations.

### B. Test Methodology

The trial consisted of physical-layer communication tests among the different LV panels and individual busbars in the different combination possibilities for the different transformers present in the SS. The devices used for the test were ZIV 4PBN modems [40], one configured as the transmitter and the other as the receiver. The transmitter was prepared to send a known pseudorandom bit pattern, repeated as many times as needed to cope with the length of the frame to be transmitted, with a known sequence of all the modulation and coding possibilities of PRIME specification 1.3e (DBPSK, DQPSK and D8PSK, with and without FEC).

TABLE I
FRAME LENGTH TESTED AND FAILURE RATE

| | Modulation | | | | | |
|---|---|---|---|---|---|---|
| | DBPSK | DQPSK | D8PSK | DBPSK | DQPSK | D8PSK |
| | FEC | | | | | |
| Length (Bytes) | OFF | OFF | OFF | ON | ON | ON |
| 19 | 14% | | | | | |
| 24 | | | | 0% | | 0% |
| 30 | | | | 0% | 0% | |
| 31 | 16% | 40% | | | | |
| 42 | | | | 0% | 0% | 2% |
| 43 | 24% | | 100% | | | |
| 78 | | | | 0% | 0% | 2% |
| 79 | 46% | 86% | 100% | | | |
| 150 | | | | 0% | 0% | 2% |
| 151 | 76% | 100% | 100% | | | |
| 222 | | | | 0% | 0% | 0% |
| 223 | 80% | 100% | 100% | | | |
| 294 | | | | 0% | 0% | 2% |
| 295 | 90% | 100% | 100% | | | |
| 366 | | | | 2% | 0% | 0% |
| 367 | 96% | 100% | 100% | | | |
| 510 | | | | | 4% | 2% |
| 511 | 96% | 100% | 100% | | | |
| 726 | | | | | 0% | 10% |
| 727 | 100% | 100% | 100% | | | |
| 1,086 | | | | | | 8% |
| 1,087 | | 100% | 100% | | | |
| 1,519 | | 100% | 100% | | | |
| 2,239 | | | 100% | | | |

TABLE II
PLC CONNECTIVITY RESULTS FOR TESTED SS

| Code | Type | Transformers | Transformer Type | Transformer Neutral Wires | PRIME Signal Coupling | Group |
|---|---|---|---|---|---|---|
| 642620 | GFB | 2 | B2+B2A | Common | Ok | 1 |
| 604060 | GFB | 2 | B2+B2 | Independent | Ok | 2a |
| 604030 | GFB | 2 | B2+B2 | Independent | No | 2b |
| 700930 | CB | 2 | B1+B2A | Independent | No | 2b |
| 603830 | CB | 2 | B1+B2A | Common | Ok, Note 1 | 1 |
| 604720 | SC | 2 | B1+B1 | Common | Ok, Note 2 | 1 |
| 703060 | SC | 2 | B2A+B2A | Common | Ok, Note 3 | 1 |
| 703080 | GFB | 2 | B2A+B2A | Common | Ok | 1 |
| 603950 | CB | 3 | B1+B2+B2 | 2 Common + 1 Independnt | No | 1& 2 |
| 604210 | CB | 2 | B2+B2 | Independent | Ok | 2a |

**Type**: GFB = Ground floor, building; CB = Cellar, building; SC = Surface, container
**Note 1**: 4 wrong, out of 18; **Note 2**: 1 wrong, out of 18; **Note 3**: 3 wrong, out of 18

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The transmitter was connected to the first LV panel, and measurements were taken in the rest of the panels. This sequence was repeated for all panels belonging to different transformers inside the SS.

Included in the measurement routine from before and with the consideration that the coupling mechanism used is single phase (one phase and neutral connection of the two wires of the modem), all three-phase combinations were tested (R in the transmit panel with R in the reception, R in the transmit panel with S in the reception, R in the transmit panel with T in the reception, and the same with the remaining S and T phases).

The connection of the modems was not made directly, but a set of protective elements was used in the middle for normative safety reasons. In the grid measured, these elements must be a tetrapolar circuit breaker and a differential circuit breaker. In practice, these elements do not disturb the results and were included because regular deployments will use them [27]. The physical connection to the bars was a set of clamps, and data were feed to the modems and stored back using a single laptop with an RS-232 connection to the modems.

### C. Measurement Results

From the transmitter side, 50 frames at maximum power [37] were sent at different frame sizes. These frame sizes considered an incremental fixed sequence of symbol/byte count, chosen from the test developed in PRIME for PHY layer testing and representative of all PRIME modulation and error-correction possibilities [33].

The output obtained in the receiver was a raw text file with information of the successful and erroneous frames. The figures were verified for each of the tested frame lengths, as shown in Table I (note that not all frame lengths have a rate attached; this is due to the specificities of the PRIME physical-layer coding).

Results show that FEC modes are the ones showing maximum success rates (coherent with previous and expected results [17]). It is expected that future PRIME commercial deployments use these FEC modes, and in any case, they will be the right choice for control packets. Differential binary phase-shift keying (DBPSK) modulation with forward error correction (FEC) was selected for analysis in this trial.

Successful communication was considered when 75% or more correct frames were received. It has to be noted that upper protocol layers will compensate for the 25% erroneous transmissions. The condition of the percentage of correct frames must be considered for all combinations of phases under test. This means that all 18 possible channels between two LV panels (both transmission and reception for RR, RS, RT, SR, SS, ST, TR, TS, and TT combinations) must render a good PLC communication channel.

### D. Discussion

Based on the results summarized in Table II, several groups with different behavior may be identified. The first one (group 1 in Table II) is composed of those SS where the transformers are connected through common wires. The communication was always successful for this case.

The second group (group 2 in Table II) refers to the case where the neutral connections of the transformers are not connected (independent wires). In this case, 50% of the cases did not present a communication channel for PLC (group 2b), and another 50% of the cases had a reliable communications channel (group 2a). This last case will represent a problem for a normalized PRIME deployment strategy, and it is the object of the tests described in the next chapter.

In the case of a single-specific SS where three transformers were present, there was good interconnection between two transformers, but not with the third. This SS presents a behavior that is coherent with the results summarized in the paragraphs before for the transformers with neutral connection, and for the third independent transformer, respectively.

The irregular behavior of the second group (unconnected transformers) was further analyzed with a second phase of tests. The main objective of this second phase was to modify artificially the connectivity between transformers of the same SS. In the cases where connectivity was already present before the artificial connection, the communication remained possible. In the cases where the communication was not successful, the interconnection of the transformers improved the situation, but still with a significant amount of unavailable PLC connections. For the specific case of the SS with three transformers, even though different interconnections among neutrals were performed, a communication channel could not be established.

The trials revealed that the connection of neutral wires of the transformers has a good correlation with the likelihood of having a PLC communications channel among the LV panels connected to these transformers. Nevertheless, there are circumstances in which the communications channel is not good enough for network stability, regardless of the neutral connectivity among the transformers of the SS.

## IV. PLC Signal Injection Tests in SS

The results described in the previous section provided evidence that there is no way to obtain *a priori* knowledge of the nature (existence and quality) of the PLC channels configured among LV panels of SS where several transformers are placed and, in theory, each SS would require an analysis to investigate the best approach. This fact is not acceptable for the realistic deployment of AMR systems in utilities. A strategy to inject PLC signals that can be applied consistently and independently of the details of the SS architecture is mandatory for the utilities.

### A. Signal Injection Alternatives

This study focused on the cases where a multitransformer situation exists in the SS, and in all of them, the tests used single-phase injection (neutral and phase connection). Designs for PRIME base nodes follow this approach [31], [32].

There are three PLC injection possibilities (Fig. 2) when several LV panels connect in different quantity to several transformers.

The first case is a single base node per SS, electrically coupled to one LV panel, with the PRIME PLC connection to the rest of the LV panels in which auxiliary devices are used to

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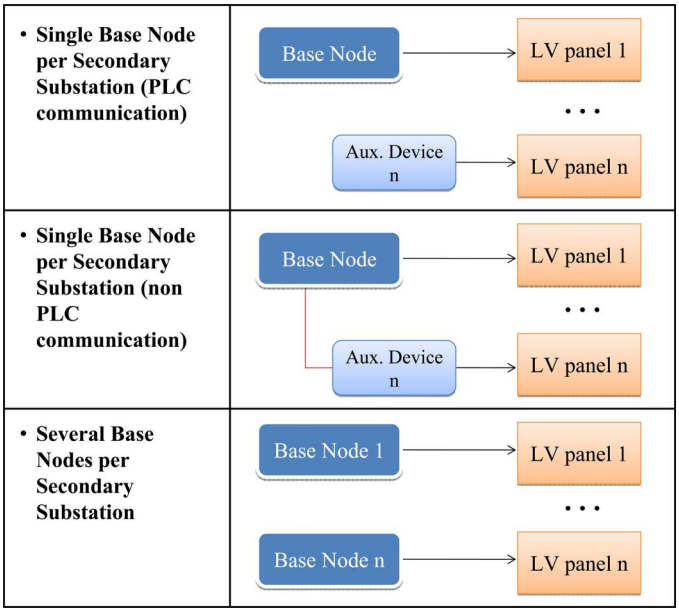



Fig. 2. Injection possibilities in multi-LV panel situations.

reach the remaining meters in the LV grid. Auxiliary devices are PRIME modems with switch functionality; PRIME defines two states for a service node (a PRIME element), terminal, and switch. When a service node is in switch state, it can retransmit MAC frames to help the base node reach all of the elements in the grid. Although PRIME networks generally assume that PRIME modems are inside PRIME meters, nothing prevents PRIME modems to be detached from meters as stand-alone devices. The connectivity between the base node and auxiliary devices is achieved over the PLC communication channel.

The second alternative is a single base node per SS, electrically coupled to a single LV panel, and with external connections (Ethernet, coax cable, ...) to some auxiliary devices (PRIME modems with Switch functionality) connected to the rest of the LV panels with the purpose of reaching the remaining meters in the LV grid. With this option, the communication between the base node and auxiliary devices will be achieved over a non-PLC channel.

The third alternative would be composed of several independent base nodes, each of them coupled to the corresponding LV panel.

In an environment where a certain channel exists between LV panels, the worst case situation is where a non or far from perfect channel exists among them, due to the fact that the PLC signal may not be enough for a good PLC channel to be established. But in a configuration with several simultaneously transmitting devices, it can be enough to harm performance, with an interferer behavior, and even worst, with a hidden node issue.

The test environment was chosen among the cases where the PLC channel among LV panels was good but far from "perfect."

### *B. Test Arrangement*

A SS was chosen with two transformers and three LV panels to carry out the tests. There are 12 LV lines flowing out from these three panels. The number of service nodes involved (real electricity meters) is 604.

TABLE III
TEST STATISTICS FOR DIFFERENT INJECTION CONFIGURATIONS

| Config. | Description | SNs | Messages | Transactions | Duration of a Message Exchange (seconds) | Duration of the measurement (hours) |
|---|---|---|---|---|---|---|
| 1 | BN + Aux (Eth) | 604 | 225,043 | 182,840 | 2.3 | 143.8 |
| 2 | BN + Aux (PRIME) | 600 | 193,549 | 127,435 | 2.5 | 135.1 |
| 3 | 2 x BN | 601 | 593,247 | 442,106 | 1.2 | 197.6 |
| 4 | BN (1st panel) | 254 | 146,484 | 109,487 | 2.4 | 99.3 |
| 5 | BN (2nd panel) | 433 | 98,021 | 61,201 | 2.5 | 69.8 |

TABLE IV
TEST RESULTS FOR DIFFERENT INJECTION CONFIGURATIONS (CONTINUED FROM TABLE III)

| Config. | Description | SNs | Message Failure Rate | Transaction Failure Rate | Latency (ms) | Retry Rate |
|---|---|---|---|---|---|---|
| 1 | BN + Aux (Eth) | 604 | 20.1% | 3.8% | 274.0 | 0.230 |
| 2 | BN + Aux (PRIME) | 600 | 38.4% | 10.0% | 341.8 | 0.541 |
| 3 | 2 x BN | 601 | 28.0% | 6.0% | 263.8 | 0.358 |
| 4 | BN (1st panel) | 254 | 27.3% | 6.2% | 271.8 | 0.339 |
| 5 | BN (2nd panel) | 433 | 42.9% | 20.9% | 336.3 | 0.663 |

Among the three LV panels, in any combination, there was a good PRIME PLC channel. Moreover, two of these panels were virtually the same electrical connection, so that for the purpose of the test, we will only consider two virtual LV panels.

The test arrangement was configured with two injection strategies. The first one was based on using one base node in one LV panel, and an auxiliary device in the other (the connections of both devices will be completed in two different ways—see configurations 1 and 2 in Tables III and IV). The second one (configuration 3 in Tables III and IV) involved two base nodes, each one connected to each of the two virtual LV panels. The devices were the ZIV 4PBN model, configured to work as either a base node or as an auxiliary device (service node with switch configuration).

The test not only included the PHY layer but also the MAC layer of PRIME. An application emulation tool was used for the MAC layer to work as recommended by the PRIME specifications [41]. For each test, the emulation tool established a closed loop involving all registered service nodes (meters) in the subnetwork created by a base node. For all registered meters, connections were established and released in a predefined dialog. Messages forming this dialog had a preagreed content, and it was straightforward to check if any of the messages involved in the transaction were either lost or corrupted. At the application level, there was also a mechanism to repeat requests (to a maximum of three repetitions) from the base node if no answer was received in a predetermined period of time. Thus, the failure rate was calculated either at the single message exchange level, or at the transaction level.

Different test configurations were considered in this study, for each of the two LV virtual panels involved. The first configuration connected one base node in the first panel, and one auxiliary node in the second panel. Two variations were considered

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TABLE V
SUMMARY OF RELEVANT DATA FOR THE TESTED INJECTION CONFIGURATIONS

| Config. | Description | SNs | Message Failure Rate | Latency (ms) |
|---|---|---|---|---|
| 1 | BN + Aux (Eth) | 604 | 20.1% | 274.0 |
| 2 | BN + Aux (PRIME) | 600 | 38.4% | 341.8 |
| 3 | 2 x BN | 601 | 28.0% | 263.8 |

for this injection; the first one when the base node and the auxiliary device were connected through Ethernet (configuration 1), and the second when they were connected only through PRIME (configuration 2).

The second configuration (configuration 3) consisted of two base nodes, each connected simultaneously to each virtual panel.

To check the integrity of the results obtained in the test, two more tests were included, connecting one single base node (without auxiliary device) to one of the LV panels in the first place (configuration 4), and to the second one as a final step (configuration 5). Configurations 4 and 5 did not provide connectivity with all of the meters in the grid.

Each configuration was tested for a long period (minimum period of 20 h, and maximum of 143 h each) to ensure the involvement of the effects of the high number of devices involved, the changing nature of PLC media, and the possible particularities of test devices at the MAC level. Each configuration was repeated four times to check the consistency of the results. To get rid of the specificities of the politics used by the specific PRIME implementation at the MAC level and the way they adapt with time to the changing nature of PLC channels, each time a new composition was checked, a complete reset of the network was performed.

The metric used to evaluate the best configuration was based on the failure rate. This rate can be analyzed at the individual message level or at the transaction level (the message level checks the correct reception of a single request/response, while the transaction level checks whether the application level repetition—up to three times—renders a correct result). The decision was made to use the first one because it provides more information than the second one (single message errors can be observed). Another figure of merit that could possibly be used is latency. However, since the target application is metering, this parameter was considered to be of secondary interest.

### C. Results

Tables III and IV summarize the statistics of the test, and Table V shows the results. A total of 1041 h were employed for the measurements, and more than 1.3 million transactions were measured for this set of more than 600 electricity meters.

If we consider the message failure rate, the configuration that provides the best results is injection strategy 1—base node and auxiliary device connected with Ethernet—followed by injection strategy 3 (two base nodes) with a 39.4% worst behavior than the first one, and injection strategy 2, 90.9% worst than the first one.

If we take the latency results into consideration, the results are coherent with the ones obtained for the failure rate. The latency for strategy 3 is slightly better than for strategy 1 (3.9%), and strategy 2 is clearly in the third position (see Table V).

## V. CONCLUSION

PLC deployments for smart metering must be simple. Metering business, from the field operations perspective, has traditionally been a straightforward business consisting of placing meters in the points of supply, without sophisticated knowledge of any telecommunication technology.

In multitransformer SS, it is not possible to have *a priori* knowledge of the PLC connection possibilities among the different LV panels. This information is not available today in the databases of utilities, and is not possible to obtain this information from a visual inspection in the field.

Moreover, with the information available today from the results of measurements in the field, it is not possible to establish the direct relationship between transformer neutral wire interconnection, and the viability and quality of the PLC channel.

When it comes to PLC energy coupling among LV panels, different PLC signal level and qualities can be observed. This circumstance, far from being helpful, imposes obstacles in system behavior of the subnetwork configured with PRIME in an SS with multiple transformers, due to interferences between elements that belong to the subnetwork itself.

This paper has shown how PLC connectivity among LV panels is unpredictable. For this circumstance, a pragmatic field approach has been tested and is offered as a strategy for PRIME PLC signal injection in SS in order to maximize smart metering figures of merit.

The strategy is based in placing one base node in any LV panel, and using auxiliary devices with PRIME repetition (switch) characteristics in the rest of them, as a sort of distributed concentrator. These auxiliary devices should be linked with the main base node with other means different to PRIME.

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## REFERENCES

[1] V. K. Sood, D. Fischer, J. M. Eklund, and T. Brown, "Developing a communication infrastructure for the smart grid," in *Proc. IEEE Elect. Power Energy Conf.*, Montreal, QC, Canada, 2009, pp. 1–7.

[2] R. Mora, A. Lopez, D. Roman, A. Sendin, and I. Berganza, "Communications architecture of smart grids to manage the electrical demand," presented at the WSPLC, Udine, Italy, Oct. 2009.

[3] H. Yan, N. Jenkins, W. Jianzhong, and M. Eltayeb, "ICT infrastructure for smart distribution networks," in *Proc. ISPLC*, Rio de Janeiro, Brazil, Mar. 2010, pp. 319–324.

[4] C. Nunn and K. Sullivan, "From theory to practice: The development and implementation of PowerNet(R)-an advanced power line carrier system for AMR, DSM, DA and non-utility applications," in *Proc. 14th Int. Conf. Exhibit.Elect. Distrib. Part 1: Contrib.*, 1997, vol. 5, pp. 8/1–8/5.

[5] A. Zaballos, A. Vallejo, M. Majoral, and J. M. Selga, "Survey and performance comparison of AMR over PLC standards," *IEEE Trans. Power Del.*, vol. 24, no. 2, pp. 604–613, Apr. 2009.

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[6] D. Sabolic, "Influence of the transmission medium quality on the automatic meter reading system capacity," *IEEE Trans. Power Del.*, vol. 18, no. 3, pp. 725–728, Jul. 2003.
[7] K. Honghai and W. Zhengqiu, "Application of AMR based on power-line communication in outage management system," in *Proc. Int. Conf. Sustain. Power Gen. Supply*, 2009, pp. 1–4.
[8] B. S. Park, D. H. Hyun, and S. K. Cho, "Implementation of AMR system using power line communication," in *Proc. IEEE Power Eng. Soc. Transm. Distrib. Conf. Exhibit.*, 2002, vol. 1, pp. 18–21.
[9] C. Nunn, P. M. Moore, and P. N. Williams, "Remote meter reading and control using high-performance PLC communications over the low voltage and medium voltage distribution networks," in *Proc. 7th Int. Conf. Meter. App. Tariffs Electric. Supply*, 1992, pp. 304–308.
[10] P. Oksa, M. Soini, L. Sydanheimo, and M. Kivikoski, "Considerations of using power line communication in the AMR system," in *Proc. IEEE Int. Symp. Power Line Commun. Appl.*, 2006, pp. 208–211.
[11] A. Hosemann, "PLC applications in low voltage distribution networks," in *Proc. ISPLC*, Essen, Germany, Apr. 1997, pp. 134–139.
[12] D. Dzung, I. Berganza, and A. Sendin, "Evolution of powerline communications for smart distribution: From ripple control to OFDM," presented at the IEEE ISPLC, Udine, Italy, Apr. 2011.
[13] N. Pavlidou, A. J. Han Vinck, J. Yazdani, and B. Honary, "Power line communications: State of the art and future trends," *IEEE Commun. Mag.*, vol. 41, no. 4, pp. 34–40, Apr. 2003.
[14] I. Berganza, A. Sendin, and J. Arriola, "PRIME: Powerline intelligent metering evolution," in *Inst. Eng. Technol. CIRED. CIRED Seminar SmartGrids Distrib.*, 2008, pp. 1–3.
[15] A. Lasciandare, S. Bois, P. Bisaglia, and A. Moscatelli, "STarGRID™: The first industrial system on chip platform full PRIME compliant," in *Proc. IEEE Int. Symp. Power Line Commun. Appl.*, 2010, pp. 308–312.
[16] A. Sanz, J. I. Garcia-Nicolas, P. Estopian, and S. Miguel, "PRIME from the definition to a SoC solution," in *Proc. IEEE Int. Symp. Power Line Commun. Appl.*, 2009, pp. 347–352.
[17] K. Il Han, B. Varadarajan, and A. Dabak, "Performance analysis and enhancements of narrowband OFDM powerline communication systems," in *Proc. IEEE 1st Int. Conf. Smart Grid Commun.*, 2010, pp. 362–367.
[18] Y. Ming and D. Jian-Hua, "The design and implementation of 128-bit AES encryption in PRIME," in *Proc. 3rd IEEE Int. Conf. Comput. Sci. Inf. Technol.*, 2010, vol. 7, pp. 345–348.
[19] M. Hoch and G. Bumiller, "Interoperability of carrier-modulated OFDM systems with PRIME," in *Proc. IEEE Int. Symp. Power Line Commun. Appl.*, 2009, pp. 201–204.
[20] M. P. Sibanda, P. A. J. van Rensburg, and H. C. Ferreira, "Passive, transformerless coupling circuitry for narrow-band power-line communications," in *Proc. IEEE ISPLC*, 2009, vol. XXX, pp. 125–130.
[21] P. A. J. van Rensburg and H. C. Ferreira, "Design and evaluation of a dual impedance-adapting power-line communications coupler," *IEEE Trans. Power Del.*, vol. 25, no. 2, pp. 667–673, Apr. 2010.
[22] K. Fezzani, C. Rebai, and A. Ghazel, "Analysis and optimization of power line coupling circuit for CENELEC-PLC Modem," in *Proc. 13th IEEE Int. Conf. Electron., Circuits Syst.*, 2006, pp. 676–679.
[23] A. Lotito, R. Fiorelli, D. Arrigo, and R. Cappelletti, "A complete narrow-band power line communication node for AMR," in *Proc. IEEE Int. Symp. Power Line Commun. Appl.*, 2007, pp. 161–166.
[24] P. A. A. F. Wouters, P. C. J. M. van der Wielen, J. Veen, P. Wagenaars, and E. F. Steennis, "Effect of cable load impedance on coupling schemes for MV power line communication," *IEEE Trans. Power Del.*, vol. 20, no. 2, pt. 1, pp. 638–645, Apr. 2005.
[25] L. Weilin, H. Widmer, and P. Raffin, "Broadband PLC access systems and field deployment in European power line networks," *IEEE Commun. Mag.*, vol. 41, no. 5, pp. 114–118, May 2003.
[26] C. J. Kikkert, "Modeling power transformers for the design of SWER line coupling networks," in *Proc. 1st IEEE Int. Conf. Smart Grid Commun.*, 2010, pp. 120–125.
[27] A. Sendín, R. Guerrero, P. Angueira, and J. Morgade, "PRIME technology in smart electricity grid. Adaptation of telecommunication systems to electricity grid," presented at the 49th FITCE, Santiago de Compostela, Spain, 2010.
[28] W. C. Black and N. E. Badr, "High-frequency characterization and modeling of distribution transformers," in *Proc. IEEE ISPLC*, Rio de Janeiro, Brazil, Mar. 2010, pp. 18–21.
[29] M. Zhai and Q. Zeng, "Signal propagation on three phases power distribution lines as communications channels for intelligent systems," in *Proc. IEEE ICICIC*, 2006, pp. 437–440.
[30] A. Pasdar and S. Mirzakuchaki, "Three phase power line balancing based on smart energy meters," in *Proc. IEEE EUROCON*, St. Petersburg, Russia, 2009, pp. 1876–1878.
[31] A. Sendin, A. Llano, A. Arzuaga, and I. Berganza, "Field techniques to overcome aggressive noise situations in PLC networks," presented at the IEEE ISPLC, Udine, Italy, Apr. 2011.
[32] A. Sendin, A. Llano, A. Arzuaga, and I. Berganza, "Strategies for PLC signal injection in electricity distribution grid transformers," presented at the IEEE ISPLC, Udine, Italy, Apr. 2011.
[33] PRIME Alliance—Technical Working Group, PRIME Spec. May 2010, ver. 1.3e. [Online]. Available: http://www.prime-alliance.org
[34] A. Arzuaga, I. Berganza, A. Sendin, M. Sharma, and B. Varadarajan, "PRIME interoperability tests and results from field," presented at the IEEE Smartgrid Conf., Gaithersburg, MD, Oct. 2010.
[35] , H. C. Ferreira, L. Lampe, J. Newbury, and T. G. Swart, Eds., *Power Line Communications: Theory and Applications for Narrowband and Broadband Communications Over Power Lines*. New York: Wiley, 2010.
[36] I. Berganza, Metering International, Iberdrola strategy on AMI and smart grids, no. 2, 2008.
[37] "Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148, 5 kHz—Part 1: General requirements, frequency bands and electromagnetic disturbances," 2001, EN 50065-1.
[38] A. Sendin, "Iberdrola PRIME project: above PHY layer," *Metering Int.* no. 4, 2008 [Online]. Available: http://www.metering.com
[39] Schneider Electric, *Electrical Installation Guide*. 2008. [Online]. Available: http://www.schneider-electric.com
[40] ZIV, "Haciendo realidad la red del futuro," ZIV Grid Automation. 2009. [Online]. Available: http://www.zivgridautomation.com/data/smartgrids/FAMI0911A.pdf
[41] PRIME Alliance—Technical Working Group, PRIME certification test cases. Mar. 10, 2010, ver 1.2. [Online]. Available: http://www.prime-alliance.org

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