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Keywords: Advanced metering infrastructure; Information and communication technologies; Internet protocol; Power line communications; Smart grid

On-field Evaluation of the Performance of IP-based Data Transmission over Narrowband PLC for Smart Grid Applications.

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Abstract: 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.

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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 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.
    - Profiles metering traffic: generated in a SM when its recorded metering data for a range of dates is requested by the DC. This traffic also coexists with the control traffic.
- Number of nodes: number of nodes that are part of the subnetwork under test. Four different scenarios were considered: 9, 13, 17 and 21 nodes.

- Transport protocol: the two most common transport protocols for IP were considered, TCP and UDP.
    - TCP is the most widely used protocol, connection-oriented and flexible in the configuration of parameters that defines its performance. Specifically, the two most influencing parameters on the TCP performance were considered for this study:
        - The segment size (M) fixes the maximum amount of data that the receiver node can handle in a unique TCP segment. The optimal size of the segment would be the greatest possible without implying the segmentation of the datagrams. Typical maximum transmission unit sizes (MTU) in TCP are 576 B for IPv4 and 1500 B for IPv6 with a minimum of 1280 B [13] [14]. The maximum segment sizes (MSS) can be calculated following the formula in (1).

$$MSS = MTU - Header_{IP} - Header_{TCP} \tag{1}$$

          Then, the following MSS are obtained: 536 B (576-20-20); 1440 B (1500-40-20) and 1220 B (1280-40-20). Despite IPv4 is the implemented protocol in the equipment, IPv6 parameters were also considered in the measurements for potential upgrading of the equipment in the future. On one side, smaller segment sizes would entail high header to data ratios, which implies an inefficient use of the available bandwidth. On the other side, greater segment sizes would entail the retransmission of bigger data sizes in case of collision, which is frequent in channels with high traffic flow.
        - The window size (W) defines the buffer size of the receiver node, which determines the amount of received data that the destination node can handle. The optimal window size is that in which the receiver is able to manage data as fast as the transmitter can send. In the measurements, the window size values were selected to be related to the segment size, resulting in 4 kB, 8 kB (default value), 16 kB and 32 kB for the segment size of 536 B; and window sizes of 8 kB, 16 kB and 32 kB for the segment sizes of 1220 B and 1440 B.
    - UDP is also a commonly used transport protocol. It is connectionless, which reduces the resources required for the connection establishment. In addition, in UDP there is no acknowledgement of the packets at the receiver node. Hence, the traffic flow is reduced, which allows the maximization of the available bandwidth.

4.2. Measurement scenario and equipment

The tests were performed in the real microgrid installed at CEDER-CIEMAT, a national institution for the research, growth and promotion of renewable energies. Specifically, the scenario selected for the measurement campaign was an area of the microgrid with a wide deployment of DG and DS, connected to a secondary substation with two power transformers (PTs) leading to two different LV branches: on one side, three single-phased photovoltaic (PV) systems and a battery charger; on the other side, a hydro system branch consisting of a turbine, a pump and a three-phased PV system [15]. The microgrid has a smart metering system installed, based on PRIME v1.3.6 standard, where each DG and DS resource includes a SN (embedded in the corresponding SM). There is a BN coupled to one of the LV branches with an external connection through Ethernet to an auxiliary device (a PRIME modem with switching functionality), with the purpose of reaching the remaining SMs in the LV grid [16]. More details about the measurement scenario are provided in [8].

For these specific field trials, the devices used in the tests are described below and are shown in Figure 1 and Figure 2.

- Portable Base Node (PBN): this device is a portable PRIME-based communication node with IP capabilities, since it implements the IP-SSCS layer. Three different PBNs were used, as showed in Figure 1 and Figure 2.
    - PBN-BN: one of the PBNs was configured as BN of the subnetwork, hence it is necessary to deactivate this option at the DC1, whose embedded node normally acts as BN.

    - PBN-SNA and PBN-SNB: the other two PBNs were configured as SNs, named SNA and SNB, respectively. These SNs register in the subnetwork handled by the PBN-BN. The process of registration of the PBNs configured as SNs in the PBN-BN is detailed in [17].
- SMs: all of the SMs available at the scenario showed in Figure 1 and Figure 2 take part in the measurements and they generate the metering traffic detailed in Section 4.1.2. Their embedded nodes will register in the PBN-BN. In the standard configuration of the measurements scenario, there are 13 SNs: 10 SNs embedded in the SMs, another SN embedded in DC2 and the two SNs of the PBNs configured as SNs (PBN-SNA and PBN-SNB).

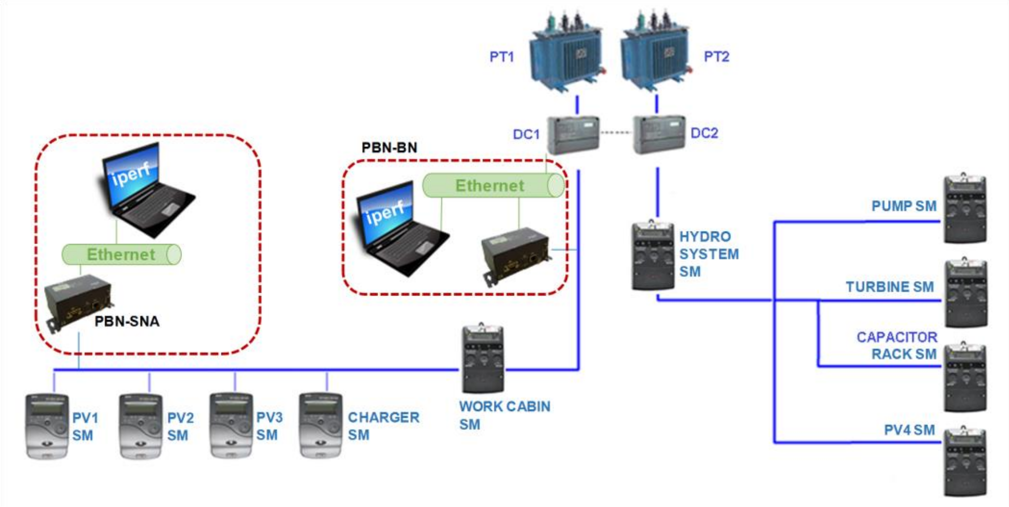

Figure 1. Scheme of the setup configuration for the measurements of the data rate for the communication between PBN-BN and PBN-SNA (dotted areas) [8].

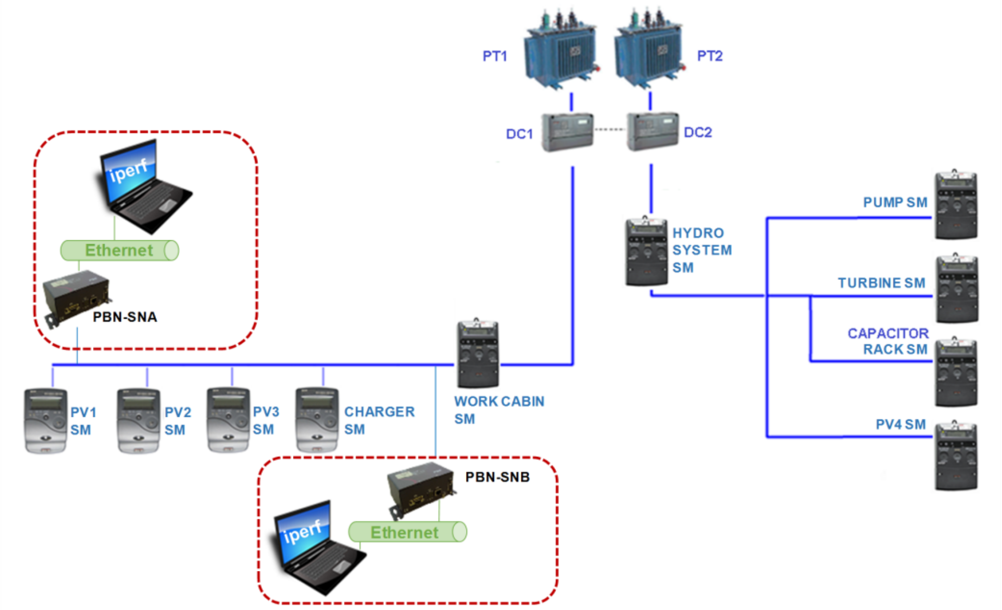

Figure 2. Scheme of the setup configuration for the measurements of the data rate for the communication between PBN-SNA and PBN-SNB (dotted areas).

In order to generate the IP traffic and measure the performance of the channel in terms of available data rate and latency, iperf tool was used [18]. This software tool works in a client-server setup. For all the scenarios, the server is the PBN-SNB and the client varies between the PBN-BN and the PBN-SNA, depending on the roles of the communication end points (Section 4.1.2). Iperf tool runs in a laptop that is connected via Ethernet to the corresponding PBN, as shown in Figure 1 and Figure 2.

4.3. Measurements summary

Table 1 shows a summary of the tests carried out for the evaluation of the performance of IP over PRIME at CEDER-CIEMAT microgrid. The measurement campaign consisted of a total number of 270 sessions.

Table 1. Summary of the considered configurations for the evaluation of IP over PRIME at CEDER-CIEMAT microgrid.

<table>
<tr><th colspan="13">Measurement Configurations</th></tr>
<tr><td colspan="3">Transmission size (payload) [kB]</td><td colspan="10">100</td></tr>
<tr><td colspan="3">Number of nodes in the subnetwork</td><td colspan="10">9, 13, 17, 21</td></tr>
<tr><td colspan="3">Type of metering traffic in the subnetwork</td><td colspan="10">PRIME control traffic
PRIME control traffic + instantaneous metering traffic
PRIME control traffic + profiles metering traffic</td></tr>
<tr><td colspan="3">Network protocol</td><td colspan="10">IPv4</td></tr>
<tr><td rowspan="3">Transport protocol</td><td rowspan="2">TCP</td><td>Segment [B]</td><td colspan="4">536</td><td colspan="3">1220</td><td colspan="3">1440</td></tr>
<tr><td>Window [kB]</td><td>4</td><td>8</td><td>16</td><td>32</td><td>8</td><td>16</td><td>32</td><td>8</td><td>16</td><td>32</td></tr>
<tr><td>UDP</td><td>Bandwidth [kB]</td><td colspan="10">1 kB</td></tr>
<tr><td rowspan="2">Roles of the communication end points and switching level</td><td colspan="2">Between BN and SN</td><td colspan="10">BN - SNB(0)
BN - SNB(1)
BN - SNB(2)
BN - SNB(3)</td></tr>
<tr><td colspan="2">Between SN and SN</td><td colspan="10">SNA(0) - SNB(0)
SNA(0) - SNB(1)
SNA(0) - SNB(2)
SNA(0) - SNB(3)</td></tr>
</table>

5. Results

This section presents the results obtained in the measurements in terms of channel occupancy, latency and data rates. They have been organised as follows:

- First, the measured channel occupancy and latency values are presented (Section 5.1 and 5.2, respectively). These results provide a rough idea of the capability of PRIME for additional data transmission beyond metering data;
- Secondly, Section 5.3 gathers different results related to the available data rate for IP transmissions.
    - The influence of different parameters on the IP data rate is analysed in Section 5.3.1. These parameters are: roles of the communication end points , switching level, type of metering traffic and number of nodes;
    - Afterwards, the influence of TCP parameters on the obtained data rates is covered in Section 5.3.2;
    - Then, the study is extended to address the influence of a higher number of nodes, since this implies not only more nodes to be managed by the BN but also an increase of metering traffic in the network (Section 5.3.3);

- The study of the influence of the transport protocol is extended to UDP, in order to compare its performance with respect to TCP (Section 5.3.4).
- Finally, the study addresses the results obtained for more switching levels, in order to determine its influence on the IP data exchange (Section 5.3.5).

5.1. Channel occupancy

The channel occupancy has been calculated with a tool specifically designed for processing the data received in and sent from the BN. The percentage of occupancy or the time duration in which there is data in the medium with respect to the total time duration of the measurement follows the formula in (2) and the numerical values can be seen in Table 2. The length of the sessions were considered long enough (8 minutes) to measure a representative amount of traffic flow. It can be observed that even for the case where the amount of data from the metering task is the highest (control + profiles), there is a significant percentage of time where the channel is free.

$$Channel\_occupancy\ \ (\%) = \frac{frames*frame\_length}{session\_length} * 100 \qquad (2)$$

Table 2. Channel occupancy for each type of metering traffic in terms of number of sent (Tx) and received (Rx) frames at the BN and the percentage of channel occupancy.

Type of metering traffic	**Control frames**		**Metering frames**		**Channel occupancy [%]**
	Tx	Rx	Tx	Rx	
Control only	849	313	-	-	2.7
Control + Instantaneous (19 SMs)	848	714	329	642	7.7
Control + Profiles	772	835	356	2171	16.6

The following subsections further analyse the results according to the type of metering traffic and include the graphic representation of the frames along time. A representation of the frames over time is useful for the visualization of the frames in scenarios with different types of metering traffic.

5.1.1. Channel occupancy with only control traffic

The results in Table 2 show that for an 8-minute session with only control traffic, the 97.3 % of time the channel was unoccupied, which agrees with the results presented in [4]. Additionally, Figure 3 and Figure 4 show the flow of frames along time, their length and separation among them.

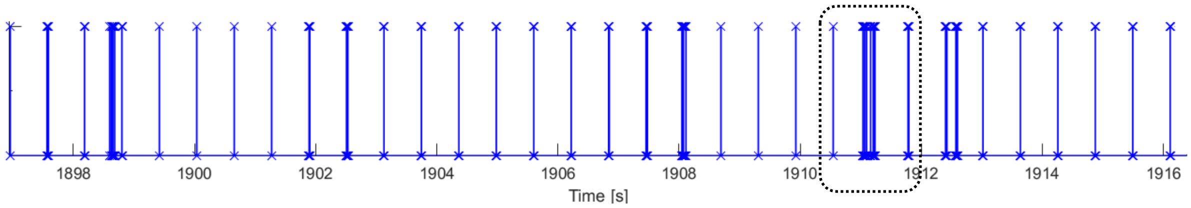

Figure 3. Graphical representation of PRIME frames with only control traffic.

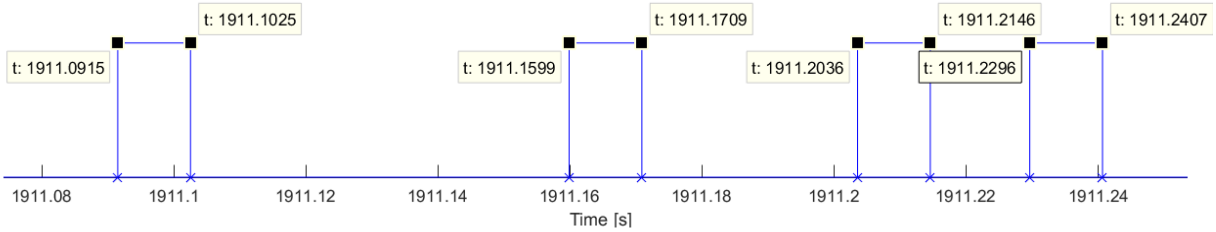

Figure 4. Graphical representation of PRIME frames with only control traffic: enlarged view of the dotted area in Figure 3.

5.1.2. Channel occupancy with instantaneous traffic

Table 2 includes the results obtained for instantaneous traffic; for this purpose, simultaneous tasks were configured at the DC, which queries all the 19 SMs within its subnetwork regarding instantaneous metering data. For the recorded session (8-minute long), it was estimated that the channel was free 92.3 % of the time. This means that the simultaneous requests to 19 SMs increase the occupation of the channel by 5 % with regards to the scenario with only control traffic. Additionally, Figure 5 and Figure 6 represent the traffic of frames with both control and instantaneous metering data. As it can be seen in Figure 5, each group of instantaneous requests starts 1 minute after the previous group.

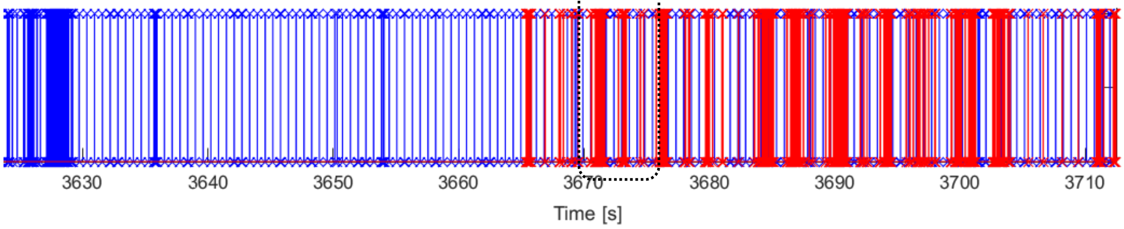

Figure 5. Graphical representation of PRIME frames with control traffic (in blue) and instantaneous requests (in red).

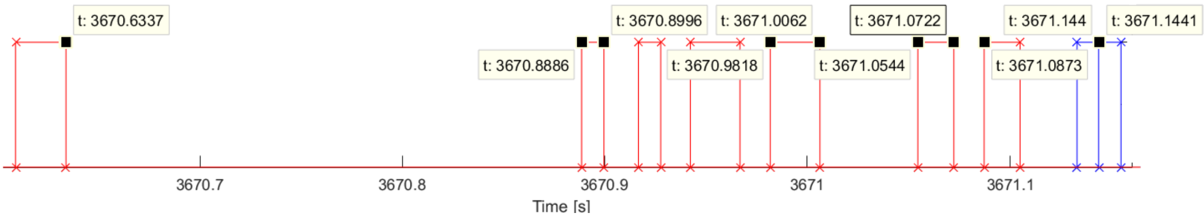

Figure 6. Graphical representation of PRIME frames with control traffic (in blue) and instantaneous requests (in red): enlarged view of the dotted area in Figure 5.

5.1.3. Channel occupancy with profiles traffic

For the session with profiles traffic, also 8-minute long, the occupancy of the channel increased by 13.9 % and 8.9 % with regards to the only control traffic and the instantaneous traffic cases respectively, as shown in Table 2. In addition, Figure 7 and Figure 8 represent the traffic of frames with both control and profiles data.

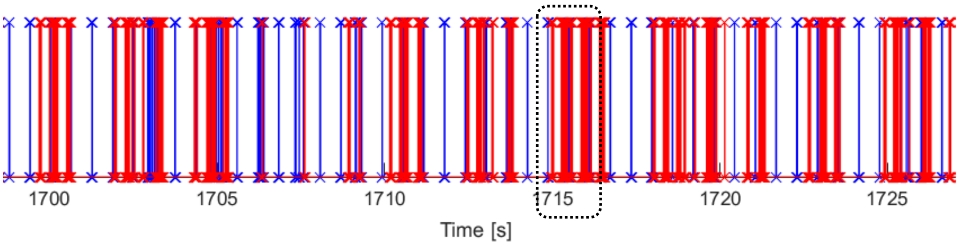

Figure 7. Graphical representation of PRIME frames with control traffic (in blue) and profile requests (in red).

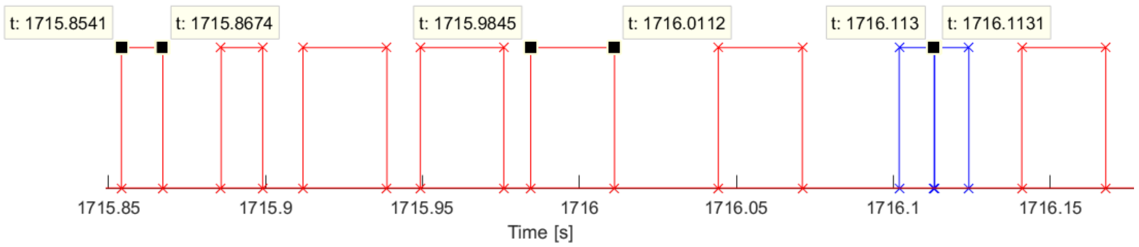

Figure 8. Graphical representation of PRIME frames with control traffic (in blue) and profile requests (in red): enlarged view of the dotted area in Figure 7.

As seen in Section 5.1.2, the instantaneous traffic includes periods of time in which there is no metering traffic, in contrast to the profile scenario, where there is traffic during the whole session. A comparison between both scenarios in a period of time with only metering data showed that there is a higher density of frames in the profiles data scenario. In particular, 267 and 146 frames were registered (both sent and received) for the profiles data and the instantaneous data scenarios, respectively. Therefore, the frames density for the same period of time and in a scenario with 19 SMs is higher for profiles request than for instantaneous requests.

In summary, the results of channel occupancy have demonstrated both numerically and graphically that there is a significant percentage of time where the channel is unoccupied in a PLC-based AMI deployment, regardless of the type of metering traffic present in the network. The study has also shown that the profiles data traffic entails higher density of frames than the instantaneous data traffic.

5.2. Latency

Latency, which specifies the time spent by a packet to reach a node from another node, is a valuable parameter to measure delays in communication networks. The latency results for the implementation of IP over PRIME can be seen in Figure 9. The measurements have been carried out with ICMP packets of 32 B and different types of metering traffic and roles of the communication end points in a scenario with 21 SNs.

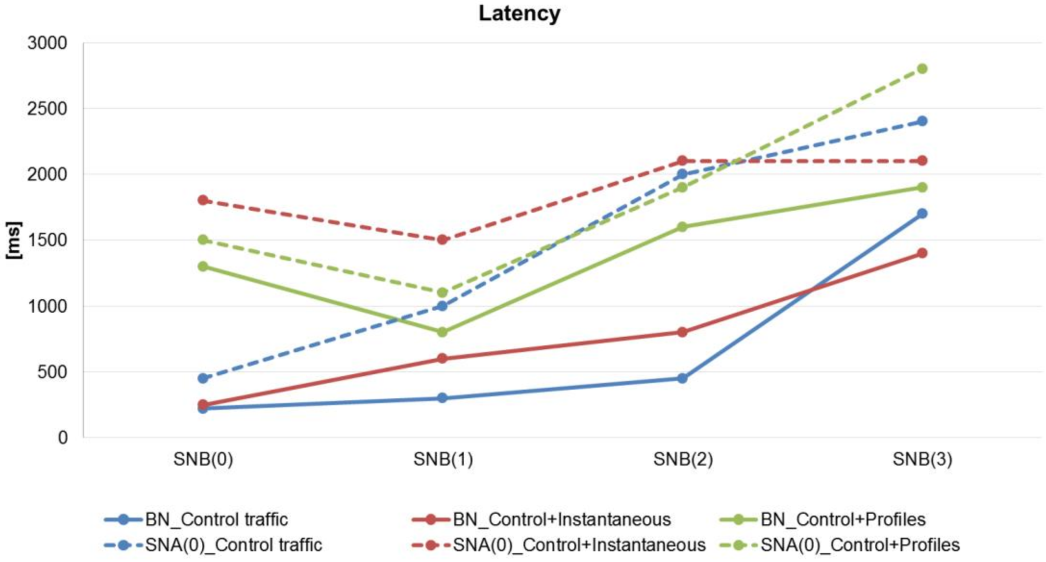

Figure 9. Average latency values for different types of traffic. Two types of communication are considered: BN-SNB(i) (solid line) and SNA(0)-SNB(i) (broken line). The switching levels are represented in the horizontal axis.

The latency values obtained for the roles of the communication end points BN-SNB(0) without metering traffic agree with the values presented in [17], where average values of latency reach 214 ms. In addition, the measurements performed at the microgrid address more types of communication and switching levels. In fact, latency was tested to remain below 1 s for BN-SNB(0), BN-SNB(1) and BN-SNB(2), except in the case of profiles traffic. In the communication between service nodes, SNA(0)-SNB(0) with control traffic was the only scenario with an average latency below 1 s (see Figure 9). In addition to the average results showed in Figure 9, the maximum values were also recorded, resulting in 3 s for BN-SNB(3) and 3.6 s for SNA(0)-SNB(3).

In Figure 9, it can be seen that latency generally increases with the introduction of traffic and with the switching level. Although the trend is different according to the roles of the communication end points, in both cases there is a range of values from which the increase of latency slows down:

- BN-SNB communication: the latency increases with the type of metering traffic (the highest values can be observed with profiles traffic) and with the switching level, so that by the third hop the differences among the latency values are narrowed, regardless of the type of metering traffic.
- SNA- SNB communication: the latency increase is more noticeable with the switching level than with the type of metering traffic (except in the case without switching). In any case, in the communication without switching, SNA(0)-SNB(0), the bottleneck can be already seen, which is the pass through the BN. The handle of traffic by the BN in the communication between SNs increases the latency to reach levels comparable to those observed in the BN-SNB(3) case (see Figure 9).

In summary, the transmission medium, the physical distance and the pass through routers or an intermediate process are the main factors influencing latency. The latter is the limiting factor represented by the pass through the BN in communications between SNs and by the existence of switching levels in communications between the BN and a SN.

5.3. Data rates

The following subsections describe the obtained results in terms of data rates for the measurements at the microgrid and for the configurations summarized in Table 1. The results extend the study presented in [8], which validated existing laboratory tests [17] in a real environment.

5.3.1. Study of the influence of the role of the communication end points, switching level, and type of metering traffic over the data rates

This section describes the data rates obtained for three different roles and relative positions of the IP nodes in the subnetwork topology with 13 SNs, and for the three types of metering traffic considered. In all cases, the TCP default configuration was evaluated. The subnetwork topologies can be seen in Figure 10, and the obtained data rates are depicted in Figure 11.

The analysis can be done considering different parameters:

- Role of the communication end points: this is the variable that affects data rate the most. In all cases, the best results can be observed in BN-SNB(0) communication, while in communication between SNA(0)-SNB(0), and between BN-SNA(1), the data rate is decreased noticeably, up to 3.48 kbps in the case of SNA(0)-SNB(0). However, the differences according to the type of metering traffic in SNA(0)-SNB(0) are less pronounced than in BN-SNB(0), which also occurs when switching is present, BN-SNB(1). The communication between SNs without switching, SNA(0)-SNB(0), can be considered as a communication with an intermediate hop, since the BN must handle all the traffic within the subnetwork. Therefore, its function is similar to that performed by a SN acting as switch, which makes that communication between BN-SNB(1) and between SNA(0)-SNB(0) present similar data rates.
- Type of metering traffic: its effect on data rates is second in importance. The only control traffic case presents the best results in all situations, closely followed by the instantaneous traffic case. On the contrary, the profiles traffic notably reduces the data rates, but these decreases vary among them depending on the role of the communication end points. Otherwise, the maximum recorded differences for communication between SNA(0)-SNB(0) and between BN-SNB(1) were

0.65 kbps and 0.36 kbps, respectively, for the same increase of channel occupancy. Therefore, the addition of a switching level masks the effect of the type of metering traffic in a microgrid of the considered size. These results highlight the role of the switch node and the need for improvements in its traffic management.

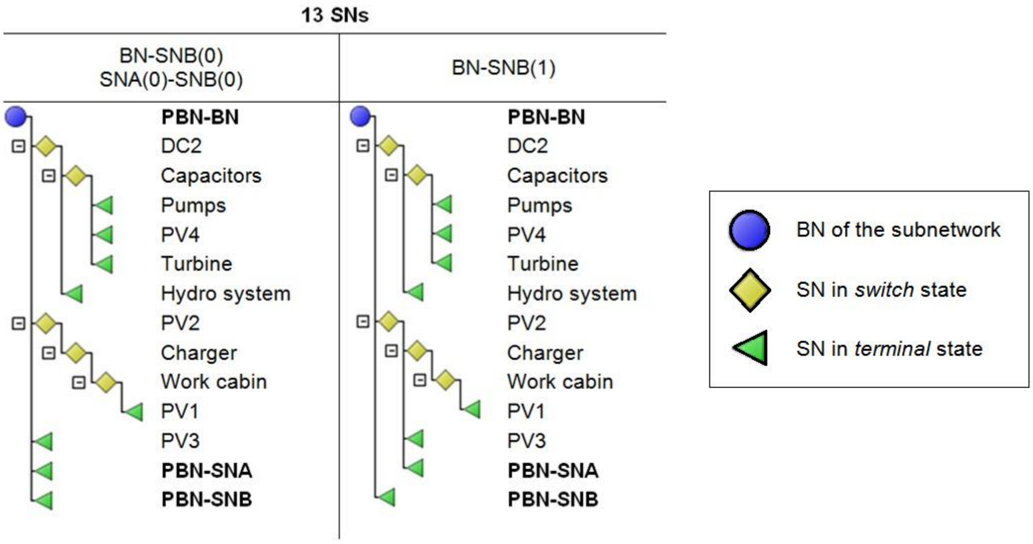

Figure 10. Topologies of the subnetworks for the scenarios with 13 SNs and types of communication considered.

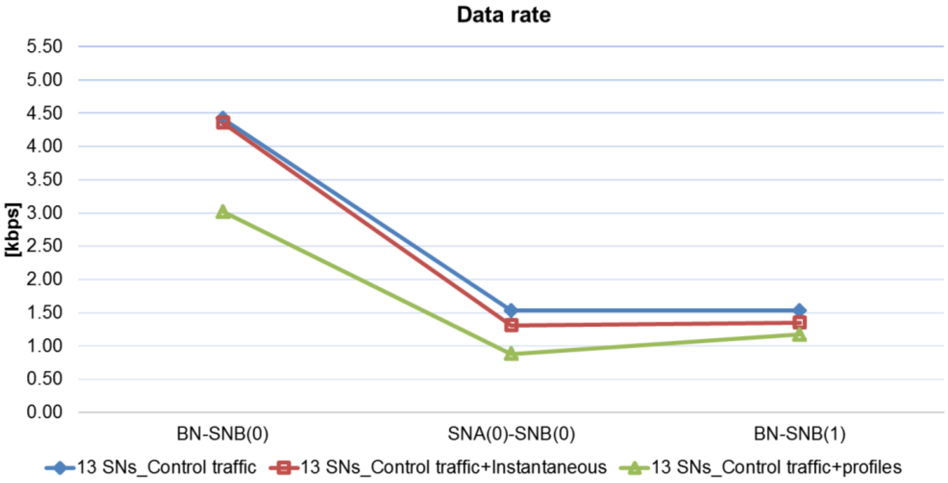

Figure 11. Obtained data rates for 13 SNs in the subnetwork with different types of communication.

5.3.2. Study of the influence of TCP parameters on the data rates

Following the scenario presented in Section 5.3.1, this paragraph addresses the influence of TCP parameters on the data rates, aiming at determining the configurations that optimize the available bandwidth. Three different segment sizes were considered and for each of them, several window sizes were measured, as summarized in Table 1. The obtained data rates can be seen in Figure 12, Figure 13 and Figure 14 for the different roles and positions of the IP nodes in the subnetwork topology.

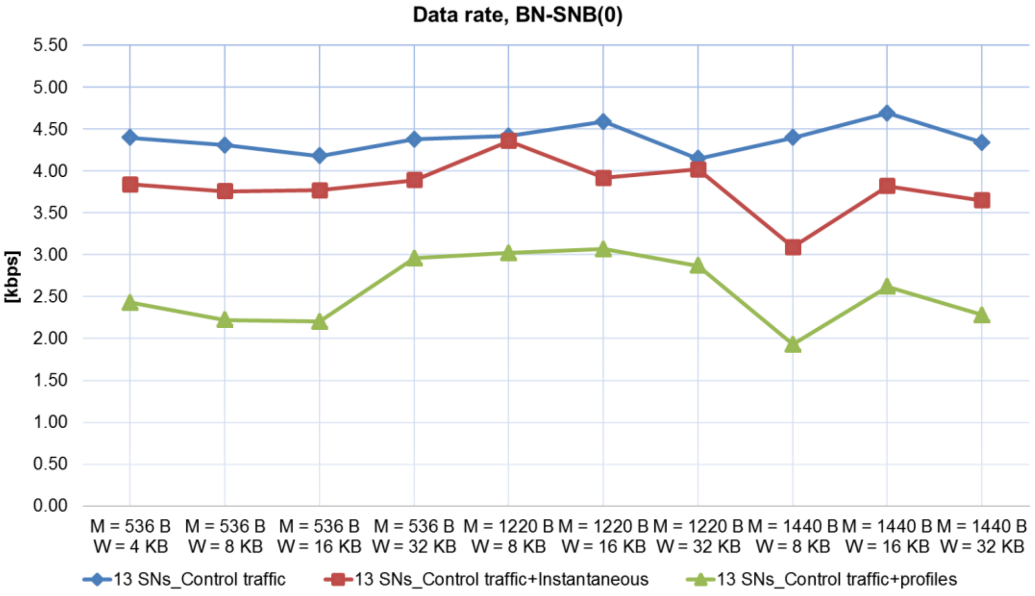

Figure 12. Obtained data rates for IP communication between BN-SNB(0) according to different TCP configurations and types of metering traffic.

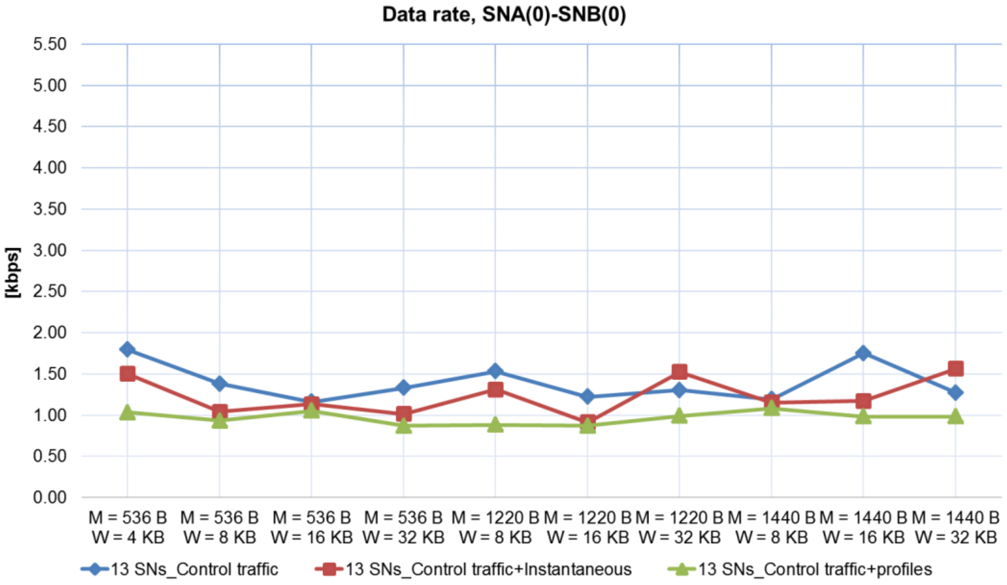

Figure 13. Obtained data rates for IP communication between SNA(0)-SNB(0) according to different TCP configurations and types of metering traffic.

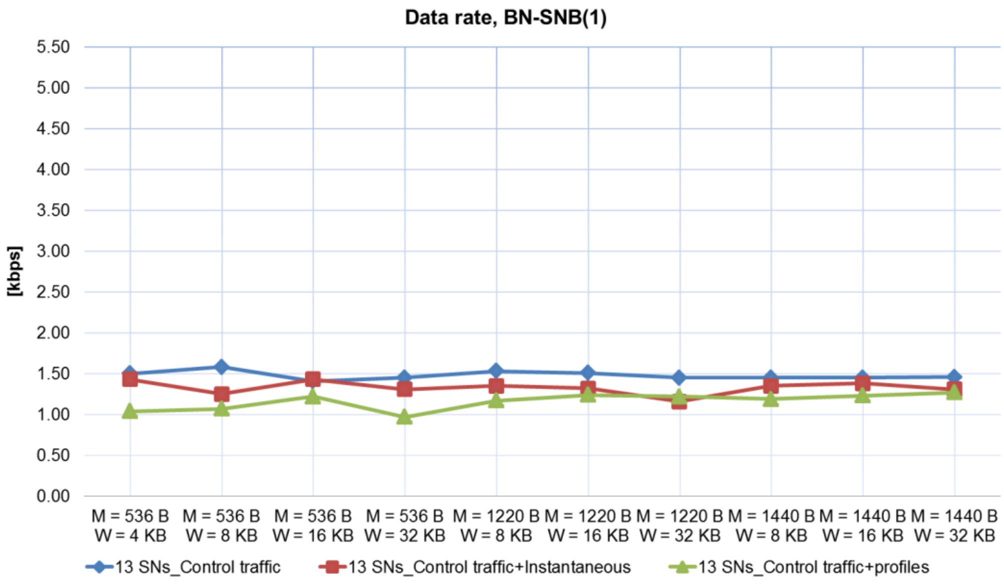

Figure 14. Obtained data rates for IP communication between BN-SNB(1) according to different TCP configurations and types of metering traffic.

According to the different configurations considered, the results can be analysed as follows:

- Segment size (M): in theory, better results can be expected when using a bigger segment size in a less occupied channel (scenario with only control traffic), while a smaller segment size would present better results in a busier channel (instantaneous and profiles traffic scenarios). However, this is not reflected in the obtained results since only in the communication between BN-SNB(0) the biggest segment size, 1440 B, presents the best results with only control traffic and the worst values with instantaneous and profiles traffic (see Figure 12). In the communication between SNs (Figure 13) and between BN-SNB(1) (Figure 14) there is not any clear trend according to the segment size.
- Window size (W): theoretically, a very small window size is inefficient since the client is idle for a longer time. In general, it can be assumed that bigger window sizes are better, but it needs to take into account the limit of the buffer at the receiver side and the ability to pass the received data to the higher layers. From the results showed in the figures, there is not a clear trend: in the communication between BN-SNB(0) (Figure 12), the variations in the window size have little effect on the data rate in the scenarios with less traffic, regardless the segment size. For the rest of cases, the variation in the data rate with the window size is more noticeable for the biggest segment size (1440 B), but it does not follow the same trend. In the communication between SNs (Figure 13), the window size affects the data rates similarly in all cases without a defined trend. Hence, for the scenarios considered in the measurements, the benefits that the window size introduces are not good enough to set a trend in the results. This situation also occurs in the communication between BN-SNB(1) (Figure 14).
- With regard to the roles of the communication end points and type of metering traffic, its effect on the data rates remains similar as described in Section 5.3.1.

5.3.3. Study of the influence of the number of nodes on the data rates

Additional SMs were installed by groups of 4 SMs thus leading to four different scenarios regarding the number of nodes: 9, 13, 17 and 21 SNs. The data rates obtained for the communication between BN-SNB(0) can be seen in Table 3. The differences among the scenarios are negligible, with a maximum recorded difference of 0.5 kbps (scenario with 13 SNs versus 21 SNs with instantaneous traffic). Taking into account that a single DC can handle more than 400 SNs [19], the number of nodes available at CEDER-CIEMAT is not enough to obtain significant results regarding the influence of the number of nodes on the data rate.

The results also confirm the existing differences according to the type of metering traffic in the channel presented in Section 5.3.1, specifically in the communication between BN-SNB(0): an increase of the channel occupancy by nearly 14 % (profiles traffic versus only control traffic), leads to the reduction of the data rate by 2.16 kbps, which means a reduction of 47.6 % (scenario with 21 SNs).

Table 3. Obtained data rates for communication between BN-SNB(0) for different number of nodes and types of metering traffic.

Data rate [kbps] – BN-SNB(0)

Number of nodes / Type of metering traffic	9 SNs	13 SNs	17 SNs	21 SNs
Control	4.50	4.42	4.20	4.54
Control +Instantaneous	4.29	4.36	3.87	3.86
Control +Profiles	2.80	3.02	2.94	2.38

In [17], some simulations were performed in order to obtain the available data rates for IP communications between BN-SN(0) with an increasing number of nodes and for different types of metering traffic. While measurements at CEDER-CIEMAT validate the laboratory results for 9 SNs, as showed in [8], the measurements for a higher number of nodes (up to 21 SNs) presented higher data rates than the results from the simulations developed in [17]. The simulations in [17] show that in a scenario with 512 nodes data rates over 1 kbps are possible in the worst case (with metering traffic in the medium), and above 2 kbps in the best case (only control traffic in the medium). If the tendency shown by the measurements was maintained for a higher number of nodes, these data rates figures would be slightly higher in a real case scenario.

5.3.4. Study of the influence of the transport protocol on the data rates

More measurements were performed with the goal of comparing the performance of TCP (default configuration) to UDP. The scenario with the maximum number of nodes available (21 SNs) and the three types of metering traffic were considered in order to determine the most appropriate protocol for each case. Graphical and numerical results can be seen in Figure 15 and Table 4, respectively.

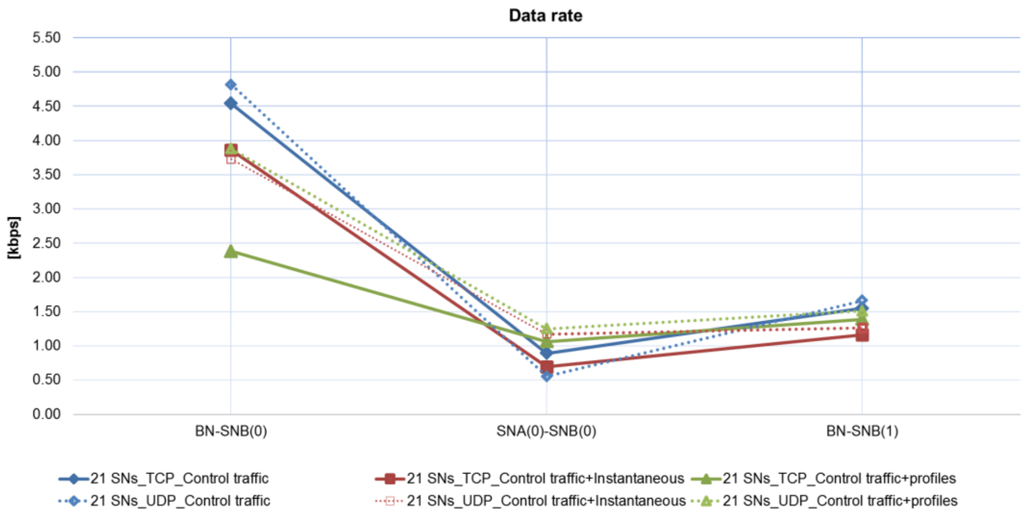

Figure 15. Obtained data rates for TCP and UDP protocols in a subnetwork with 21 SNs. Different types of IP communication and metering traffic are considered.

The results can be analysed as follows:

- According to the roles of the communication end points: the introduction of a hop also affects data rates in UDP, regardless of being the pass through the BN (communication between SNs) or a node acting as switch (communication between BN-SNB(1)). This issue is further addressed in the next section (5.3.5)
- Considering the type of metering traffic: the introduction of intermediate hops smoothes the differences caused by the different types of metering traffic that can be clearly noticed in the communication between BN-SNB(0). This is observed for both TCP and UDP.
- Depending on the transport protocol: in general, UDP presents higher data rates than TCP, with a maximum difference of 1.50 kbps (BN-SNB(0) case). However, these differences do not happen in all scenarios and they smooth with the introduction of an intermediate hop, where, at best, UDP increased the data rate by 0.48 kbps. The improvement in the data rate lies in the operation of UDP: since there are not packet reception confirmations (as occurs in TCP), there is less traffic in the medium. For UDP, it is interesting to evaluate the jitter and the datagram loss, presented also in Table 4:
    - The jitter noticeably increases with the introduction of an intermediate hop, with results no less than 5.8 s, and even exceeding 8 s in some scenarios, regardless the type of metering traffic, which evidences an increase of the congestion in the channel. This contrasts with the communication between BN-SNB(0), in which the jitter ranges between 1 and 3 s.
    - Regarding the datagram loss, for the communication between BN-SNB(0), no datagram was lost in any of the scenarios. However, the loss of datagrams highlights in the communication between SNs, varying from 39 % to 83 %, as showed in Table 4. By contrast, the percentage of lost datagrams is zero in the communication between BN-SNB(1) in all cases. This situation evidences that not only an intermediate hop affects the data rate, but also the handle of the traffic by the BN increases this effect.

Table 4. Results for TCP and UDP protocols, respectively, with 21 SNs in the subnetwork. Different types of roles of the communication end points and metering traffic are considered.

Protocol	**TCP**	**UDP**			**Improvement of UDP with respect to TCP [kbps]**
Roles of communication end points and metering traffic	**Data rate [kbps]**	**Data rate [kbps]**	***Jitter* [ms]**	**Lost datagrams (%)**	
BN – SNB(0)					
Control	4.54	4.82	1546.04	0	0.28
Control +Instantaneous	3.86	3.73	2189.81	0	-0.13
Control +Profiles	2.38	3.88	1300.32	0	1.50
SNA(0) – SNB(0)					
Control	0.89	0.55	8742.77	83	-0.34
Control +Instantaneous	0.69	1.17	8007.26	39	0.48
Control +Profiles	1.06	1.25	5822.63	49	0.19
BN – SNB(1)					
Control	1.55	1.66	5846.96	0	0.11
Control +Instantaneous	1.16	1.26	8872.11	0	0.10
Control +Profiles	1.39	1.51	6488.55	0	0.12

5.3.5. Extension of the study of the influence on the data rates with more switching levels

Finally, the measurements were completed by adding switching levels between the client and the server nodes. The results in Figure 11, Figure 12 and Figure 14 already showed a noticeable decrease in the data rate in the communication between BN-SNB(1) in comparison to the communication between BN-SNB(0). Then, more scenarios with additional switching levels were tested for both communications between the BN and the SNB, and between SNs and also for TCP and UDP. The topologies of the subnetworks under test can be seen in Figure 16 and the results are depicted in Figure 17, Figure 18 and Table 5. Latency values showed in both Figure 17 and Figure 18 correspond to the results from Figure 9, which shows the average latency values obtained for different types of traffic in the medium (PRIME control traffic, PRIME control traffic + instantaneous metering traffic and PRIME control traffic + profiles metering traffic).

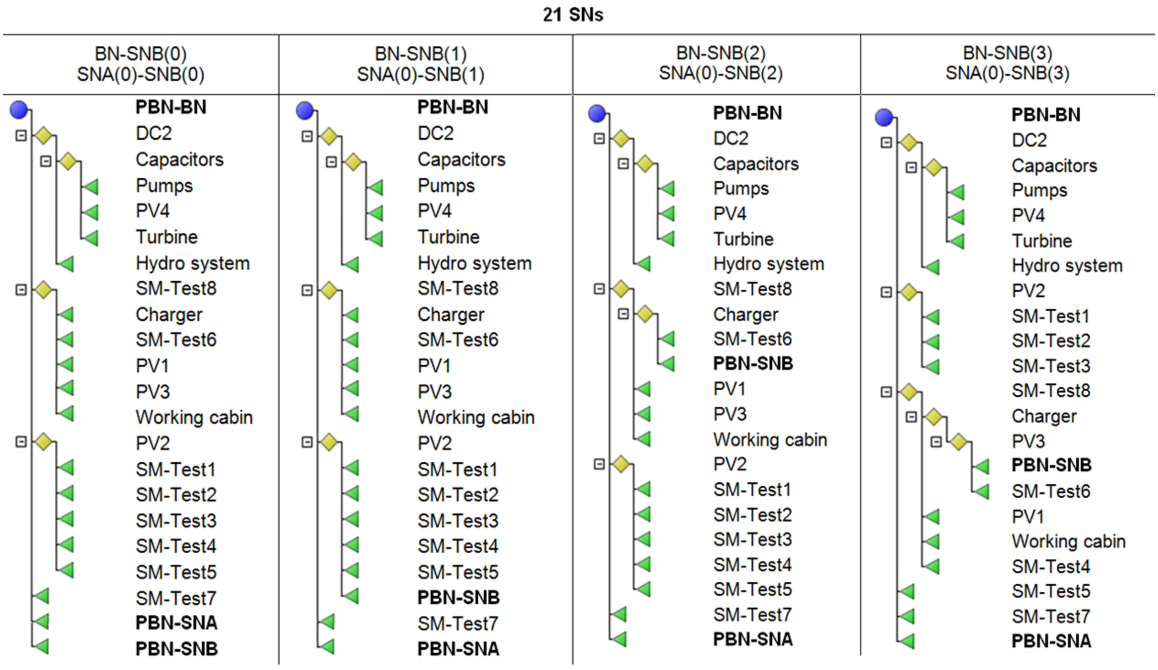

Figure 16. Topologies of the subnetworks for the scenarios with 21 SNs and roles of the communication end points considered for each case.

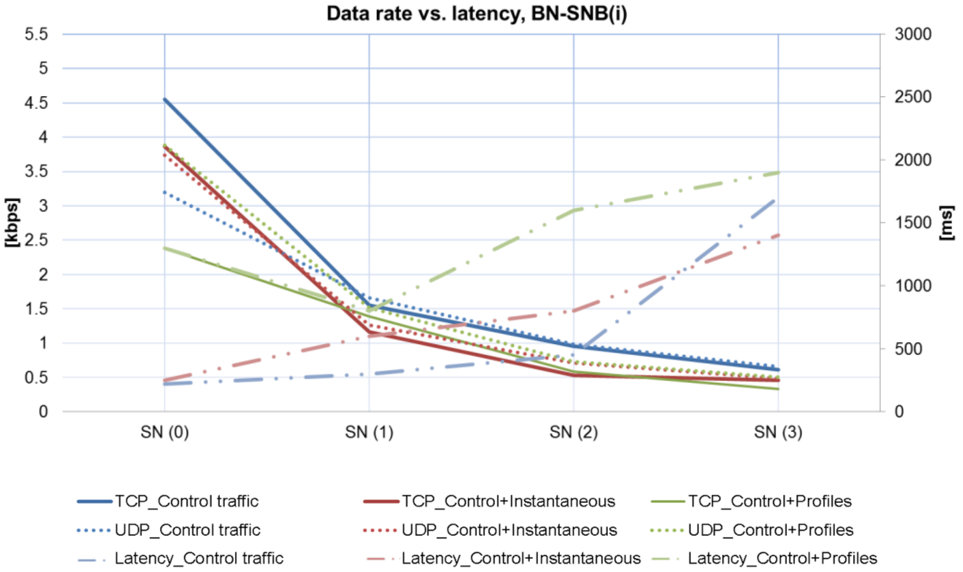

Figure 17. Obtained data rates [kbps] for communication between BN and SNB with several levels of switching, in a scenario with 21 SNs. TCP and UDP protocols and different types of metering traffic are considered. Latency values [ms] are also included and the roles of the nodes can be consulted in Figure 16.

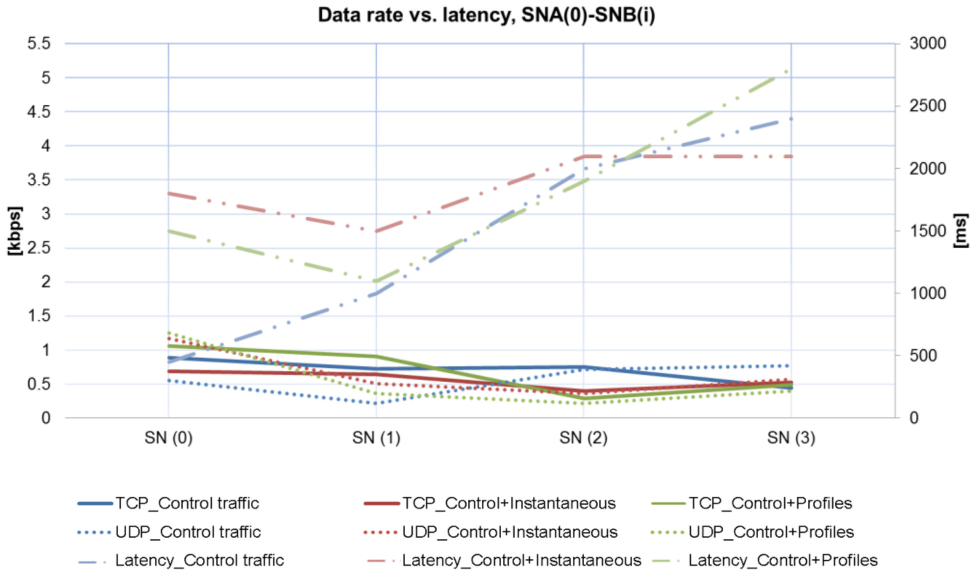

Figure 18. Obtained data rates [kbps] for communication between SNA and SNB with several switching levels for the server node (SNB), in a scenario with 21 SNs. TCP and UDP protocols and different types of metering traffic are considered. Latency values [ms] are also included and the roles of the nodes can be consulted in Figure 16.

Results can be described according to each role of the communication end points:

- In the communication between the BN and the SNB (Figure 17 and Table 5), the decrease of the data rate with the first switching level is very noticeable, as also shown in Figure 11, and the maximum difference reaches 2.99 kbps (BN-SNB(0) versus BN-SNB(1) with only control traffic). However, this decrease in the data rate does not continue gradually with the switching level. In fact, in the second and subsequent levels the decrease is markedly smaller and the differences between the hops smooth. This situation occurs for both TCP and UDP scenarios. Regarding the performance of UDP against TCP, the improvements introduced by UDP are small and they are not present in all cases. In addition, datagram loss was recorded in all cases from the second switching level. The jitter also increased remarkably and exceeded 16 s in some cases.
- In the communication between SNs (Figure 18 and Table 5), the obtained data rates are remarkably smaller than the data rates in the communication between BN-SNB. However, the decrease with the switching level is much less pronounced and the data rates in the second and subsequent levels remain quite similar. Then, it can be concluded than the highest decrease in the data rate is caused by the pass through the BN and from then on, the switching levels do not affect decisively. With regard to UDP, the better results that presents in comparison to TCP when there is no switching, disappear with the switching level. The high percentage of lost datagrams is remarkable and occurs in all cases. Finally, the effect of jitter is also very noticeable and it exceed 20 s in the worst case (communication between SNA(0)-SNB(3) with profiles traffic).

The results in Figure 17 and Figure 18 show that the relation of the latency with the data rate is different according to the roles of the communication end points. In the communication between BN-SNB, the data rate varies in inverse proportion to the latency, that is, the latency increases as the data rate decreases. However, the first switching level results in a noticeable decrease of the data rate that is not reflected in a proportional increase of the latency. The reason for this is the routing and transmission of the data by the switches, which constrains both latency and data rate values. For this very reason, in the communication between SNs, the inverse proportion between the latency and the data rate cannot be seen, since the latency increases with the switching level while the data rate is totally conditioned by the pass through the BN and therefore, by its management of the data transmission.

Table 5. Results for communication between BN and SNB, and between SNs with different switching levels in a scenario with 21 SNs for both TCP and UDP protocols.

Protocol		**TCP**	**UDP**			**Improvement of UDP with respect to TCP [kbps]**
Level	**Type of metering traffic**	**Data rate [kbps]**	**Data rate [kbps]**	***Jitter* [ms]**	**Lost datagrams (%)**	
BN – SNB(i)						
SNB(0)	**Control**	4.54	4.82	1546.04	0	0.28
	Control+Instantaneous	3.86	3.73	2189.81	0	-0.13
	Control +Profiles	2.38	3.88	1300.32	0	1.50
SNB(1)	**Control**	1.55	1.66	5846.96	0	0.11
	Control+Instantaneous	1.16	1.26	8872.11	0	0.10
	Control +Profiles	1.39	1.51	6488.55	0	0.12
SNB(2)	**Control**	0.95	0.98	10983.54	0	0.03
	Control+Instantaneous	0.53	0.71	10961.77	65	0.18
	Control +Profiles	0.58	0.73	4772.22	40	0.15
SNB(3)	**Control**	0.61	0.66	16774.97	69	0.05
	Control+Instantaneous	0.46	0.48	11142.45	81	0.02
	Control +Profiles	0.33	0.50	16185.86	71	0.17
SNA(0) – SNB(i)						
SNB(0)	**Control**	0.89	0.55	8742.77	83	-0.34
	Control+Instantaneous	0.69	1.17	8007.26	39	0.48
	Control +Profiles	1.06	1.25	5822.63	49	0.19
SNB(1)	**Control**	0.73	0.22	4775.44	93	-0.51
	Control+Instantaneous	0.64	0.51	13102.54	75	-0.13
	Control +Profiles	0.91	0.36	10975.78	88	-0.55
SNB(2)	**Control**	0.75	0.72	11532.93	59	-0.03
	Control+Instantaneous	0.40	0.36	13338.5	83	-0.04
	Control +Profiles	0.29	0.22	14155.09	91	-0.07
SNB(3)	**Control**	0.44	0.77	11083.11	36	0.33
	Control+Instantaneous	0.53	0.57	14453.56	62	0.04
	Control +Profiles	0.49	0.40	20130.78	72	-0.09

As done with the scenarios with different types of metering traffic (Section 5.1), Table 6 includes the sent and received frames for the scenarios with switching, which have turned out to be the most challenging in terms of data rate. The analysis also includes the IP traffic, both sent and received at the BN, and the length of the sessions, estimated as the time needed to complete the IP transmission at the receiver (server). Some conclusions can be drawn from these results:

- With regard to the IP traffic, Table 6 shows that the flow of IP frames noticeably increases with the switching level. This situation reveals the increase of IP retransmissions due to collisions and frame errors. Hence, IP frames must be retransmitted until being successfully received at the server.
- Focusing on the switching level, comparing the communication between BN-SNB(1) to the communication between SNA(0)-SNB(0), both with an intermediate hop, the number of IP frames is higher in the latter case (SNA(0)-SNB(0)). Then, the retransmission mechanism at the BN produces more IP traffic for the same amount of exchanged data.

- Regarding the length of the sessions, they are inversely proportional to the obtained data rates since the same data size was sent in all cases (100 kB). Table 6 clearly shows the increase in the sessions length with the switching level and, for the same size of data transmission, the length might increase up to 35 minutes merely due to the topology of the subnetwork (communication between BN-SNB(0) with profiles data against communication between BN-SNB(3)). Similarly to the data rate, the differences in the length session according to the type of metering traffic are masked for increasing switching levels.

Table 6. Channel occupancy for each type of metering traffic in terms of number of sent (Tx) and received (Rx) frames at the BN and the length of each session.

Type of metering traffic	**Control frames**		**Metering frames**		**IP (TCP) frames**		**Session length (mm:ss)**
	Tx	**Rx**	**Tx**	**Rx**	**Tx**	**Rx**	
BN-SNB(0)							
Only control + IP	363	92	0	0	1837	320	2:56
Control + Instantaneous + IP	400	117	228	272	1873	352	3:27
Control + Profiles + IP	639	170	317	1344	2094	406	5:36
BN-SNB(1)							
Only control + IP	1176	793	0	0	2715	2555	8:36
Control + Instantaneous + IP	1344	920	592	1420	2884	2653	11:29
Control + Profiles + IP	1163	802	242	1220	2710	2520	9:35
BN-SNB(2)							
Only control + IP	1577	884	0	0	3510	3817	14:02
Control + Instantaneous + IP	3150	1826	1569	3769	4243	4847	25:09
Control + Profiles + IP	2747	1621	286	2207	3777	3952	22:59
BN-SNB(3)							
Only control + IP	2463	1799	0	0	4935	7502	21:51
Control + Instantaneous + IP	3331	2711	1426	3839	5091	7945	28:59
Control + Profiles + IP	5174	4022	856	7194	6263	11214	40:24
SNA(0)-SNB(0)							
Only control + IP	1892	759	0	0	5863	5864	14:58
Control + Instantaneous + IP	2384	1030	1274	2150	6685	6993	19:19
Control + Profiles + IP	1433	576	648	2641	3086	3149	12:34
SNA(0)-SNB(1)							
Only control + IP	2064	962	0	0	3935	5967	18:15
Control + Instantaneous + IP	2551	1227	1032	2409	4178	6152	20:50
Control + Profiles + IP	2069	950	225	1282	3988	5471	14:39
SNA(0)-SNB(2)							
Only control + IP	1987	1202	0	0	4198	6670	17:46
Control + Instantaneous + IP	4917	2840	2840	5259	4823	8798	33:20
Control + Profiles + IP	5119	3259	1378	8155	5982	10457	45:58
SNA(0)-SNB(3)							
Only control + IP	3374	1461	0	0	3999	7774	30:18
Control + Instantaneous + IP	3406	2180	1515	3227	4635	7797	25:09
Control + Profiles + IP	3417	2119	559	3165	4540	7629	27:12

The channel occupancy results highlight the presence of frame errors and the retransmission of IP frames, especially with the switching level. Hence, the transmission mechanism highly affects the data rates and this effect increases with the switching level for the communication between BN-SNB.

6. Discussion

The additional channel capacity existing in an AMI deployment for IP-based communications has been empirically assessed through a measurement campaign. In order to optimize the implementation of IP-based applications over NB-PLC, the following aspects have to be considered. Additionally, Table 7 summarizes the most relevant parameters and the performance of the implementation in terms of data rate and latency.

- First, it is necessary to verify that there is additional space in the channel when the AMI system is operating. According to the measurements at CEDER-CIEMAT, when there is only control traffic in the subnetwork, the channel is unoccupied 97.3 % of time. For the same session length, the instantaneous petitions to all the SMs within the subnetwork (19 SMs) and the profiles traffic increased the channel occupancy by 5 % and by 13.9 % with regard to the first case, respectively.
- Then, the latency was evaluated aiming at determining the bottlenecks in the channel. Figure 9 clearly shows the most affecting parameters:
  - In the communication between BN-SNB, the latency progressively increases with the type of metering traffic (the highest values of latency can be seen for the profiles data) and with the switching level. By the third switching level the latency values are similar, regardless of the type of metering traffic. Then, the bottlenecks are the switching levels. Mean values can be consulted in Table 7 and the worst recorded value was 3 s.
  - In the communication between SNs, the bottleneck occurs directly in the communication between the nodes, without switching, for both the scenarios with instantaneous and with profiles traffic. This is due to the pass through the BN, since it is in charge of handling the traffic in the communications between SNs. Mean values can be seen in Table 7. In the worst case, the latency increased up to 3.6 s.
- Finally, the data rate was evaluated through an extensive measurements campaign. In the specific case of IP over PRIME the analysed variables, in order of importance with respect to their effect on data rates, are the following:
  - The existence of an intermediate hop, regardless of being the pass through the BN in communications between SNs or being a switching level in the communication between BN-SN. According to the measurements performed at the microgrid, the pass through the BN is the most restrictive scenario. This is because the BN has to handle the data traffic of the entire subnetwork, leading to a reduction of the data rate in the specific case of the communication between SNs. Regarding the influence of switching, the reason for the data rate decrease is the routing and transmission of the data by the switches. Before forwarding the data, switch nodes must look up for the specific node in their internal data base and only if it is in the data base they forward the frames following SCP method. With the insertion of hops (pass through switches), the data transmission progressively slows down since this process has to be done for each hop.
    - In the communication between nodes, there is a proportional reduction of the data rate with the switching level but there are no significant differences according to the type of metering traffic, as showed in Table 7. Despite there are no significant differences in the data rates for the considered number of nodes, it is expected that the influence on the data rate would be noticeable if a higher number of nodes was considered.
    - In the communication between BN-SN, the introduction of a switching level, BN-SN(1), noticeably decreases the data rate with regard to the communication without switching, BN-SN(0), and the reduction is proportionately higher in the case with only control traffic (approximately 3 kbps). For more switching levels, the reduction is less pronounced in absolute terms and the highest recorded difference was 0.81 kbps. As for the communication between SNs, for the considered number of nodes there were not significant differences in the data rates.

  - The type of metering traffic is related to the increase of the traffic flow in the channel. The influence of the type of metering traffic is especially important in the communication between BN-SNB(0) (Table 7). By contrast, the differences introduced by the type of metering traffic are masked when there is an intermediate hop in the traffic flow.
  - In general, UDP presents higher data rates than TCP, but the differences reduce with the introduction of intermediate hops. However, UDP maximizes the available bandwidth at the expense of control mechanisms of the frames reception. Then, the final application of the implementation of IP over PRIME would determine if the tight improvements provided by UDP compensate for the lack of control mechanisms. In any case, UDP is discarded for the communication between BN-SN with two or more switching levels and for the communication between SNs, regardless the switching levels, due to the datagram loss, as Table 5 and Table 7 show. With regard to the jitter values, they noticeably increase with the switching level.
  - The variation in the number of nodes considered for the measurements (9, 13, 17 and 21 SNs) had minor effects on the data rate, with a maximum difference of 0.5 kbps. Considering that a single DC can handle more than 400 SNs [19], the available number of nodes at CEDER-CIEMAT is not enough to obtain significant results. Existing simulations including up to 512 SNs show that data rates above 1 kbps are possible for the worst case considered (communication between BN-SN with metering traffic) [17], which suggest that the implementation of IP over PLC in a real scenario with a wide deployment of nodes might be possible.
  - Regarding TCP configuration, the variation of both the window and segment values does not result in significant variations and does not follow a specific trend, either. Then, the default configurations (window size of 8 kB and segment size of 1220 B) were considered representative for the study.

Table 7. Summary of data rate and latency results of the implementation of IP over PRIME according to the most relevant parameters.

Sender node	Switching level (i) of the receiver	Applicable protocol	Type of traffic	Data rate	Latency
BN	0	TCP/UDP	Control	~ 4.5 kbps	~ 200 ms
			Instantaneous	~ 3.5 kbps	~ 250 ms
			Profiles	2–3.5 kbps	~ 1.3 s
	1	TCP/UDP	Any	1–1.5 kbps	300 - 800 ms
	2 ≤ i ≤ 3	Only TCP	Any	~ 0.5 kbps	0.5 – 2 s
SN(0)	0 ≤ i ≤ 3	Only TCP	Any	≤ 1 kbps	1 - 3 s

Focusing on the mechanisms of the standard that affect data rate, several considerations can be made. The analysis is done for the version implemented by the equipment of the measurements, PRIME v.1.3.6, and the latest version, PRIME v1.4.

- PRIME version 1.3.6 defines direct connections between SNs, but these are not implemented in the equipment under test. In direct connections, the SNs exchange the frames directly between them through the switches, if required, without the need of going through the BN. This feature would reduce the bottleneck at the BN but it would not solve the data rate reduction that occurs in the traditional switching.

  Focusing the analysis on the switch nodes, they forward the data selectively, discarding frames whose destination or origin data do not come from nodes connected to them. On one hand, this feature reduces the flow of traffic in the subnetwork. On the other hand, it delays the exchange of data since the source or destination node must be identified each time. By suppressing this option, switches would forward all the arriving data, occupying the channel unnecessarily. However, it would be interesting to evaluate the effect on the data rate that would entail the increase of the traffic in exchange of reducing the computational cost. In addition, it is possible to address the improvement of the operation of switches focusing on the method to transmit the data:

  - SFP: corresponds to the period of time in which any node in the subnetwork can transmit data. Collisions that may arise during this period are avoided with the algorithm CSMA-CA, which fixes priority levels for the packets to be transmitted between 1-4, e.g., control MAC frames have the highest priority (1). In the devices under test, the SFP period is the whole MAC frame. Since the frame size is fixed (276 OFDM symbols), this SFP period cannot be changed. Regarding priorities, for the equipment in the measurements it is only possible to set them for the preprogrammed tasks in the DC. Priorities may be useful for cases where there is a lot of metering data, since IP transmission could be prioritized. However, in a scenario with only control traffic, both traffics would have the highest priority, so it is not expected that the resulting data rates were very different from those obtained in Figure 17 and Figure 18.
  - Contention Free Period (CFP): defines a period of time free of collisions. It is included in the standard but the devices under test do not implement it. In CFP, nodes have to previously request access to the collision-free medium to the BN, which, according to the occupation of the channel, provides this access or not. In a transmission with several levels of switching, the CFP period is assigned to all intermediate switches of the whole path. Despite the inherent advantage in a collision-free transmission, the increase of CFP reduces the SFP (both share the same MAC frame whose size is fixed), which is precisely the period that MAC control frames use. Therefore, the overall operation of the subnetwork may be affected, meaning that CFP should be considered for critical applications that do not affect the stability of the subnetwork [4].

- The most recent version of PRIME, v.1.4, introduces several improvements (e.g., reduction of signaling frames, flexibility of the size of the MAC frames) that reduce the traffic at a global level, as showed in [20]. However, existing traffic in the subnetwork has not turned out to be the most influential aspect for the obtained data rate, as previously demonstrated. Regarding the operation of the switch nodes, the latest version introduces new features:
  - The main improvement of the MAC layer that is relevant for this work is that the MAC frames have been redefined. The size of the MAC frame is flexible, which is especially interesting for the improvement of the data rate. Since IP traffic can be associated with longer MAC frames, the available channel would be better utilized. In the case of co-existence with different types of traffic, the introduction of MAC priorities could be advantageous.

From the analysis of the standard, two main ideas can be drawn. First, there are features in the standard, both in version 1.3.6 and version 1.4, which might contribute to the improvement of the data rate for IP applications over PRIME. Specifically, it deals with the direct connections between SNs (which eliminates the pass through the BN) and a new MAC frame, more flexible in size. In addition, the use of MAC priorities could reduce the latency of priority traffic. Second, the selective forwarding of the switches seems to have a significant weight considering the results, but it is difficult to assess the delay that entails the source and destination check of the frames with the available tools. As an alternative for networks with a small number of nodes, it might be interesting to allow the deactivation of this option and configure the switches so that they were simple repeaters of the frames that arrive to them.

7. Conclusion

This work presents an empirical implementation of IP communications over a PRIME-based AMI deployment of the real microgrid at CEDER-CIEMAT facilities. The performance of the implementation has been measured through the study of the channel occupancy, latency and data rates. The results validate existing laboratory tests and further analyse the variables and parameters that affect the data rate, in which the topology of the subnetwork plays a key role. In fact, the data forwarding from repeaters nodes (either SNs acting as switches or the BN handling the communications between SNs) have resulted the most affecting factor in the obtained data rate. Additionally, further measurements have demonstrated the suitability of TCP or UDP or both depending on the role of the communication end points. For higher switching level of the receiver node, only TCP is suitable since UDP presents lost datagrams. The existing type of traffic in the channel is only relevant in the communication BN-SN without switching. Other factors, such as TCP parameters (window and segment sizes) barely affect the data rate for the considered scenarios. Finally, regarding the influence of the number of nodes on the data rate, the number of nodes considered for these measurements (up to 21 SNs) does not allow to obtain significant conclusions. Taking into account that real deployments can consist up to 400 SNs, meaningful variations on the data rate can be expected. However, existing simulations reveal that the presented implementation might be possible in real scenarios with a wider deployment of nodes. Finally, the analysis of the influence of PRIME standard in the data rate shows that some improvements can be expected depending on the particular implementation of manufacturers. Additionally, new features included in the latest version of the standard may improve the performance of IP over PRIME, since the most limiting aspects are related to the traffic management between nodes and at switching levels.

The results are a significant contribution for the complementary uses of AMI deployments and PLC-based technologies, i.e., new applications over NB-PLC based on IP data transmission such as low complexity applications related to the management of DG, which is in line with the current efforts for the transition toward the *Smart Grid* paradigm. In addition, the results can be also helpful for future PLC standards development. Additional open issues such as the influence of noise over data rates and the effects on AMI traffic will be addressed in future research lines.

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