Realistic Model for Narrowband PLC for Advanced Metering Infrastructure

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Abstract—Advanced Metering Infrastructure (AMI) is a key enabler of the Smart Grid. Narrowband Power Line Communication (PLC) technology is currently the preferred choice for many AMI use cases. Different PHY/MAC standards and dedicated routing protocols are emerging. New trustworthy models and simulation tools are needed for their evaluation in large scale deployments. This paper presents a realistic model for the latest generation of OFDM-based narrowband PLC standards. The model has been implemented in a popular network simulator – OPNET. Furthermore, the model and the simulator are validated against a real-world testbed. Finally, we present the calibration process and the scalability of the simulator. The results show that it is possible to simulate large topologies of up to 1000 smart meters under a proactive (RPL) or reactive (LOAD) packet routing.

I. INTRODUCTION

Advanced Metering Infrastructure (AMI) is a key enabler of the Smart Grid. AMI relies on efficient and robust Neighborhood Area Networks (NAN) to carry information between power meters and data concentrators (DC).

In a wide range of use cases, the utilities and meter industries worldwide have selected the narrowband (< 500 kHz) Power Line Carrier (PLC) technology to guarantee the physical and medium access robustness. Several standards for the physical and data link layers are emerging, such as the ITU-T 9903 and IEEE P1901.2. In a generic smart grid network profile, utilities have approved IPv6 to enable convergence of smart grid networks with standard IT network management and configuration tools.

Narrowband PLC technologies are intrinsically limited in terms of data rates and implement specific algorithms to increase reliability and robustness in noisy and uncontrolled impedance environments. Dedicated routing protocols have been developed to accommodate the singularities of narrowband PLC technologies in order to maintain adequate reliability and performance levels required for AMI applications. The PLC technology studied in this paper defines the physical layer, medium access sub-layer, adaptation sub-layer and the network layer. Routing mechanisms may be defined as mesh-under in the adaptation sub-layer or mesh-over in the network layer and are both studied in this paper with the reactive LOAD (6LoWPAN Ad Hoc On-Demand Distance Vector Routing) [1] and the proactive RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) [2].

To evaluate a PLC technology, the AMI industry relies on performance metrics reported on large scale cells (1500 nodes per concentrator), on a wide range of topologies (rural, urban, mixed) and on different impedance and noise profiles. Real field evaluations are generally limited to a small numbers of nodes, topologies and noise profiles. The main limitation is the resources and logistic costs related to pilot deployments. The only alternative to real field deployments are simulation-based evaluations. Several popular network simulators exist (e.g. OMNET++, ns2, ns3) each having its strengths and weaknesses. In this paper we present our methodology for developing a realistic model for narrowband PLC-based AMI communications. The model was implemented in OPNET, which was selected as a preferred tool in term of its industry-wide acceptance, existing physical libraries, MAC source code availability and graphical presentation. However, the simulation tool by itself does not provide guarantees of credible, realistic and fair results. A model is reliable and realistic only after a proper validation against a real-world implementation.

The rest of this paper is organized as follows. Sec. II provides a high-level description of the narrowband PLC technology and the routing protocols used as basis for our model and simulations. Sec. III dives further in the PLC G3 technology with a detailed exposition of the physical and MAC layer characteristics, along with the the way we modeled and implemented them. The reference testbed used for validation of our simulator is presented in Sec. IV. The validation methodology and the main results are provided in Sec. V. Finally, we review the related work in Sec. VI before concluding this paper in Sec. VII.

II. SYSTEM ARCHITECTURE

A. Physical Layer Overview

PLC physical channel characteristics are subject to significant variations and the environment remains hostile for applications requiring reliability and guaranteed data rates. Two standards IEEE P1901.2 and ITU-T 9903 are currently being driven by a large group of key AMI industry players. Those standards define different sets of physical layer depending on
the frequency bands and regulations existing over the world. As a first step, we focused on the specification that was used as starter point for both standardization processes: the PLC G3 Cenelec A band [3], [4].

PLC G3 Cenelec A works in the 35kHz–91kHz band range [3] and uses OFDM modulation over 36 carriers. The PLC G3 physical layer also implements a time frequency interleaver over the entire PHY frame coupled with a Reed Solomon and Viterbi Forward Error Correction for maximum robustness. The noise level in each sub-carrier can vary significantly. PLC G3 specifies two complementary mechanisms allowing to fine-tune the robustness/performance tradeoff implicit in such systems. More specifically, the first (coarse-grained) mechanism, defines the modulation from several possible choices (robust (ROBO), BPSK, QPSK,...). The second (fine-grained) maps the sub-carriers which are too noisy and deactivates them.

The existence of multiple modulations and dynamic frequency exclusion renders the problem of selecting a path between two nodes non-trivial, as the possible number of combinations increases significantly, e.g. use a direct link with low robust modulation, or use a relay meter with fast modulation and 12 disabled sub-carriers. In addition, PLC G3 technology offers a mechanism for periodic exchanges on the link quality between nodes to constantly react to channel fluctuations – the Adaptive Tone Map (TM) mechanism. Every meter keeps a state of the quality of the link to each of its neighbors by either piggybacking the tone mapping on the data traffic, or by sending explicit tone map requests.

B. Data Framing

The physical characteristics of narrowband PLC resemble the ones of low-power, lossy radio links. As a consequence, PLC G3 reuses parts of the MAC layer and channel access methods of IEEE 802.15.4. However, as PLC G3 defines several modulations, a PHY-layer header has been defined to specify parameters relative to the payload.

Every frame starts with a preamble followed by the Frame Control Header (FCH) [4]. The FCH includes information such as the type of frame, its length, modulation and tone map. The FCH is always sent in robust mode and is protected with a CRC. The MAC layer frame follows the FCH and is based on the IEEE 802.15.4 with almost identical structure.

C. Packet forwarding

Two major protocols can be considered for packet forwarding in lossy, narrowband networks – LOAD and RPL.

LOAD (6LoWPAN Ad Hoc On-Demand Distance Vector Routing) [1] is a reactive protocol, which finds a route only when it is necessary, e.g. when a node has data to send to a given destination. It relies heavily on broadcasting requests through the entire network in order to find the destination. LOAD is a straightforward protocol with good performance, and is part of the PLC G3 specification.

RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) [2] is a proactive protocol, which constantly updates the routes from and towards a specific node (e.g. the data concentrator). Contrary to LOAD, RPL does not require network-wide broadcasts, but needs to be carefully configured so that the network topology updates are neither too frequent nor not frequent enough. RPL is the IETF protocol for low power, lossy networks. It is highly configurable, but also much more complex than LOAD.

Both protocols have their strengths and weaknesses and their behavior may affect the performance of the network. For that reason it is important to be able to evaluate them and estimate the best use cases for each one, and the appropriate parametrization. The latter point is of crucial importance for RPL, as it can drastically change its behavior.

III. PLC SIMULATOR

A. Physical Model

The Physical Model is mainly based on Signal-to-Noise Ratio (SNR) computation as it is used for node reachability, data transmission and tone map procedures. The available band is divided into 6 subcarrier groups, with independent SNRs. The subcarrier SNR is used to select the modulation and the usable group of subcarriers between two meters. The effective SNR is the average SNR over all enabled subcarrier groups. The average SNR is used to detect transmission errors – upon reception, the simulator performs a look-up in a reference BER vs SNR table to decide if a frame can be correctly decoded by the node. BER vs SNR tables are computed with G3 PLC Matlab demodulator using field noise captures as input. A threshold SNR determines the neighbors of a meter. We use the following equation (Eq. 1):

$$SNR = SNR_0 + 10 \log_{10} \left[ e^{-\frac{2 \pi d}{B_w}} \left[ e^{-\frac{2 \pi d}{B_w}} \left[ e^{-\frac{2 \pi d}{B_w}} - e^{-\frac{2 \pi d}{B_w}} \right] \right] \right]$$

(1)

as introduced in [5] for calculating SNR in multipath PLC channels, where \(d\) is the distance between two nodes, \(a_0\) and \(a_1\) stand for attenuation parameters. The values of these parameters depend on the link distance. \(B_w\) is the channel bandwidth and \(f_{min}\) (resp. \(f_{max}\)) denotes the minimal (resp. maximal) frequency. The SNR per subcarrier is obtained by randomizing the average SNR with an exponential distribution.

B. Simulator overview

A set of supporting tool has been developed for OPNET simulator. External PLC Physical Link Simulator allows to define complex PLC G3 topologies. The tool generates a topology file with the SNR Matrix \(c_{ijk}\), both imported in OPNET. \(c_{ijk}\) represents the SNR for every pair of nodes \(i\) and \(j\) on every group of channels \(k\). The SNR matrix \(C = \{c_{ijk}\}\) is (possibly) asymmetric, thus allowing the simulation of non-isotropic signal propagation. During the simulations, the OPNET model uses the \(C\) matrix to determine the transmission range, the Bit-error-rate (BER) for all available modulations and for all subcarrier groups. This is in turn used to dynamically calculate the Tone Map and the neighbors of a node.

Since the calculation of all these characteristics can prove to be extremely time-consuming for large topologies and long simulations, we’ve introduced an interface providing the MAC layer with a macroscopic view of the PHY layer. The interface
layer (Fig. 2) has a limited number of macro (MAC-layer) states indicating the state of the medium at each node, as well as the modulation to be used by a node to reach its neighbors. The link state is modeled as a vector \( L \) where \( L_i \) indicates the link status for node \( i \). The link at each node can be:

- **F** (Free) – There is no ongoing transmission. CSMA/CA will not sense any carrier and will allow the node to start transmitting after the expiration of the backoff period.
- **U** (Unknown) – There is an ongoing transmission but the channel is considered free. CSMA/CA will not sense the carrier and will allow transmission, thus provoking a collision. This state is necessary in order to model collisions due to propagation delays. The state transitions from \( U \) to \( B \) after the maximum propagation time elapses. It may also transition to \( C \) if a collision occurs.
- **B** (Busy) – There is an ongoing transmission and the channel is occupied. CSMA/CA will sense the carrier and will prevent the node from sending any data (backoff).
- **C** (Collision) – There are two or more ongoing transmissions at this node’s position. If the node is sending data it will continue to do so as it cannot sense the collision (instead, a missing ACK will trigger retransmission). The frame will be silently discarded by the PHY layer if this is not the sender node. This state may occur whenever there is a hidden node phenomenon or a collision has occurred due to propagation delays.

A sending node changes the link state of its neighbors – the nodes in its transmission range. Figure 1 presents the possible transitions for the link of our CSMA/CA channel model.

The granularity can be adjusted by varying the frequency of updating the macro states from the physical layer information. Moreover, we can update the SNR matrix during the simulation. We can thus have situations where the characteristics of the medium change drastically, e.g. a line getting damaged, or a big load added to the circuit. In addition, it is possible to consider the \( C \) state as one in which some communications are possible with a higher BER. Currently we associate a collision with a frame loss. Sec. V shows that this simplification does not interfere with the validity of the simulations.

C. Overview of the implementation

OPNET implements devices with a Node Model (NM). Fig. 3c shows the NM’s correspondence to the PLC G3 network stack and the testbed implementation. Each NM consists of several Process Models (PM) that can communicate together, with separate networking layers being implemented through different PMs. The physical model (Sec. III-A) is used in MAC PM to check CSMA/CA channel state, and to compute the SNR (average or per subcarrier) in the pipeline stage.

D. Calibration

RPL was designed to cover a wide variety of link layers. We based our study on Contiki 2.5 (http://www.contiki-os.org), which is the de-facto RPL reference stack. The IETF RPL standards leave many parameters up to the implementer – many more than LOAD. For example [6] showed that a single address report message (DAO) timer can create massive congestion near the RPL root if not selected properly. Thus, we calibrated our RPL simulator to emulate the choices made by Contiki’s developers. The selected values lead to a correct behavior but are not optimized for an AMI environment.

Concerning LOAD, routing entries’ lifetime can also change drastically the results. For example, flooding for route discovery occurs each time there is no route to the destination. Thus, the simulator mimics the implementation provided by Texas Instruments (see Sec. IV).

IV. Reference Testbed

In order to validate the simulation methodology proposed in Section III, we use a real-world testbed allowing us to construct several relevant Smart Meter deployment scenarios...
The testbed consist of nine PLC G3 nodes – Texas Instruments Reference Design kits. The kits have a dual-processor architecture, with a Digital Signal Processor (DSP) for the networking functions, and a Cortex M3 processor for the routing protocols and the application development. The kits implement the complete PLC G3 specification (PHY, MAC, LOAD) in the DSP. However, no implementation of RPL was available. Thus, we developed a full RPL implementation in the Cortex M3 core based on the reference stack from Contiki 2.5. As Cortex M3 is using FreeRTOS Operating System, a full port of Contiki IPv6 Stack has been done to FreeRTOS. Fig. 3b shows the protocol implementation point (DSP or Cortex). RPL used for the platform is using Objective Function 0 [7] with hop-count as a metric.

The 9 nodes have been setup in the following configuration:
- One Concentrator (DC) interacting with the meters;
- Six Smart Meters reporting to the DC;
- Two sniffer nodes allowing the observation and analysis of the traffic on the line. A modified version of Wireshark is used for collecting the traces.

The construction of the deployment scenarios is achieved by inserting signal attenuators to the power lines connecting the nodes. Each 40dB attenuator has an impedance of $50\Omega$. Selecting the meter’s lowest transmission power, two power meters communicate through one attenuator, but not through two consecutive ones, equivalent to 200m in the simulator.

V. RESULTS

In this section we present the validation of the simulator against the performance observed in the real-world testbed. The validation scenarios have been carefully selected in order to represent some of the most frequently met real-world situations, and address Urban, Rural and Mixed topologies (Fig. 5). All scenarios contain a Concentrator (DC) and six Smart Meters (SM) as shown in Fig. 5.

A. Methodology

In order to validate the simulator and the developed models, we chose a set of representative scenarios (topology, traffic patterns, etc.), which were executed on the testbed and in the simulator. A set of metrics was collected in both contexts and the resulting values analyzed for statistical resemblance.

The validations were carried over the behavior of two fundamentally different routing protocols (RPL and LOAD) and their influence on the data plane. The data traffic patterns presented in this paper correspond to typical interactive Smart Meter reading, where the DC sends requests to the meters, which respond immediately. Specifically, the DC sends UDP datagrams of payload 50 bytes to every Smart Meter every 30 seconds. The Smart Meter responds with the same payload. We selected the metrics which are most representative for the performance of the protocols, and which validate essential parts of the simulator. The metrics are the following:

- End-to-End delay (E2E): round-trip time for a data request/response.
- Route Formation Time (RF): time and volume of signaling data needed to establish all routes C ↔ SM.
- Route Maintenance Signaling Traffic (RM): volume of signaling data needed to maintain the topology.

B. Validation

We validated the simulation tools and models were in three topologies (Fig. 5), with three different metrics. As these metrics measure the performance of the network in different stages of its life (e.g. initialization, steady state) we performed separate tests for each metric. Table I presents the number of tests performed per metric per topology. We fixed the threshold SNR value to 12 dB.

The performance of the network for each metric was collected per SM and averaged over all SM for every scenario. Finally, the simulation results are compared to the experiments performed on the testbed (i.e. the baseline). Results obtained for E2E delay comparison between simulation and implementation in the Rural Case are displayed in Fig. 7. While visualization offers a quick way to check the similarity between implementation and simulation, we prefer to use the deviation to formally compare the E2E delay.
Table II summarizes the deviation (i.e., the error) under E2E delay metric of the simulation compared to the testbed in percents. $E_{avg}$ is the average error for every given case, e.g., for a given protocol (LOAD or RPL), scenario (Urban, Mixed, Rural) and E2E delay for a given node (nodes 2–7). Similarly, the maximum ($E_{max}$) and minimum ($E_{min}$) metrics provide the worst (resp. best) deviations. The differences simulation/experimentation are limited in most cases (e.g., in all but three cases the $E_{avg} < 6\%$), which validates the behavior of the simulator. The E2E metric is independent from the used routing protocol under a stable topology. Thus, these results validate the simulation of PHY and MAC layers both in terms of model and implementation.

We observe the biggest deviation between the testbed and the simulations for RPL in Mixed and Rural scenarios (Table II). Indeed, Fig. 7 reveals a tendency to have more requests with longer E2E delays with every hop in the testbed. The major reason is that RPL was running on a secondary processor (Cortex M3), compared to LOAD, which runs directly on the DSP where we always have consistent behavior simulation (and none for the LOAD implementation). All these factors add up to difficult to simulate non-deterministic timing deviations. However, the E2E delays are very close, with most
error being inferior to 6%.

We performed validation through several visualization techniques, but in order to have a formal confirmation of the graphical results we calculated the correlation coefficient $r$. We considered the collected data as time series and calculated $r$ over the time. The closer $r$ is to 1, the stronger is the linear relation between the two. The Route Formation (RF) represents a transitional state of the network during which the routes are established. The individual points in Fig. 8 present the pairwise correlation between all individual simulations and all experimental runs, with most $r > 0.93$. In contrast, Route Maintenance (RM) corresponds to the steady-state operation of the network. The results for both RF and RM (for averaged time series, as shown in Fig. 6) are presented in Table III and show conclusively the correlation for both RF and RM, with values higher than 0.98 for both LOAD and RPL.

### C. Scalability

One of the goals of the simulator is to be used for large-scale topologies ($\geq 1000$ meters) and it was important to study the scalability. Table IV shows results obtained for LOAD when each meter is sending 50 bytes of payload to the DC with frequency uniformly distributed in $[0s; 900s]$.

As expected, RPL results show longer simulation times. Indeed, RPL is a proactive protocol which generates control traffic all along the simulation while LOAD, being reactive, generates control traffic only for establishing routes. Thus, it takes longer time to simulate RPL scenario as there are a higher volume of control messages to handle by the simulator. However, this does not imply that LOAD is better than RPL in terms of routing performance – it only suggests that it may be more time consuming to simulate big topologies with the latter than with the former.

### VI. Related work

Smart-Grid architectures have been widely described in the literature. In [8] the authors summarize the considerations and challenges in the power system settings. The focus of [9] is more specifically on the feasibility of using PLC in AMI environment. To the best of our knowledge, [10] is the only available comparison between LOAD and RPL routing protocol. While this study is complete and tackles interesting conclusions, it is studied in the context of a Wireless Sensor Network. As stated in [6], [11], enhancements could be needed for an optimal performance of RPL in AMI architecture. To the best of our knowledge, our paper is the first to present a systematic way of simulating and validating narrowband PLC network for AMI context with implementations of RPL and LOAD.

### VII. Conclusion

The calibration and validation methodology of our RPL Contiki and LOAD PLC G3 simulator against the implementation proved the accuracy of the approach. We demonstrated a trustworthy simulator tool capable of answering the problematic of large scale performance evaluation. We focused our first studies on PLC G3 stack to compare simulation and implementation, but the model is flexible enough to follow standardization evolutions and to include ITU-T 9903, IEEE P1901.2 and LOADng new features. Its scalability and flexibility allow to run different large scale scenarios, more specifically focusing on topology, traffic load profile, noise pattern and asymmetric links. It can also be used to identify the strengths and weaknesses of Contiki RPL and LOADng.

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### References