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On-field evaluation of the performance of IP-based data transmission over narrowband PLC for smart grid applications

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A R T I C L E I N F O

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A B S T R A C T

One of the current efforts for the grid modernization is the deployment of Advanced Metering Infrastructure systems. Regarding AMI technologies, NarrowBand PLC is one of the most spread technologies worldwide. While current AMI deployments based on NB-PLC focus on metering applications, this work addresses the operation of IP over NB-PLC for Smart Grid applications. IP is a well-established standard that might become the key enabler for the interoperability amongst numerous applications for the Smart Grid. In this scenario, on-field measurements become essential to test the coexistence of AMI systems and data transmission beyond metering applications. This paper analyses the configurations and parameters that affect the performance of IP over PRIME such as the number of nodes in the subnetwork, switching levels and transport layer protocols, among others. Results show that the topology of the subnetwork plays a key role for the resulting data rates and provide a meaningful contribution towards the implementation of new applications over NB-PLC based on IP data transmission.

1. Introduction

The improvement of the management and control of electricity grids is a key requirement for the transition towards the Smart Grid (SG) paradigm. In this process, the current efforts on the modernization of the grid are the deployments of Advanced Metering Infrastructure systems (AMI), which are based on the introduction of Information and Communication Technologies (ICTs) within the electricity context [1,2]. One of the most spread technologies for AMI is Power Line Communication (PLC) and, specifically, Narrowband PLC (NB-PLC) [3].

Once the communication infrastructure is deployed, it can be used for additional applications rather than metering. In this sense, in [4] it is demonstrated through simulations that the existing NB-PLC deployments and specifically, those based on PoweRline Intelligent Metering Evolution (PRIME), have additional capacity in the channel for applications beyond AMI. Despite there is still no clear consensus, it seems that IP-based communications could take advantage of this additional resource and guarantee interoperability between different technologies, a key aspect for the success of SGs [5]. IP is a mature open standard that provides the basis for higher layer protocols that lead to reliable, simple, secure and robust applications [6]. These features can face several challenges of the SG such as scalability, resilience and reliability, among others. In fact, IP is increasingly being used in monitoring and control applications in the energy sector, such as demand management, control of Distributed Generation (DG) and Distributed Storage (DS), and consumer integration [7].

The possible applications of the implementation of IP must be compatible with the metering tasks of the AMI system. The authors have previously demonstrated the viability of the implementation of IP over PRIME [8], validating on-field the data rates obtained in laboratory tests [9]. The present work intends to extend this study by further analysing the parameters and configurations that allow optimizing such implementation, under different metering traffic scenarios.

The document is organized as follows: Section 2 summarizes the objectives of the paper. Section 3 describes the main features of PRIME. Section 4 presents the measurement setup and methodology employed. Section 5 presents the obtained results and analysis of the aforementioned measurements, taking into account several parameters and

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variables. Section 6 further discusses the obtained results and contributions of the work. Finally, Section 7 summarizes the main conclusions from this research work.

2. Objectives

The main objectives of the paper are defined as follows:

- Description and quantification of the PRIME channel occupancy for different types of metering traffic in the subnetwork.
- Measurement of the communication delays in a PRIME channel implementing IP, under several types of roles of the communication end points and for different metering traffic scenarios.
- Analysis of the channel capacity under different scenarios: roles of the communication end points, type of metering traffic in the channel, number of nodes, TCP configuration and transport protocol (TCP/UDP).

3. PoweRline Intelligent Metering Evolution (PRIME)

The PLC technology analysed in this work is PRIME (ITU-T G.9904) [10], a NB-PLC standard for advanced metering, widely deployed worldwide [11]. It employs OFDM in the PHY layer, which allows the use of the full available bandwidth, and provides high data rates and robustness in noisy scenarios [12].

In the MAC layer, PRIME devices are disposed in a tree structure where two types of nodes are possible: Base Node (BN), which acts as a master node of the subnetwork; and Service Node (SN), in charge of keeping connectivity within the subnetwork and switching the data of other nodes to extend connectivity, if required. While BNs are commonly embedded in Data Concentrators (DCs), the SNs are included in the Smart Meters (SMs). SNs can have three functional states:

- Disconnected: it is the initial state, in which SNs are not able to communicate or switch data.
- Terminal: where SNs are able to establish connections and transmit data, but not to switch the data of other nodes.
- Switch: in this state SNs are able to forward data to and from other nodes within the subnetwork. Additionally, they keep all terminal state functions. Switch nodes forward the data selectively, i.e., they just resend the frames whose source or destination node is connected to it. Thus, a switch node has to check in its internal data base whether the specific node is connected to it before forwarding the frames.

Both BNs and SNs can access the channel in the Shared Contention Period (SCP). Since SCP does not require channel arbitration, the transmitting devices need to respect the SCP timing boundaries defined in the MAC frames. Additionally, SCP includes CSMA-CA, a mechanism that avoids collisions resulting from simultaneous attempts to access the channel. Each device listens to the signal level to determine when the channel is idle prior to the transmission. Then, the device waits for a random period of time before trying to send a packet [10].

PRIME specification also defines a Convergence Layer (CL) for adapting specific upper layer services to the lower layers. The CL is separated into two sublayers: the Common Part Convergence Sublayer (CPCS), which provides a set of generic services; and the Service Specific Convergence Sublayer (SSCS), which contains services that are specific to one network protocol. The IP SSCS is specifically designed for both IPv4 and IPv6, providing an efficient method for transferring IP packets over PRIME subnetworks. Therefore, the BN is able to manage communications related to different upper layer services, such as smart metering (432-SSCS) and any other application running over IP (IP-SSCS). Then, when a SN initiates a connection to the BN, the CL is responsible for redirecting the connection to the corresponding SN. The type of connection included in the connection request specifies the CL to be used.

4. Measurement methodology

This section describes the measurement methodology, including the parameters considered for the measurement configurations, the selected scenario for the tests and the equipment.

4.1. Measurements definition

The parameters and variables considered for the IP performance evaluation can be described as follows:

4.1.1. Analysis parameters

The analysis parameters were selected according to the presented objectives:

- Channel occupancy has been estimated as the time duration in which there is no metering data in the medium with respect to the total time duration of the measurement.
- Delays in the communications between the nodes are quantified through latency and jitter. Latency specifies the time spent by a packet to reach a node from another node in a communication network, while jitter defines the latency variation in the packets arrival to a node. Jitter is only evaluated for UDP protocol.
- Channel capacity is measured in terms of data rate, which defines the number of transmitted bits per unit of time through a communication system or maximum transfer speed.
- Additionally, errors in the communication using UDP are measured through the percentage of lost datagrams. Since in UDP lost packets are not retransmitted if they do not reach the receiver node, this parameter has to be analysed in addition to the data rate for the evaluation of the UDP performance.

4.1.2. Analysis variables

- Roles of the communication end points: specifies the type of the sender and receiver nodes, which can be either a BN or a SN. Then, two different scenarios were considered:
  - Communication between the BN and a SN: entails the data transfer between the BN and a SN from its subnetwork.
  - Communication between two SNs: entails the data transfer between two different SNs from the same subnetwork. The BN handles the communication between SNs, hence the traffic must pass through it.
- Switching level: as explained in Section 3, the nodes that are unable to connect to the BN directly will use a neighbour SN acting as a switch to access the BN. The SNs connected to the BN without switching are at level 0, while the nodes requiring a switch will be at a level equal to the number of switches in between. For instance, a SN at level 2 or with 2 switching levels means that it needs two switches to reach the BN. For the sake of clarity, in this work the switching level of a node is included between parenthesis, e.g. SN (2).
- Type of metering traffic: the traffic related to metering applications already existing in the communication network. Three different common types of traffic within a microgrid were considered and it was guaranteed that the metering data requests were properly performed for all the scenarios.
  - PRIME control traffic: the traffic in charge of maintaining the subnetwork, always present in the channel.
  - Instantaneous metering traffic: generated when the DC requests instantaneous data to all the SMs within the subnetwork (preconfigured task). It refers to the measured consumption or generation data recorded by the meter in the specific moment of the petition. This traffic coexists with the control traffic.