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Smart Grid Applications for a Practical Implementation of IP over Narrowband Power Line Communications

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Abstract: Currently, Advanced Metering Infrastructure (AMI) systems have equipped the low voltage section with a communication system that is being used mainly for metering purposes, but it can be further employed for additional applications related to the Smart Grid (SG) concept. This paper explores the potential applications beyond metering of the available channel in a Power Line Communication-based AMI system. To that end, IP has been implemented over Narrow Band-Power Line Communication (NB-PLC) in a real microgrid, which includes an AMI system. A thorough review of potential applications for the SG that might be implemented for this representative case is included in order to provide a realistic analysis of the potentiality of NB-PLC beyond smart metering. The results demonstrate that existing AMI systems based on NB-PLC have the capacity to implement additional applications such as remote commands or status signals, which entails an added value for deployed AMI systems.

Keywords: narrowband power line communications; smart grid applications; Smart Grid communications; internet protocol

1. Introduction

Most of the existing research works that address grid improvements without communication focus on automation issues and local control tasks [1–3]. By contrast, a proper communication infrastructure enables the electric system to increase its efficiency to a much greater extent than automation without communication capacities could ever do [4]. In this context emerges the concept of the Smart Grid (SG), which highly relies on the introduction of Information and Communication Technologies (ICTs) for its success. Overall, ICTs allow the traditional power grid to become more reliable, resilient, and efficient. There is a wide range of research works endorsing this concept, including the definition of applications for the SG and their requirements [5–7]. These applications are supported by bidirectional communication systems that must meet the needs of each specific application: technical aspects such as data rate, latency, reliability, coverage range, and security. However, other factors such as the deployment cost, the integration with legacy technologies, the grid distribution system arrangements, and specific deployment strategies from the involved stakeholders must be also addressed.

In this context, Narrowband PLC (NB-PLC) present some valuable features, whose suitability for the SG has been widely covered in the literature [8–10]: low initial deployment cost, the use of existing infrastructure, and the total control over communications by distribution system operators without the need for external communication system operators. These features have all contributed to the relevant presence of NB-PLC in European Advanced Metering Infrastructures (AMI) deployments [11]. However, NB-PLC presents some drawbacks, mainly related to its performance dependency on the channel conditions [12]. In any case, it is expected that future improvements of the technology will lead to increased levels of performance and robustness [13].

Once the NB-PLC infrastructure for AMI has been successfully deployed, it can be used for additional applications apart from metering. The objective of this work is to analyze the new potential applications for SGs of a NB-PLC system. Considering the existing number of AMI deployments based on this technology, the new potential applications can entail a notably improvement for the grid. The study is based on the results of a measurement campaign performed in a real microgrid with a wide range of distributed energy resources (DERs), which also includes an AMI system based on NB-PLC. A thorough review of potential applications for SGs that might be implemented for this representative case is included in order to provide a realistic analysis of the potentiality of NB-PLC beyond smart metering.

The paper is divided as follows: Section 2 describes emerging applications for SGs, while the opportunities for NB-PLC beyond Smart Metering are described in Section 3. Then, Section 4 discusses the potential applications of the implementation of IP over NB-PLC in a real microgrid and, finally, Section 5 summarizes the most important ideas of the presented work.

2. Review of Applications for Smart Grids

Some of the most important applications for the SGs regarding their communication requirements can be seen in Table 1 [6,7,14–16]. The communication requirements are given in terms of data rate and latency. The data rate specifies how fast the data is transmitted between two communication nodes and can be considered the most restrictive parameter, and the latency defines the delay of the data when transmitted from one node to another. Latency becomes crucial in applications that require fast responses, while for some other applications is less important (e.g., metering for billing). The applications are arranged in order of increasing data rate, so that Table 1 can be consulted for evaluating potential applications to be implemented in an existing communication deployment.

In addition to traditional applications such as monitoring, control, and substation automation, there are important agents whose relevance in the SG is growing. These are mainly the distributed energy resources (DERs) and microgrids, the consumers evolving towards prosumers, and the electric vehicles (EVs), from which new applications are emerging. These applications are reviewed below.

Table 1. Classification of applications for the Smart Grid according to their communication requirements.

Data Rate Range	Latency Range	Application	Approximated Specific Data Rate	Approximated Specific Latency	Tasks	Typical Data Size	Indicative Data Sampling	Reliability
bps	ms–s	Remote control	~bps	100–500 ms	Connections/disconnections	100–500 B	Occasional	>99%
		Pricing	~bps	10 s	Prepayment services	100–200 B	Regular (per month)	>99%
		Lighting, traffic control	~bps	100–300 s	Signaling and commands	10–50 B	Occasional	>99%
<10 kbps	ms–s	SCADA	~kbps	300–3000 ms	Monitoring and control commands	100–500 B	"Polling"	>99%
		Domestic applications	~kbps/device	2–15 s	Customer information requests and responses	100–500 B	Regular and under demand	>99%
					Premises network administration	25 B	As needed	>99%
10–100 kbps	<200 ms	Substation automation (SA)	9.6–56 kbps	15–200 ms	Monitoring and control commands	150–250 B	Several times per day and under demand	>99.99%
		Overhead transmission line monitoring	9.6–56 kbps	15–200 ms	Monitoring and data maintenance	100–1000 B	Several times per day and under demand	99.0–99.99%
		Distribution automation (DA)	9.6–56 kbps	20–200 ms	Monitoring and data maintenance	100–1000 B	1 device per hour	>99.99%
					Control commands	150–250 B	1 device per hour (minimum)	>99.99%
					Fault detection, clearing, isolation and restoration	25 B	1 device per 5 s (minimum)	>99.99%
	200 ms–5 s	Distribution management	9.6–100 kbps	100 ms–2 s	Monitoring, data maintenance and control commands	100–1000 B	1 device per hour (minimum)	99.0–99.99%
		Home Energy Managemnt (HEM)	9.6–56 kbps	200 ms–2 s	Signaling and commands	100–500 B	Regular and under demand	99.0–99.99%
		Distributed Energy Resources management	9.6–56 kbps	200 ms–2 s	Operation commands	25 B	Several times per day	99.0–99.99%
		Demand-side management (SM)	14–100 kbps/node	500 ms–5 s	RTP programs	100 B	1 per device per price, several times per day	>99%

Table 1. *Cont.*

Data Rate Range	Latency Range	Application	Approximated Specific Data Rate	Approximated Specific Latency	Tasks	Typical Data Size	Indicative Data Sampling	Reliability
10–100 kbps	<2 s	Outage management	56 kbps	2 s	Outage and restoration management	25 B	1 per power lost	>99%
		AMI (per node)	10–100 kbps	≥2 s	Meter reading–on demand	100 B	As needed	>99%
					Meter reading–scheduled	1600–2400 B	Several times per day	>99%
	2 s–5 min	EVs—vehicle to grid (V2G)	9.6–56 kbps	2 s–5 min	Pricing signals and commands	255 B	1 per EV per day	99.0–99.99%
		EVs—charging	9.6–56 kbps	2 s–5 min	Charge status signals and commands	100 B	2–4 per EV per day	99.0–99.99%
		Demand-side management (DSM)	14–100 kbps/node	2 s–5 min	TOU programs	100 B	1 per device per price, several times per year	>99%
					CPP programs	100 B	1 per device per price, several times per year	>99%
					Service switch operation	25 B	1–2 per group of meters per day	>99%
100–1000 kbps	20 ms–2 s	Wide area awareness	600–1500 kbps	20–200 ms	Synchrophasor, command controls	50–100 B	Regular and under demand	>99.99%
		Surveillance	500–1500 kbps	~s	Monitoring and response	100–500 B	Regular and event-driven	>99.99%
		AMI (backhaul)	500 kbps	≥2 s	Meter reading–bulk transfer	~MB	Several times per day	>99%
Mbps	ms	Automated Distribution automation (ADA)	~Mbps	25–100 ms	Monitoring: power oscillations, voltage stability, states estimation	>55 B	Once every 0.1 s (minimum)	>99.99%
					Control: voltages, cascade failures, transients, power oscillations	4–160 B	Once every 0.1 s (minimum)	>99.99%
					Protection: adaptative islanding and predictive behaviour	4–160 B	Once every 0.1 s	>99.99%

2.1. Distributed Energy Resources and Microgrids

The rise of DERs worldwide is a fact that is progressively changing the grid planning. Additionally, the fluctuating and intermittent nature of renewable energy sources (RES) causes variations in the power flow that can affect the overall operation of the grid. As a consequence, efficient monitoring and control applications are required to operate these resources in a reliable and safe way. Current DERs management strategies focus on enabling an increase of the DERs in existing power grids and promote the use of more RES with minimum costs for the power grid [5]. Additionally, DERs and microgrids are closely linked and many microgrid control schemes include specific DER monitoring and control applications.

The management of DERs and microgrids is closely related to metering tasks, since it requires efficient and reliable consumption and generation measurements (e.g., through AMI deployments). Three main metering processes can be found [7]:

- On-demand metering: SMs are read when needed, e.g., when the utility needs to backfill missing information or during a decision-making process;
- Scheduled metering: provides the data collection from a meter on a regular basis, e.g., several times per day. Usually, the readings are stored automatically at the meter and then retrieved by the control center or the utility;
- Bulk transfer: this action is performed to collect data from all the requested meters. The communication requirements highly depend on the number of involved meters.

The communication requirements for DER management applications vary based on the specific service, but required data rates can be located in the 9.6–56 kbps range, while latency requirements are usually above 200 ms and up to a few seconds [6].

2.2. Prosumers

The relevance of the prosumers in order to deliver sustainable, economic, and secure power supply has been widely accepted. However, there has been still little investigation in prosumer management schemes in existing SG energy sharing approaches [17]. Three main methods can be found:

- Individual integration: in which there is a direct energy sharing between the prosumers and utility grid;
- Simple-group integration: the prosumer groups contain different prosumers with diverse behaviors and the prosumers collectively increase the amount of power to be auctioned to the grid. These groups can be also found as Virtual Power Plants (VPPs);
- A novel approach (goal-oriented virtual prosumer-communities), which connects the prosumers to the grid in the form of goal-oriented virtual communities [17].

The individual integration has been the most addressed approach, specially through a set of measures known as Demand response (DR). DR refers to short-term changes by customers in their electric consumption patterns to reduce or shift electric load over time and then improving the overall energy system reliability and energy efficiency. The prosumers participate in the energy market by changing their energy consumption approach instead of being exposed to fixed prices, resulting in profits for both the companies and end-users [15]. DR applications can be further classified into [18]:

- Incentive-based DR programs: customers get payments or preferential prices for non-DR periods from reducing electricity usage during periods of system need or stress. On one hand, in some programs the grid operator gets total access to the customer premises (direct load control). The utility sends commands to a load controller that turns on/off selected devices at the customer premises. Typical devices under these programs are domestic appliances such as central air conditioning systems, heat pumps, electric water heaters, and pool pumps. On the other hand, other measures (energy demand, interruptible rates, demand bidding, and capacity market programs) require customer involvement, which decides whether they will participate or not according to the prices and their needs.

- Time-based DR programs: customers vary their demand according to the received price signals. The oldest and the most prevalent DR program is the time-of-use (TOU), in which customers shift their electricity usage to off-peak hours to lower their bills. Implementation experience of TOU rates shows that they can partially influence patterns of electricity demand [19].
- A variation of TOU is critical peak pricing (CPP), which relies on very high critical peak prices, as opposed to the ordinary peak prices in TOU rates. If the utility needs to limit the loads, it sends CPP messages to enrolled customers for a radical load reduction. Finally, real-time pricing (RTP) offers short-term, time-varying pricing information, reflecting the wholesale price of electricity.

As occurs with DERs, the applications for prosumers highly rely on metering systems. Regarding communication requirements, relatively low-speed communications can be used within prosumer management, and the latency requirements are not strict (a few seconds).

2.3. Electrical Vehicles (EVs)

The rise of EVs also entails a suitable communications system able to deal with their impact on the grid. Two main services can be identified regarding EVs communication.

- Vehicle to grid (V2G) operation, which is the supply of the power flow stored in the car to the power grid. Basically, in this operation the EV acts as a portable battery. Hence, it can be considered also as a DER. During this operation, it is necessary to monitor both the states of the grid and the EV and measure the transferred power.
- Charging state is a derived application of EVs. Ideally, charging operations should be done according to external parameters such as the grid state, renewable energy production, or even electricity prices. Therefore, different tasks of monitoring and measuring are required.

Communication requirements for EVs applications are between 5 and 10 kbps in terms of data rate and latency around 2 s. However, if the operations are related to load balancing and billing, the required data rate can increase up to 56 kbps [15].

2.4. Other Applications

New applications have arisen from the SG concept and are expected to grow in the future, for example, economical services related to the electricity market, such as the infrastructure for power generation and electricity market information exchange described in [20]. In this scenario the supply is provided according to real-time price signals. Another relevant application is the Home Energy Management (HEM) concept, related also to prosumers, which focuses on the power management on the consumer side. Thus, home appliances are monitored and controlled to balance and optimize the power supply and consumption [21]. The requirements of data rates of this applications depend upon the specific tasks. Since they are not critical services, requirements in terms of latency are less strict, between 2 and 15 s [15].

3. Opportunities for NB-PLC beyond Smart Metering

3.1. The Role of PLC in the Smart Grid

On one hand, PLC presents some valuable advantages for SGs applications, as it has a wide potential coverage due to the electricity wires, making every line-powered device a potential target of value-added services through PLC. Moreover, the installation is already deployed, easy to manage, and stable. On the other hand, the greatest disadvantages of PLC are mainly related to the medium, due to existing disturbances, noises, and attenuations, and consequently, the global capacity of PLC in terms of bandwidth is less than other technologies.

The use of PLC for applications related to the management of the grid has long been used by electric power utilities, even before the SG concept arose. In the beginning of the nineties, some studies pointed out PLC as the enabler of the Automatic Metering Reading (AMR), the subsequent AMI, and also some control applications [22]. In the following years, prepaid and load response were identified as potential applications of PLC [23]. Additionally, ref. [24–26] include examples of applications implemented with PLC related to voltage and reactive power control, emergency signaling, security systems and maintenance, and remote control. In addition, it is also common to find combinations of PLC with different tools to increase the range of control applications, such as SCADA systems [27] and multi-agents architectures [28]. Most of the first uses of PLC were related to the HV section of the grid. In addition to being considered the most critical section of the grid, the HV section is a better medium for communications than Medium Voltage (MV) and Low Voltage (LV) lines, since they present lower attenuation [8]. However, this scenario has changed over time since the MV and LV sections, especially the latter, are increasingly getting the attention of the grid operators. In addition, some features, such as OFDM modulation, have facilitated the presence of PLC in LV grids.

Very promising applications of PLC for the SGs are also located within the MV section, such as fault detection and management, remote control, diagnostic services, and distribution automation [29–33]. Also, applications within the area of DERs can be found in [34,35]. New applications are emerging also in the LV section, in particular thanks to the rise of AMI systems, which are equipping the LV section with a true communication system for the first time. This scenario sets a new opportunity for applications and management of the SGs in the LV section, where the smart meter becomes an enabler of new applications rather than a digital meter. In fact, there is a wide range of projects making use of the implementation of PLC in the LV section. For instance, PRICE, Grid4EU, Sustainable, Smart City Malaga, and Discern use AMI systems based on PoweRline Intelligent Metering Evolution (PRIME) and G3-PLC for the optimization and management of the grid [36–40]. The Smart Grid Vendee and Nice Grid projects follow the same idea of using AMI systems (both based on G3-PLC) but include also DG [41,42]. A common feature of these projects is that all of them use PLC only for AMI purposes. PLC also presents advantages for EVs applications, since it provides a physical association between the vehicle and the supply equipment, which provides security and guarantees authentication [8]. In this sense, especially NB-PLC presents promising features for these applications, and some versions of the technology offer the advantage of being able to communicate through transformers [10].

3.2. The Role of IP

The implementation of communications based on IP emerges as a good candidate for making use of the additional available channel in NB-PLC, because IP seems to be able to guarantee the interoperability among different technologies [23]. It also presents several important advantages for SG applications: reliability, security, strength, simplicity, and the fact of being an open standard. Specifically, IP is able to address the following key challenges for the SG success [43,44]:

- Flexibility: it is widely accepted that the future SG will be a heterogeneous scenario of multiple communication technologies, since there is no unique solution that can address all the functionalities expected from the SG. Not surprisingly, the integration and operation of multiple technologies and vendor solutions was found to be the top concern about communications for grid operators [45]. In this sense, IP can run over any link layer network (e.g., Ethernet, wireless radio networks, and serial lines) providing a common and flexible way to use and manage the SG. Then, SG applications become independent of the physical media and data link communication technologies, which greatly reduces the complexity for developing upper-layer applications and enables interoperability [46].
- Resilience: the SG has to be able to evolve together with the new technologies, applications, and devices, and so the communication systems must do. In this sense, one of the principal benefits of IP is its ability to add a capability (e.g., a new application or service) without having to change IP itself.

- Scalability: the SG architecture must enable communication and handle data for millions of devices connected to the grid (substations, transformers, smart meters, DERs, and other equipment) and growing annually. The last version of IP, IPv6, offers addressing and routing for a huge network such as the expected SG [47].
- Stability and reliability: the SG data network must be reliable so that it can guarantee uninterrupted and high quality electrical service. After more than 30 years of existence, it has been demonstrated that IP is a workable solution considering its large and well-established knowledge base [47].
- Security: ensuring a high degree of security is a crucial requirement for the success of SGs, as commented on in the previous section. Despite the fact that IP was designed to be open and flexible, over the years more and more tools have been built to provide security in the communications that make use of IP networks. In fact, IP is the communication protocol with the biggest number of tools for securing and managing the transport of data. Many applications, such as energy metering in the SG, have emerged from a decade of research in wireless sensor networks. However, the lack of an IP-based network architecture precluded sensor networks from interoperating with the Internet, limiting their real-world impact [23]. But that is now changing and IP is increasingly being used in supervision and control applications in the energy field, such as demand response, DG control, and consumer integration [48]. As pointed out in [23], IP has to be implemented up until the last node of the communication network in order to be the reference protocol. Therefore, it is essential to reach the LV section.

3.3. IP Data Transmission over NB-PLC: Practical Implementation

The AMI infrastructure might allow additional applications beyond smart metering, as studied in [49]. In [9], it was demonstrated by laboratory tests that IP can be implemented in the available channel of a NB-PLC system (specifically, PRIME technology), and in [50], measurements performed in a real environment demonstrated the viability of IP transmission over PLC. The measurements were performed in a real microgrid implementing a PLC-based AMI system consisting of 21 nodes. Detailed features of the microgrid and the AMI deployment can be consulted in [51]. The devices used for the measurements are briefly described below. Additionally, they can be identified in the communication topology of the scenario showed in Figure 1.

- Portable Base Node (PBN): acts as a communication PLC node and includes IP capabilities. Three PBNs were used, whose roles were configured as follows:
    - PBN-BN: one of the PBNs was configured as the subnet manager node (base node).
    - PBN-SNA and PBN-SNB: the other two PBNs were configured as service nodes (SN). These PBNs will be registered in the subnetwork governed by the PBN-BN.
- SMs: all the SMs within the considered subnetwork are part of the measurements as they will be registered in the PBN-BN as well. The SMs are responsible for generating different types of traffic, which were also considered for the measurements since the implementation of IP should not affect the normal metering tasks of the microgrid:
    - Control data (C): it is automatically generated for the maintenance and operation of the subnetwork, and consists mainly of signaling data and topological information. Control traffic is always present in the subnetwork;
    - Basic instantaneous metering data values (I): these are request tasks configured in the data concentrator, which interrogates each minute to all the SMs within the subnetwork regarding their instantaneous measurement data, whether of consumption or generation. This traffic is added to the control traffic;
    - Load profile metering data values (P): these are also request tasks configured in the data concentrator, which interrogates a specific SM regarding its measurement data stored between a start date and an end date via web service.

Finally, Iperf software tool is responsible for generating IP traffic and measuring the performance of the network in terms of data rate [52]. A detailed description of the configurations and devices can be consulted in [50].

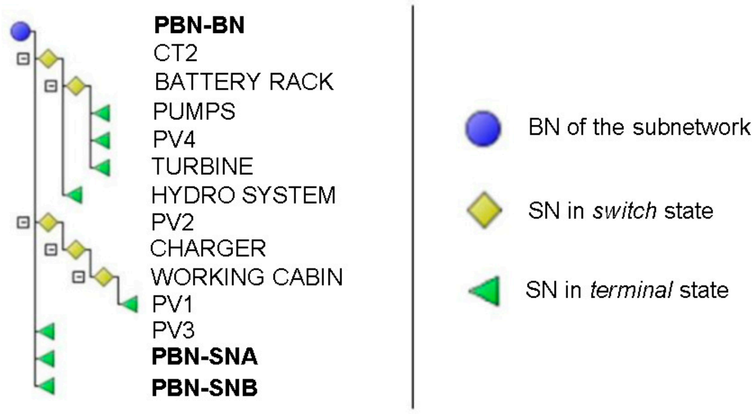

Figure 1. Example of subnetwork topology for the measurements.

Aiming at testing a wide range of parameters, several configurations and scenarios were measured, as summarized in Table 2, and the results can be seen in a schematic way in Figure 2. The analysis of the obtained results is addressed in [53]. For the present work, the numeric values of the obtained data rates and latencies are the parameters under consideration, since they are the key parameters to take into account when evaluating communication networks [5,6].

Overall, it can be seen that for the communication between the BN and a SN, the level of switching of the receiver node (i.e., the communication hops between nodes through a repeater or switch) is the main limiting parameter followed by the type of traffic within the subnetwork. For each case, the resulting data rate and latency can be seen in Figure 2. For the communication between a node directly connected to the BN (its switching level is zero) and another node, regardless of its switching level (up to three), the available data rate is less than 1 kbps and the latency range is 1–3 s.

Table 2. Summary of the considered configurations for the evaluation of IP over PLC-PRIME.

Measurement Configurations		
Transmission size (kB)		100
Number of nodes in the subnetwork		21
Type of metering traffic in the subnetwork		Control (C) Control + instantaneous (I) Control + profiles (P)
Considered transport protocols		TCP and UDP
Type of IP communication and switching level (i)	Between BN and SN	BN–SNB(0) BN–SNB(1) BN–SNB(2) BN–SNB(3)
	Between SN and SN	SNA(0)–SNB(0) SNA(0)–SNB(1) SNA(0)–SNB(2) SNA(0)–SNB(3)

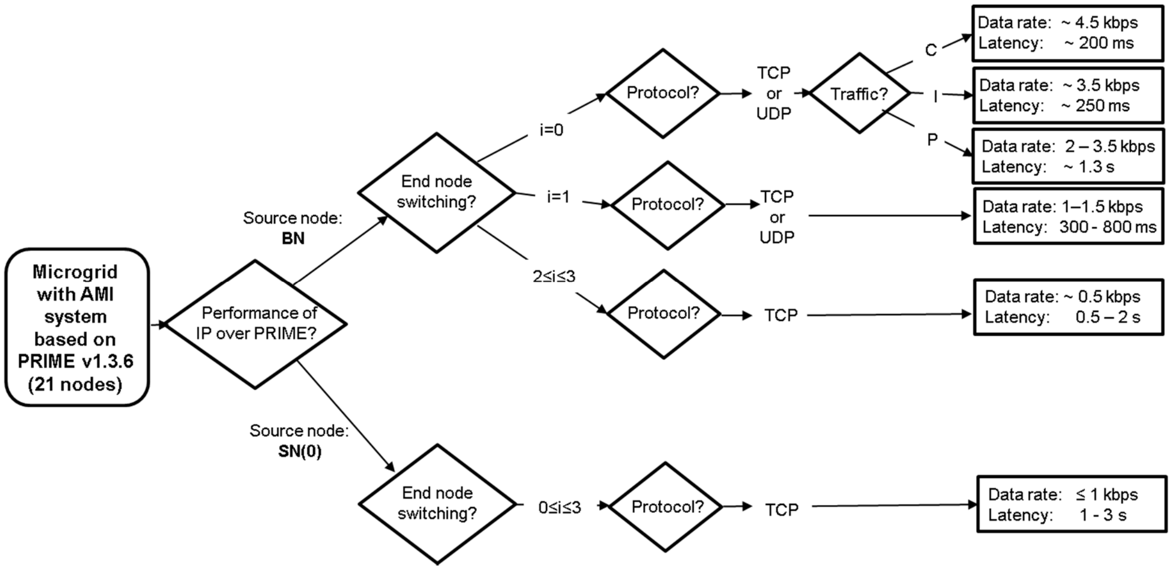

Figure 2. Results from the implementation of IP over PLC-PRIME, in terms of data rate and latency, in a microgrid including an Advanced Metering Infrastructure (AMI) system with 21 nodes. The two main branches differentiate the source nodes (clients in the IP communication). Then, different sub-branches emerge according to the level of switching (i) and the type of traffic: control (C), control+instantaneous (I), and control + profiles (P). Additionally, the suitability of implementing Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) is also shown.

4. Discussion of Potential Applications of the Implementation of IP over PLC-PRIME

Observing the results in Figure 2 and the data rates and latency values given in Table 1, it is clear that applications requiring real-time o nearly real-time responses would not be possible with the presented implementation. Thereafter, applications that require data rates in the order of bps up to a few kbps could be addressed with the analyzed implementation. Regarding latency, it is crucial in applications requiring fast responses, which are out of reach of the case under study. However, the obtained latency results are in line with the latency requirements of the applications whose data rates vary between bps and a few kbps. The possible applications are described below:

- Focusing on the analysis on the management of the DERs of the microgrid, the requirements for their monitoring and control range from 9.6 to 56 kbps [6], which is beyond the reach of the implementation. Additionally, the features of the presented system would not be applicable to complex management systems [54]. However, it would be possible to implement some less strict tasks in terms of requirements for DER management. The management of resources can be approached as a system, in turn, consisting of a monitoring system and several control actions. The monitoring system, located at the grid operator premises, would be responsible for reporting the situation of the system by evaluating the state of each of the DERs. This task could be implemented through simple information signals from each resource, taking advantage of its associated SM. The response signals would return to the grid operator, which together with additional supplementary information (e.g., metering data from the SMs themselves via PLC, task planning, and meteorological forecast) will generate actions to be carried out. At this point, SCADA systems are usually employed. The implementation of a SCADA system with the presented implementation could be made just for low performance versions due to the required data rate (see Table 1). However, those actions can be also implemented as simple signals with P/Q commands. P/Q commanding for assets control are a widely used technique to keep the voltage values within the desired range while minimizing system losses [55]. These control parameters would be then encapsulated in packets that would travel as data frames within the PLC-PRIME subnetwork. Once they reach the target node, the signals would be conveniently extracted and executed by actuators. Additionally, connection/disconnection commands and payment tasks could also be introduced within the available data rate. Connection/disconnection commands allow to switch on/off different assets remotely, according to prefixed set-points, while payment tasks are useful for dynamic pricing and resources savings for the system operator. Figure 3 shows a schematic representation of this management proposal, specifying the communications at each point as well as the energy flow according to the resource. In addition, the specific traffic flow for some applications is also included. The advantage of implementing IP (or an alternative service) over a PLC-PRIME deployment is that the implementation benefits from the features of the standard (e.g., network auto configuration, robustness, and topological information, among others), as well as having direct access to the assets (distributed resources and loads) through the SMs installed as part of the deployment. In addition, since two SNs can communicate between them without the need of passing through the BN, the data flow does not necessarily need to start always from the BN, which is interesting from the point of view of networking optimization. In a subnetwork as the proposed microgrid, with up to three repetition levels (see Figure 1), all nodes would be accessible with this implementation and could perform the applications discussed above.

- Communications in home networks: some applications in domestic premises can be addressed with the presented implementation, e.g., pricing signals and control commands operating within a HEM system. There are numerous NB-PLC deployments in which end users already count with a SM. Hence, these deployments are setting the basis for making use of the existing infrastructure for additional applications. Furthermore, there is a progressive increase of domestic devices that include some type of communication. Despite the fact that households have been an environment with multiple protocols and different vendors [8], IP continues to play a very important role, which makes the implementation of IP over PLC of relevance. The possible applications would be related with pricing services and remote control.
- Applications in wide area networks: in this context the Smart City concept arises and by extension a wide range of applications that require data rates of the order of bps or kbps, such as lighting, irrigation, signaling, monitoring, remote control, and even the management of different assets of the city such as energy resources, if applicable. As occurs in the domestic premises, cities begin to be a field with multiple vendors and different solutions in which IP could act as a seamless communication enabler. In metropolitan scenarios with highly urbanized areas, a great advantage of PLC against wireless options is that attenuation losses to wireless communications are high due to interferences with physical objects, and signal strength is low. Then, the assets might not always be accessible in all locations or at all times [10].
- Applications for utilities and grid operators: the scenario presented can be useful for some important tasks for grid operators such as signaling and management of connections and disconnections. These tasks do not have very strict data rate requirements and the needed data sample can be performed with the presented implementation. As commented above, other services such as SCADA could be included just for very low performance versions.

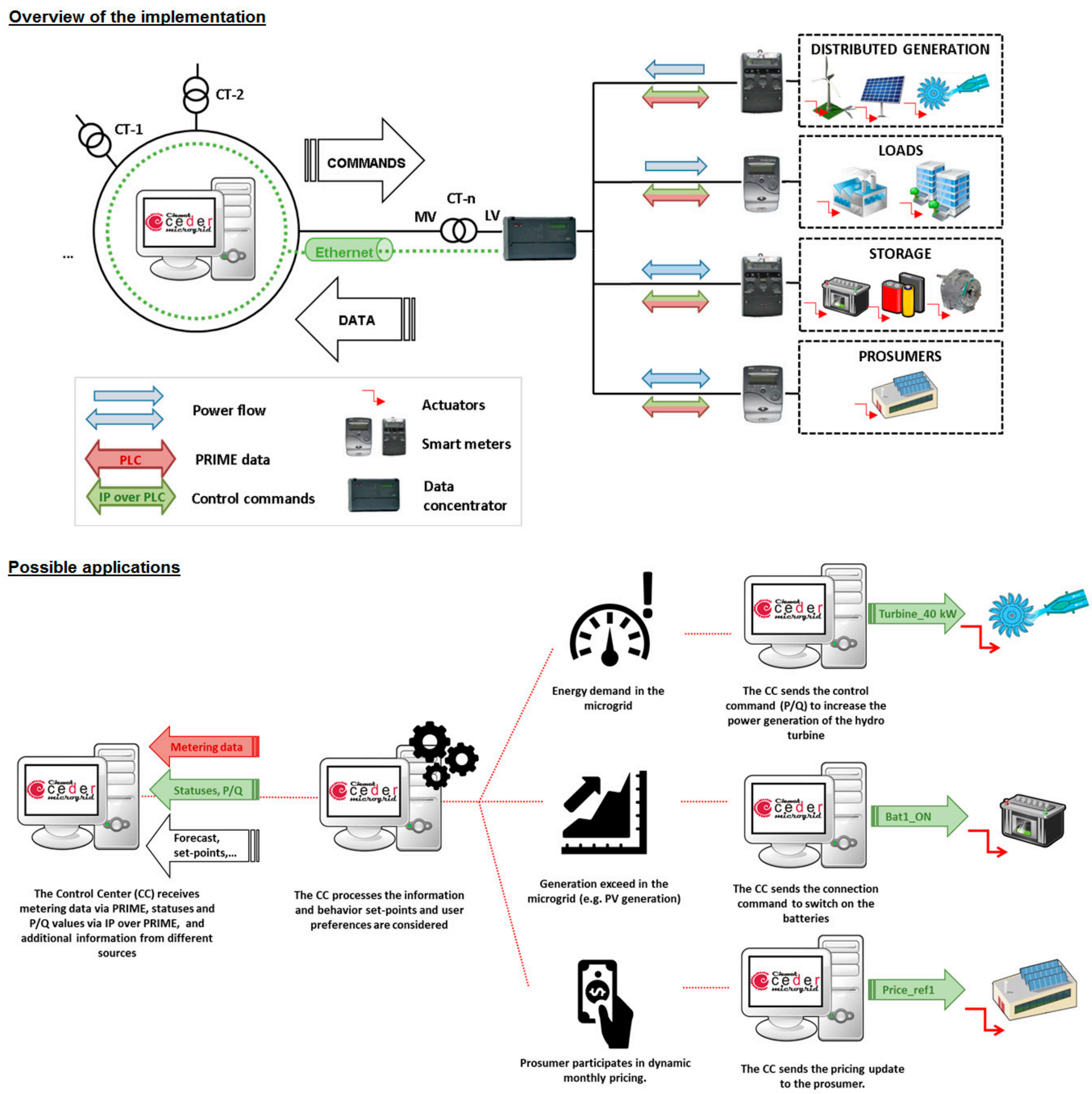

Figure 3. Proposed scheme for including additional tasks in a microgrid with the implementation of IP over PLC-PRIME: IP-based control commands are sent from the grid operator via Ethernet to the data concentrator, in which IP data is encapsulated into PLC-PRIME frames towards the receiver node. Once the frames arrives at the destination, the data is conveniently interpreted by an actuator which acts over the desired distributed energy resources (DER). IP-based status information from the DERs travels in reverse, towards the operator via the data concentrator. Additionally, three possible applications are depicted: P/Q commands, remote connection/disconnection, and payment tasks.

Although the study of security-related aspects is outside the scope of this work, it is worth mentioning it due to its relevance in SG applications such as those discussed above. Ensuring the security of SGs is key for their success, which also involves ensuring availability, confidentiality, integrity, and authentication [8]. As described in [12], it is possible to establish three types of secure associations between the application level and the PLC equipment. The choice of the most appropriate criterion will depend not only on the features of the final application but also on the communication protocols used.

- Secure association between the application and the PLC node ("end-to-end"). For this purpose, an uninterrupted safety tunnel is established between both ends of the communication;

- Secure transmission in the PLC section and at the application level, separately. In this case, the tunnel is established in two different domains: from the PLC network to the gateway, and from the gateway to the final application.
- No specific safety tunnel. In this scenario, the security techniques included in the communications protocols are used. In the specific case of the technology used for the implementation, PLC-PRIME v.1.3.6, it includes secure connection methods, authentication, and privacy. Version 1.4 of the standard also includes encryption mechanisms.

5. Conclusions

In contrast to existing works that address applications in SGs focusing on their requirements or on the features of each particular technology, this work analyzes the potential applications to be supported by existing communication deployments. Hence, this compilation can be consulted as a guideline for implementing potential applications of an existing deployment whose initial purpose differs from what can be further implemented.

This is the specific case of AMI systems: their success has led to numerous PLC-based deployments whose infrastructure is currently being used only for metering purposes. This work explores the viability of using the available channel existing in an AMI system based on NB-PLC for SG applications beyond Smart Metering. It has been demonstrated that several applications such as remote connections/disconnections and status signals could be implemented. Additionally, applications for domestic networks and smart cities could be also addressed. This analysis provides an added value to existing and future PLC-based AMI deployments, which entails an overall enhancement of the SG. Future work will tackle the performance of the implementation on the new version of PRIME and the practical execution of the presented applications.

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