Influence of Communication Technologies in Smart Grid Power Congestion Management

Adrien Gougeon, François Lemercier, Anne Blavette, Anne-Cécile Orgerie

Influence of Communication Technologies in Smart Grid Power Congestion Management

Adrien Gougeon*, François Lemercier*, Anne Blavette†, Anne-Cécile Orgerie*
*Univ. Rennes, Inria, CNRS, IRISA, Rennes, France, Email: firstname.lastname@irisa.fr
†Univ. Rennes, ENS Rennes, CNRS, SATIE lab, Rennes, France, Email: anne.blavette@ens-rennes.fr

***Abstract*—One of the main target of smart grids consists in deploying efficient demand-side management strategies. Several communication technologies are used to transfer monitoring data and control commands from and to smart meters with different quality of service depending on the technology. The quality of service provided by cyber-physical networks can significantly impact the performance of demand-side management strategies. But, this quality of service is rarely considered in research works on smart grid management, leading to over-estimating the advantages of smart grid technology. Therefore, the goal of our work is to quantify the performance degradation on demand-side management due to the quality of service provided by three communication technologies used for smart grids – namely PLC, Wi-Fi and Ethernet. This quantitative analysis relies on a residential grid congestion management case study and a coherent co-simulation environment. Two simple energy management policies (one centralized, the other decentralized) are considered. In addition, we present a sensitivity analysis over several parameters to highlight the limitations of communication technologies in this context of power congestion management.**

***Index Terms*—Cyber-physical network, Smart Grid communication, co-simulation, performance evaluation.**

I. Introduction

The ever-increasing demand in electricity, due for instance to the increasing grid integration of electric vehicles or distributed renewables such as photovoltaics [1], [2], may lead to congestion in the electrical grid. Traditionally, this was prevented by reinforcing the grid, which represents a costly and time-consuming process, not to mention the fact that it may potentially raise public opposition. Nevertheless, the advent of the smart grid allows to harness flexibility sources, for instance in the form of Demand-Side Management (DSM) [3] to postpone, or even to avoid, the need for grid reinforcement.

Among the different sources of flexibility existing on the demand side, electric heaters represent an interesting option for grid congestion management as the impact of their (full or partial) temporary shedding on a household may be relatively negligible thanks to the building envelope acting as a thermal storage capacity. This option is also particularly interesting because the electric heater flexibility can be controlled almost instantaneously, except for the delay due to the information transmission in the communication network. In contrast, other loads may not be able to react so quickly (e.g. washing machine finishing the current phase in its cycle before stopping).

Exploiting the thermal inertia of buildings, known as "building as a battery", has been considered in several works [4]–[7]. In these works, the cyber-physical communication network is considered as ideal, i.e. without delay. However, a real communication infrastructure may present significant delays which impact the performance of the smart grid [8]. Hence, the aim of our work is to quantify the performance of communication technologies employed by smart grids. We compare communication technologies – namely Power Line Carrier (PLC), Wi-Fi and Ethernet – on a grid congestion management case study through the short-term shedding of electric heaters. This quantitative analysis relies on a coherent co-simulation environment combining two well-known open-source simulators: one from the communication network community (ns-3) and the other from the electrical engineering community (pandapower). In addition, we also explore several other parameters (e.g. communication delay, command message size, etc.) in order to highlight the limitations of communication technologies in this context. The contributions of this paper are:

- A fine-grain modeling of three communication means on a realistic smart grid use-case: a three-phase electrical network of an existing urban district.
- An open-source co-simulation framework to evaluate performance impact of communication means over electrical network management.
- A simulation-based quantitative analysis of the performance of two DSM approaches (i.e. centralized and decentralized management) on a precise scenario involving heater shedding in a residential context.
- A sensitivity analysis of the most influencing parameters on DSM performance depending on the communication technology for a given use-case and scenario.

The paper is organized as follows. Section II details the state of the art. Section III presents our case study. Section IV introduces the co-simulation environment and the network models. Sections V and VI describe the experimentation and the results respectively. Finally, Section VII concludes this paper and provides thoughts on future work.

II. State of the art

Smart grids are based on an Advanced Metering Infrastructure (AMI) to gather information (about local production/consumption, network state, etc.), including smart meters. These latter are connected to the utilities Meter Data Management System through data concentrators allowing two-way communication between the consumers smart meters and the distribution system operator. A smart grid relies on one or several communication technologies to transfer data and control commands from and to smart meters placed in each house of the smart grid.

Most of the contributions related to DSM algorithms use general concepts where the smart grid communications are not modeled [9], or where a network architecture is presented but the communication links between the smart meters and the Home Energy Management System or utilities are not defined [10]. Consequently, the quality of service related to a given communication medium, such as delay or bandwidth, is not taken into account. However, this quality of service is highly dependent on the employed communication technology.

Several communication technologies are explored in the literature and are deployed in smart grids experimentation. The PLC communication technology is widely used in smart grid networks [11]. It represents a legacy of the traditional Automated Meter Reading (AMR) programs, where signals for on/off-peaks hours are sent through the power system conductors [12]. Hence, communication is based on the existing infrastructure which reduces considerably the deployment costs. Other technologies used to connect the data concentrators to the smart meters include wired (i.e. optic fiber, Ethernet) or wireless technologies (i.e. Zigbee, GPRS, Wi-Fi) [13]–[15].

However, the choice of a given communication technology over another is often not justified in the literature, and to the best of our knowledge, there is few contributions comparing communication technologies in a smart grid context [12], [16]–[18]. Moreover, in these studies, the provided comparison remains at a qualitative level, without any quantitative analysis of potential impacts on DSM performance.

Generally, the PLC technology is cited as a reference in most of smart grid communication works. Despite its sensitivity to interference, the attenuation of the signal at every transformer and the low bandwidth compared to other communication technologies, PLC is often selected due to its lower costs, as it can be deployed on an existing electrical infrastructure [19]. On the other hand, wired and wireless technologies offer better performance.

Some works in the literature propose different solutions based on specific technologies, or a combination of these. For instance, in [16] the authors have selected a combination of Zigbee and PLC communication links. This choice is motivated by the cost criterion and the ease of the implementation, without any justification on the impact on the ICT infrastructure's performance. Other works use multiple technologies concluding that each one can meet the requirements of specific applications [17], [20]. Authors in [17] conduct an experimentation comparing the physical access characteristics metrics, such as the latency. But, despite giving some recommendations on technology choice, this study does not take communication limitations into account in the proposed solution except for encouraging hybrid communication. In the same context, Samarakoon et al. [12] propose an experimentation of a Zigbee load control installation. They measure the delay and its impact on the primary frequency response using smart meters. This study shows the importance of the smart meter, and especially its communication medium, since most of the operation duration to update the frequency measurement is attributed to the communication itself. Similarly, Jahić et al. [21] demonstrate the feasibility of a DSM system with the control of heating appliances connected using Wi-Fi and highlight the necessity of low delays in DSM. However, this study only presents a single scenario and do not provide a comparative analysis of communication technologies.

III. Case Study

The goal of this work is to study and compare communication technologies in a smart grid context. In order to provide a quantitative analysis, we rely on a case study of a typical DSM problem with real data coming from a well-known public benchmark [22]. The case study explores a grid congestion management scenario where the goal of the energy management consists in maintaining the current flowing through the substation of a residential district below a maximum allowed safety threshold, while minimizing the effect on the electricity consumers. In order to explore a challenging case communication-wise, we have selected a reactive approach [23], as opposed to an anticipative approach, for the energy management of the considered smart grid. Reactive approaches enable to react to events whereas anticipative approaches are based on forecasts. The former have the advantage of being able to mitigate events when they actually occur, with the drawback on relying heavily on the ICT infrastructure.

The case study considers a residential district with several households, each equipped with a smart meter and electric heaters that can be shed temporarily on demand by the smart meter. The district is powered by a single substation, connected to the electrical grid through a three-phase low-voltage distribution network. The substation may be subject to grid congestion, which is intended to be mitigated by the flexibility of several households, for instance in exchange of an economic compensation. Grid congestion management is considered to be achieved here through short-term load shedding, where control commands are sent to the smart meters to temporarily shed houses electric heaters. We compare two simple management policies, a centralized one and a decentralized one, based on the same approach [24]. We opted for a simple approach so as not to hide the effects of communication technologies behind complex algorithms, and thus provide generic conclusions.

A. Shedding policy

The substation has an upper current threshold, simply called "current threshold". It defines a maximum level of current that is allowed to flow through the substation and can be less than or equal to the current rating of the substation. Whenever the current goes above the current threshold, a shedding process is initiated. This process tries to shed temporarily several houses' electric heaters to reduce the power demand. When a house is selected for shedding, a command is sent to its smart meter and all its heaters are shed.

Equation 1 is used to determine the number of houses that need to receive a shedding command to maintain the current bellow the threshold.

$$n_{H,x} = \left\lceil \frac{(I_{Line1,x} - \Theta) \times V_{PN,x}}{P_h} \right\rceil \quad (1)$$

where $I_{Line1,x}$ is the current measured at the substation for phase x (as we are in a three-phase unbalanced electrical network, grid congestion may happen on one or several of the three phases A, B or C), Θ is the current threshold, $V_{PN,x}$ is the phase-to-neutral voltage for phase x, P_h is the power of a single heater, and $n_{H,x}$ is the number of houses to which shedding commands must be sent to mitigate the grid congestion. Although there is actually three electric heaters per house in our case study, any number of them may be active at any given time. Indeed, to maintain their objective temperature, electric heaters permanently switches between an ON phase and an OFF phase, where they do not consume electricity. Equation 1 considers a worst case where only one heater per house is in active phase. Thus, only the current due to one heater may be subtracted from the grid congestion if the house is shed.

The post-shedding rebound effect is not modeled in this study. Our goal is indeed not to present a complete shedding policy considering inhabitants thermal comfort, but to highlight key differences between communication technologies in a DSM context. The shedding of electric heaters is only used as a case study. In addition, the rebound effect, if creating any grid congestion issue, would be treated in a similar manner as the initial grid congestion event. Besides, our co-simulation environment, described in the next section, allows to integrate detailed thermal models implemented in dedicated simulators enabling to integrate this effect in future work. The shedding policy is ensured by management algorithms, either in a centralized or decentralized way, detailed in the following.

B. Centralized management

The centralized management is based on a direct communication between a policy master and the smart meters located in each house. With a centralized management, every smart meter measures the household power consumption every second. This consumption is averaged locally over a sliding window, and the substation sends it to the master periodically. All these data exchanges happen via a communication network.

When receiving data from the substation, the master may detect that the current is above the current threshold for one or several phases. If so, it starts a shedding process. The shedding process begins by using Equation 1 to determine the number of houses that need to shed their electric heaters to solve the grid congestion issue. Then, the master sends directly shedding commands to smart meters connected to the congested phase to shed temporarily houses electric heaters. We suppose that houses participating in the shedding plan have the same economic compensation, and as a consequence the master sends in priority shedding commands to houses consuming the largest amount of energy, using data collected from the smart meters.

While there is always the same number of houses in the district, only a subset of them is considered as volunteering in the shedding plan in exchange for an economic compensation. In our simulations, the participating houses are selected randomly. In the centralized management, a fair shedding policy is ensured by a cycle mechanism. When a house is shed during a specific cycle, it cannot be shed again during the same cycle. When every house participating in the shedding plan has been shed, the master moves to the next cycle.

C. Decentralized management

The decentralized algorithm differs from the centralized one since it does not communicate directly with each house. Instead, it relies on a token-based algorithm where houses volunteering for shedding are organized randomly in 3 virtual rings, depending on which phase they are connected to.

Similarly to the centralized management, the substation measures the current periodically for each phase and sends it to the master. When the master detects that the current is above the current threshold for a phase, it determines the number of houses that need to shed their electric heaters to mitigate the grid congestion, using Equation 1. Then, in opposition to the centralized management, the master creates a token containing the number of houses to shed. This token is sent to the first house of the concerned ring. When receiving a token, a house shuts its heaters down if possible, and forwards the token to the next house in the ring if more shedding is needed. Otherwise, the token stops. During the next grid congestion event, a new token will continue its way along the ring where the previous one stopped. Excessive shedding may happen if a new token is sent before the shedding initiated by the previous token is carried out due to communication delay. As a consequence, an unnecessarily large number of smart meters would receive a shedding command. To avoid this issue, a new token cannot be issued until the previous has finished.

In the decentralized approach, the fair shedding policy is ensured by the token ring mechanism itself. A house that has been shed cannot be shed again until every other house of the ring has also been shed.

IV. Experimental framework

Experimenting on real infrastructures is costly and constraining in the very least, or even impossible. Using simulators reduces costs, experimentation time, and is also very convenient to explore a broad range of parameters. However, to provide acceptable and convincing results, simulations require models that are proved either theoretically or experimentally, or at least recognized by their community and well established. As good as they are, simulators are often limited to their very specific domain. Co-simulation allows to combine several dedicated simulators into a single environment where each model can interact dynamically with the others. In this work, we combine dedicated simulation tools into a coherent co-simulation environment.

A. Co-simulation environment

The co-simulation environment takes advantage of several domain-specific simulators and makes them co-evolve at run time. A simplified view of the usage and interactions of each simulator used in this work is depicted in Figure 1.

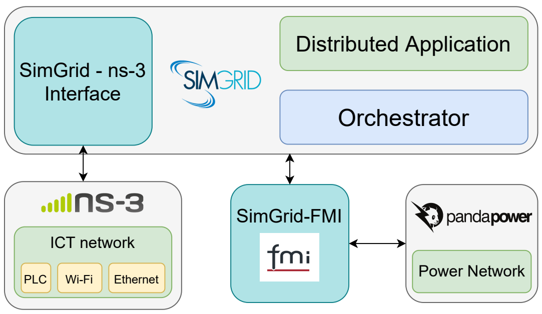

Fig. 1: Co-simulation environment. SimGrid acts as an orchestrator and interacts at run time with ns-3 and pandapower.

This environment gathers three simulators: SimGrid, ns-3 [25] and pandapower [26]. SimGrid is a simulator dedicated to the simulation of distributed applications over distributed platforms that has been proven theoretically and experimentally [27]. As our work relies largely on the accuracy of communication models, we decided to use ns-3 – a widely used and recognized communication simulator – to simulate communication between nodes. pandapower is an electrical network simulator intended for power flow analysis that has been validated against PowerFactory [26], [28], another popular simulator. For this work, we developed an FMI compliant tool based on pandapower which can be imported using SimGrid-FMI [29].

SimGrid plays the role of co-simulation orchestrator and contains the main simulation loop and the shedding algorithms. The others simulators are updated on request by SimGrid. For instance, when a communication between two nodes is needed, SimGrid creates a communication using the ns-3 simulator and retrieves the results. Similarly, SimGrid provides input consumption data to pandapower to feed the power network loads. The power network is updated on request, for instance whenever the current is measured at the substation, when SimGrid asks for results from pandapower.

To perform the co-simulations, the framework relies on two networks: an electrical network and a communication network that are detailed in the following sections.

B. Electrical network

The case study is based on the publicly available electrical network IEEE model ”European Low Voltage Test Feeder” (ELVTF) [22]. This model provides data of a 3-phase, low voltage electrical network. This network describes a typical residential district of the United Kingdom [30], with 55 houses and a 11 kV/416 V substation feeding the district. There are respectively 21, 19 and 15 houses connected to phases A, B and C. The provided data also contains time series of one-minute averaged consumption for each house. A peak period in terms of consumption is considered since it represents the most challenging one for congestion management. The average consumption profile is depicted in Figure 2.

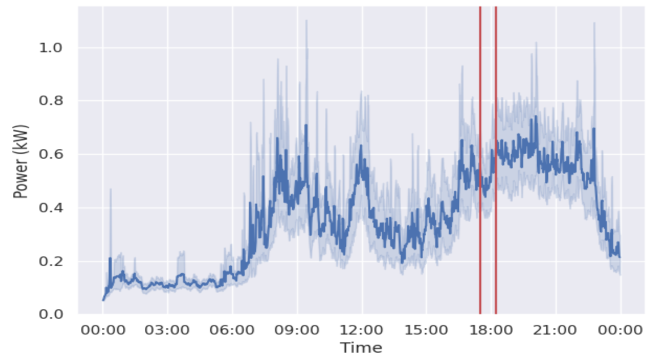

Fig. 2: Average consumption profile as provided by the ELVTF model. Our shedding scenario is simulated between 5:30 PM to 6:15 PM, between the two red bars.

We explore a shedding scenario considering houses equipped with direct-acting electric heaters, a typical solution in France. However, the ELVTF model describes a UK district where no direct-acting electric heaters are assumed to be used [31]. Consequently, we suppose that the traces provided with the model do not include the electrical heating.

We modified the model to consider that each house of the district is equipped with 3 electric heaters. All heaters are supposed identical with a consumption profile permanently switching between 2 kW and 0 kW while on. The on/off traces used for the heaters are based on measurements done on a real electric heater, in Rennes, France. Moreover, we added two random delays for the heaters start-up times as heaters are a priori not synchronized.

C. Communication network

In this work, we explore and compare three communication technologies in a DSM context: wired Ethernet, Wi-Fi and PLC. More specifically, we refer as *wired* the Ethernet standard IEEE 802.3 using 1GBps links, as *wireless* the Wi-Fi standard IEEE 802.11n with a theoretical throughput of 54Mbps, and as *PLC* the G3 standard in CENELEC Band A (35 kHz - 91 kHz), in accordance with the French Linky project. We fixed the PLC modulation to the maximum possible rate with DQPSK and fixed the transmit power spectral density to - 50 dBm/Hz to make all smart meters reachable by the substation and to each other. Finally, we use a NAYY150SE power supply cable and a typical colored background noise.

The study conditions for each technology reflect realistic deployment scenarios. As detailed in Section I, PLC currently represents a cost-effective and widely deployed technology although it suffers from performance issues when the number of communicating smart meters increases. On the other side, wired and wireless technologies offer appealing alternatives by leveraging already deployed Internet Service Providers (ISP) networks, with better performance in terms of data transfer time and concurrent communication handling.

The wired case, Figure 3(a), considers a fully wired end-to-end communication from the smart meter to the central utility, also know as the master. In this case, a communication from a smart meter to the master goes through the house's home router, to an edge router using the ISP's network, and ultimately reaches the master going through the core network. The wireless case, Figure 3(b), only differs from the wired case in the medium used to communicate from the smart meter to its home router. The PLC case, Figure 3(c), differs significantly from the two others as the communication does not go through the ISP's network but through the electric cable. In this case, smart meters can communicate directly with one another, and a concentrator makes the junction between the PLC network and the edge router. In all three cases, the communication between the substation and the edge router is wired.

Several communication delays apply in each case, as depicted in Figure 3. D_{HAN} is the communication delay in the Home Area Network and is fixed at 1 ms as it can be observed in a close point-to-point communication [32]. D_{NAN} is the communication delay in the Neighboring Area Network. In our study, this delay covers the links between home routers, the concentrator and the substation with the edge router. This delay varies from one user to another, notably due to the technology in use [33], [34]. For this delay we selected 10 ms, as it represents an average between DSL, cable and optical fiber users in EU [34]. D_{WAN} is the communication delay in the Wide Area Network. Different values are explored in this study ranging from 0 to 150 ms, to explore cases as various as a master located in the neighborhood or in another country (in a Cloud computing environment for instance). D_{WIFI} and D_{PLC} are determined at run time by the simulator depending on several specific parameters such as the distance between the two communicating points or interference.

The communication network supports the message transmission between entities composing the smart grid. In this case study, we consider three types of messages detailed in the following sections: data messages, control messages, and status messages.

1) Data Messages: Data messages are sent periodically from two sources: the substation and the smart meters. The substation sends data messages providing monitoring information about the current flow in each phase, every second, regardless of the management policy (centralized or decentralized). On the other hand, data messages from the smart meters are sent following a sampling period, which is one of the explored parameters, as detailed in Section V-A. The data size of these messages is also explored. It must be noted that no data messages are sent from the smart meters with the decentralized policy.

2) Control Messages: Control messages carry information about the control of the smart meters. With a centralized management policy, only the master may send control messages to the smart meters, carrying a command to shed their heaters. However, tokens are also considered as control messages, and are sent by smart meters during simulations with a decentralized management policy. According to [35], the typical data size for a demand-response action request (e.g., load shedding) in a Neighbor Area Network (NAN) application is 100 B. Here, control messages' size are fixed to 1 kB to account for potentially more complex requests and for the token required data. Messages are sent sequentially, meaning that the master can only send another control message after the reception of the last one. While this property reduces the reactivity to grid congestion events, it is necessary to propose a coherent comparison between the communication technologies as parallel messages transmission may be difficult with PLC, contrary to with the wired and wireless technologies.

3) Status Messages: Status messages are sent by smart meters. They appear only during simulations with a centralized management policy. Smart meters acknowledge the reception of a control message by sending their new status, e.g. heaters off, to the master. Smart meters also send their new status after waking up at the end of a shedding procedure, signaling themselves as available again for shedding if needed.

V. NUMERICAL SIMULATIONS

This section details the numerical simulations. First, we introduce the different parameters explored. Then, we present the metrics used for the comparative analysis.

A. Explored parameters

The sensitivity analysis concerns several key parameters related to communication means used by DSM strategies that are presented hereafter.

1) Number of sheddable houses: it defines the number of houses that are available for shedding during the simulation. While this number varies, the total number of houses connected to the network does not change and is always equal to 55. Similarly, the number of houses connected to each phase is always the same: 21 on phase A, 19 on phase B and 15 on phase C, as in [22]. However, the number of sheddable houses connected to the same phase can vary between two simulations as sheddable houses are selected randomly at the beginning of the simulation. We choose to vary the number of sheddable houses from a minimum of 15 to the maximum of the 55 available houses. From a communication point of view, more sheddable houses means more potential destinations for shedding commands.

2) Current threshold: it represents a maximum allowed current value that may flow through the 11/0.4 kV substation. It may be less than or equal to the current rating of the substation. The current is measured directly at the substation, and detecting a value above the current threshold initiates the shedding process. The objective of the shedding process is to maintain this current under the current threshold value. Based on the consumption profile shown in Figure 2, we chose to explore current threshold values ranging from 0.4 kA to 0.6 kA. Lower thresholds imply more shedding situations, and thus more control messages.

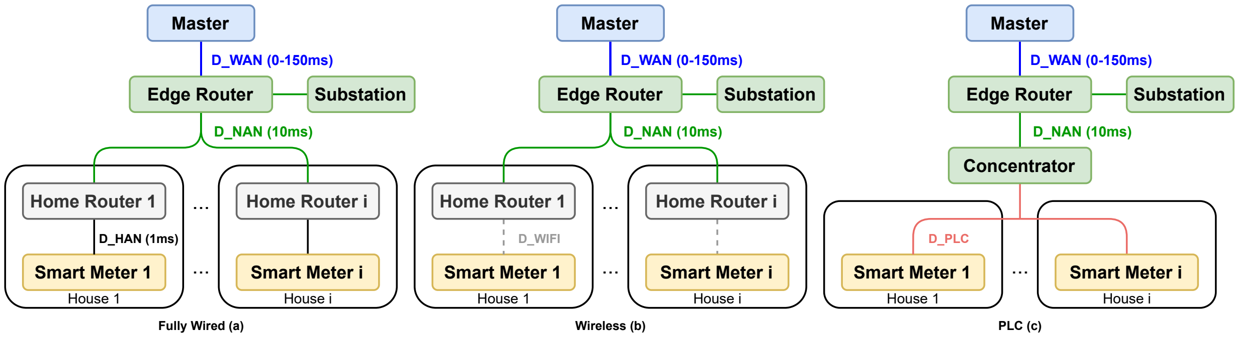

Fig. 3: Communication topology. (a) is the fully wired case; (b) is the wireless case; (c) is the PLC case.

3) Message size: the shedding process makes extensive use of communication between smart grid actors to maintain the current below its maximum allowed threshold. We explore several values of message size to observe the impact of this parameter on the DSM mechanism, depending on the communication technology. As the size of status messages and control messages (which include token messages) are fixed to 100 B and 1 kB respectively, variable message sizes apply exclusively to the data messages. We explored three data message size values: 1 kB, 10 kB and 100 kB. Depending on the communication medium, larger data size may cause data congestion on the communication network.

4) Shedding duration: when a heater receives a shedding command, it is shut down for a predefined duration, which is the same for all heaters. We explore a shedding duration ranging from 10 s to 300 s. This short time is intended to provoke a negligible impact on the inhabitants' comfort. Given the average consumption profile (shown in Figure 2), a longer shedding duration should imply less shedding commands.

5) Sampling period: the centralized management policy relies on consumption data from the smart meters placed in each house to select to which one it should send shedding commands in priority. While consumption data are updated every second locally at the smart meter, these data are not sent at the same rate to the master. Instead, it is averaged over a sliding window of 5 minutes and this average value is sent periodically to the master. The frequency of these updates depends on the sampling period, for which we explore values ranging from 15 s to 1800 s. It must be noted that, in the decentralized management policy, no central actor selects which houses to shed. Consequently, this parameter has no influence on the decentralized policy.

6) Communication technologies: either fully Gigabit Ethernet (IEEE 802.3), or IEEE 802.11n Wi-Fi (between the smart meter and the home router) with a theoretical throughput of 54 Mbps associated with Gigabit Ethernet, or G3-PLC.

7) D_{WAN}: defines the communication delay from the master to the edge router located near the district. The other wired communication delays D_{HAN} and D_{LAN} are fixed to 1 ms and 2.5 ms respectively. D_{WAN} varies from 0 ms to 150 ms, to explore scenarios ranging from a master close to the edge router, to a master located in another country (hosted on a Cloud for instance).

B. Evaluated metrics

We use two main metrics to evaluate the efficiency of the algorithms with respect to all the parameters given above, and for the three communication technologies considered (wired Ethernet, Wi-Fi and PLC): the total overcurrent and the mean shedding time.

The total overcurrent accounts for the number of measurements when the value at the substation is above the current threshold. This metric shows the efficiency of the shedding process from the Distribution System Operator (DSO) point of view, which aims to mitigate the grid congestion. The mean shedding time is calculated by dividing the total shedding time of each sheddable house by the number of sheddable houses, sorted by phase. This metric shows the efficiency of the shedding algorithm from an inhabitant point of view, for whom shedding should be minimized.

VI. Results

In this section, we present the results of the simulations exploring the selected parameters. An imbalance exists between the phases: less households are connected to phase B and C than to phase A. As a consequence, the results for phase B have a similar shape than for phase A, but are less pronounced, and the lack of shedding on phase C in most simulations induces results either without any variance, or with excessively high variance. For these reasons and by lack of space, we only present hereafter the results for phase A.

TABLE I: Default simulation parameters values. When a parameter is explored during a simulation, the other parameters are set to the default values.

Parameter	Default Value
Number of sheddable houses	30
Current threshold	0.5 kA
Data message size	1 kB
Shedding duration	60 s
Sampling period	20 s
WAN delay	10 ms

We explore the influence of several parameters independently, the others being fixed to their default values, shown in Table I. The mean overcurrent over all the simulations

Fig. 4: Total overcurrent versus number of sheddable houses. The current threshold is set to 0.5 kA, message size to 1 kB, shedding duration to 60 s, sampling period to 20 s and latency to 10 ms.

for a given configuration (i.e. technology type, policy, etc.) ranges between around 1 and 2 measurements. It means that when an overcurrent is detected after a current measurement at the substation, in most cases the overcurrent has been mitigated before the next measurement, which is deemed to be considered acceptable from a DSO perspective.

Each bar of a plot is the result of 50 simulations with the same parameters. The variance comes from several factors changing for each simulation: the subset of sheddable houses, the time shift between heaters of the same house as well as their initial start time, the order of the sheddable houses inside the virtual ring in the decentralized management, and also a randomization internal to ns-3 influencing slightly wireless and PLC communication.

1) Number of sheddable houses: Figure 4 shows the total overcurrent depending on the number of sheddable houses. It can be observed that the number of sheddable houses does not have a large impact on this metrics. However, a low number of sheddable houses (less than 25) can be insufficient to reduce satisfactorily the congestion issues. Moreover, it also increases greatly the variance of the results. Excluding results where the number of sheddable houses is less than 25, we observe a decrease in the total overcurrent of respectively 6%, 8% and 13% for the wired, the wireless and the PLC technologies between the centralized and decentralized management policies. As expected, the management policy can have a significant impact on the smart grid performance. Considering the same policy (centralized or decentralized), it can be observed that there is less than 2% difference between the wired and wireless technologies. With PLC technology, the total overcurrent is 32% higher (respectively 23% higher) with the centralized approach (resp. the decentralized approach) than with wired technology. This difference is due to the low robustness of the PLC technology to concurrent communications of smart meters in the centralized approach, and to the low bandwidth and high delay for the decentralized approach.

As shown in Figure 5, the shedding time per house decreases with the number of sheddable houses. The trend is non linear with the number of sheddable houses. The management policy seems to have a negligible impact on this metric with wired or wireless communication technologies, but not with PLC. From the consumers thermal comfort standpoint, the decentralized approach remains better than the centralized one when PLC is used, as the shedding time per house is lower in the former case, as shown in Figure 5, along with a lower total overcurrent, as depicted in Figure 4. As already mentioned, this shows that the type of technology may have a significant influence when comparing centralized and decentralized approaches.

The shedding time per house can reach high values, should the number of sheddable houses be sufficiently low, depending also on the considered management policy and communication technology, which may affect the thermal comfort of the inhabitants. In other words, in smart grids with a low number of flexible entities, the type of policy (centralized or decentralized) and the type of communication technology can have an important influence on the electrical network performance.

2) Current threshold: Figure 6 shows that, as expected, the current threshold has an important impact on the total overcurrent. A high threshold reduces the congestion issues and therefore, the need for shedding, while a low threshold increases the stress on the system. The wired and wireless communication technologies produce similar results with a linear increase in the total overcurrent as the current threshold decreases, whereas the total overcurrent increases exponentially with the PLC technology. This confirms that the PLC technology is less able to deal with large and/or recurrent congestion issues than the wired and wireless technologies which occur when the current threshold is sufficiently low. When the congestion issue is less important (high current threshold), all the technologies seem to lead to similar results. For all the considered communication technologies, the decentralized management performs better than the centralized management, or has at least a similar level of performance in terms of cumulated overcurrent duration. This is even more visible with the PLC technology, for which the difference in terms of performance between the centralized and the decentralized approaches is the largest. This difference may be explained by the fact that PLC shows poor performance when

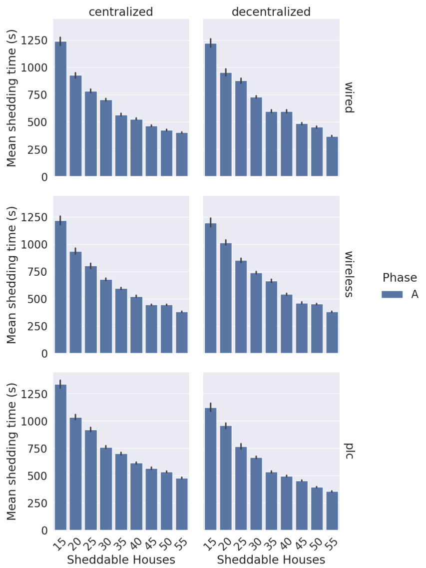

Fig. 5: Mean shedding time per house versus number of sheddable houses. The current threshold is set to 0.5 kA, message size to 1 kB, shedding duration to 60 s, sampling period to 20 s and latency to 10 ms.

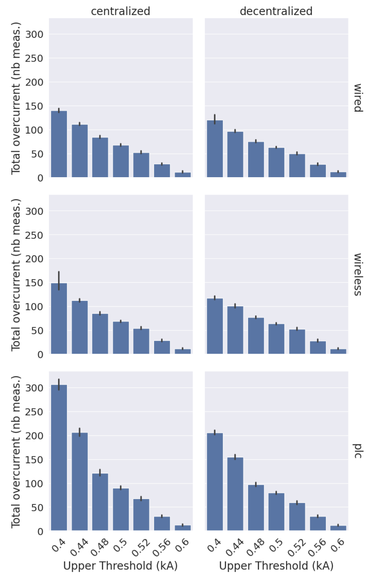

Fig. 6: Total overcurrent versus current threshold. The number of sheddable houses is set to 30, message size to 1 kB, shedding duration to 60 s, sampling period to 20 s and latency to 10 ms.

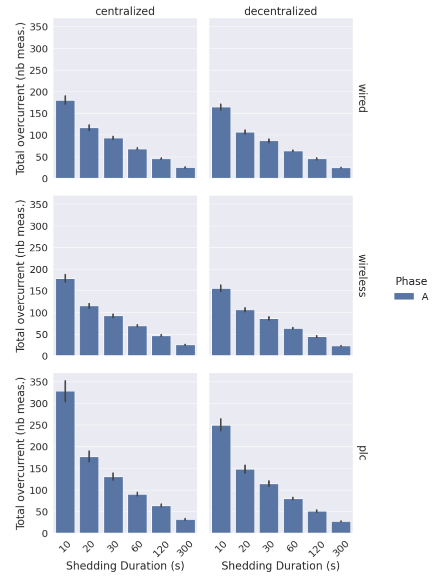

Fig. 7: Total overcurrent versus shedding duration. The number of sheddable houses is set to 30, current threshold to 0.5 kA, message size to 1 kB, sampling period to 20 s and latency to 10 ms.

multiple messages are sent simultaneously, which occurs with the centralized approach, even with small message sizes such as 1 kB. This shows again the necessity to take into account the type of communication technology when considering reactive approaches with a highly stressed electrical network.

3) Message Size: Communication tests were performed to determine the average communication delay between two smart meters, depending on the technology and payload size. The payload delay is determined by measuring the time between the beginning of a TCP communication, and the last acknowledgment received for that payload. The results are shown in Table II. There is no standard deviation in the wired case because from one end to the other, the latency is fixed for each wired link in the simulation. No significant differences are observed depending on the payload size for values ranging from 1 kB, 10 kB to 100 kB between the wired and wireless communication technologies. This was expected since we do not consider here overloaded communication networks. The wireless case presents better results than the wired one as an ideal scenario is considered with a single station connected to each access point. Regarding the PLC technology, the average delay is larger but still of the same order of magnitude as the wired and wireless technologies for 1 kB messages. However, the communication channel is often unable to deliver messages with size larger than or equal to 10 kB. This shows that the PLC technology may be irrelevant if a reactive energy management is required in the case where a significant amount of data has to be transferred.

4) Shedding duration: The shedding duration has an important impact on both the total overcurrent duration and the shedding time per house, as it can be observed in Figures 7 and 8.

TABLE II: Average payload delay between each smart meter, depending on the communication technology and payload size.

Comm.	Payload size	Average delay (ms)	Standard deviation
Wired	1 kB	88.0	0
	10 kB	220.0	0
	100 kB	352.1	0
Wireless	1 kB	83.8	3.9
	10 kB	207.8	4.1
	100 kB	347.2	5.7
PLC	1 kB	428.7	50.2
	10 kB	N/A	N/A
	100 kB	N/A	N/A

With each communication technology, the total overcurrent duration increases as the shedding duration decreases. This may be explained by the reactive approach of the management policies: as soon as the shedding is over, the current is more susceptible to get over the threshold again. Then, the more often congestion is detected, the more often shedding is required again. However, repeated detection of congestion issues leads to an increasing total overcurrent. Hence, the greater the number of detections (due to a short shedding duration), the greater the total overcurrent duration.

In addition, decreasing the shedding duration increases the communication traffic, which constitutes an important burden for the PLC technology, thus increasing heavily the total overcurrent in short shedding duration cases. Although increasing shedding duration decreases importantly the total overcurrent, Figure 8 shows also that a long shedding duration is more likely to cause excessive shedding, when compared to the remaining total overcurrent, and therefore to affect the inhabitants' thermal comfort unnecessarily.

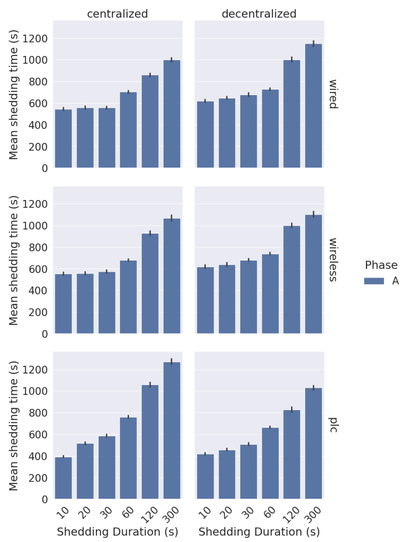

Fig. 8: Shedding time per house versus shedding duration. The number of sheddable houses is set to 30, current threshold to 0.5 kA, message size to 1 kB, sampling period to 20 s and latency to 10 ms.

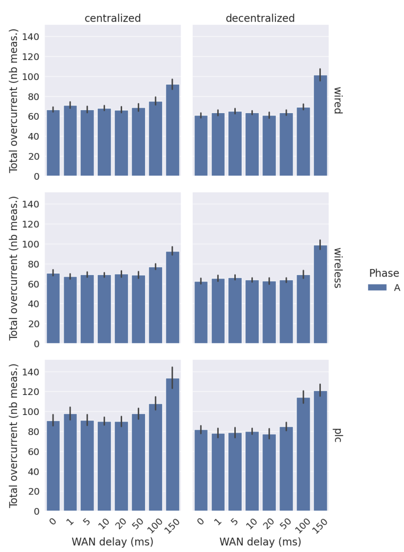

Fig. 9: Total overcurrent versus latency. The number of sheddable houses is set to 30, current threshold to 0.5 kA, message size to 1 kB, shutdown duration to 60 s and sampling period to 20 s.

5) Sampling Period: According to the simulations (not plotted here), the sampling period does not impact the efficiency of the shedding process for any of the considered technologies. This is due to the fact that the fair shedding policy implies that, even if a house consumes far more energy than the others, it will not be shed again until the shedding has been applied to every other sheddable houses.

6) WAN delay: We explore a wide range of WAN delay values, as depicted Figure 9. We observe that performance losses could happen if WAN delay, including processing time, reaches more than 100 ms with any communication technology. The decentralized management policy seems more impacted than the centralized one in the wired and wireless cases. Nevertheless, delays below 100 ms have a negligible impact on the total overcurrent, for all communication technologies and management policies.

VII. Conclusion

In this paper, we propose a comparative performance analysis of three different communication technologies — Ethernet, Wi-Fi and PLC — to mitigate congestion issues in a smart grid through both a centralized and a decentralized shedding algorithm. A reactive approach, as opposed to an anticipative one, is considered here, the former representing a more challenging scenario than the latter from a communication point of view. Based on a realistic case study, relying on publicly available data, we observed the shedding performance through our open-source co-simulation framework considering both the DSO and the inhabitants' perspectives. A sensitivity analysis on key parameters, such as WAN delay, message size, and shutdown duration has been carried out to highlight the cases where communication technologies could reduce the shedding algorithm efficiency.

The simulation results show that Wi-Fi and Ethernet offer similar performances. Conversely, the PLC technology may exhibit significantly poorer performance, with respect to the wired and wireless technologies. This occurs when a centralized management policy is adopted and when control messages must be sent repeatedly to a limited number of sheddable houses. Also, the message size has a negligible impact in the case of the wired and wireless technologies. However, in case of large message sizes, the delay between two smart meters may become prohibitive with PLC if fast-acting demand response is required.

Regarding performance, it can be greatly impacted by the characteristics of the communications links. However, the performance of all the technologies considered here is in the same order of magnitude when the stress on the electrical grid is reduced, i.e. when it is subject to less frequent congestion issues (e.g. more sheddable houses, greater shutdown duration, etc.). Finally, the communication technology may have a significant impact when comparing the centralized and the decentralized version of a demand-side management algorithm. The performance of the centralized policy may be better than the performance of the decentralized one with a given technology whereas the contrary may be true for another.

In the future, we plan to explore other demand-side management algorithms in order to assess their performance under realistic communication conditions. We will also investigate other communication technologies.

Acknowledgments

This project has received financial support from the CNRS through the MITI interdisciplinary programs with the Momentum project RI/RE. Experiments presented in this paper were carried out using the Grid'5000 testbed, supported by a scientific interest group hosted by Inria and including CNRS, RENATER and several Universities as well as other organizations (https://www.grid5000.fr).

References

[1] N. Xu and C. Chung, "Challenges in Future Competition of Electric Vehicle Charging Management and Solutions," *IEEE Transactions on Smart Grid*, vol. 6, no. 3, pp. 1323–1331, 2015.

[2] E. Yao, P. Samadi, V. W. S. Wong, and R. Schober, "Residential Demand Side Management Under High Penetration of Rooftop Photovoltaic Units," *IEEE Trans. on Smart Grid*, vol. 7, no. 3, pp. 1597–1608, 2016.

[3] K. Ding and J. Zhi, "Chapter 6 - wind power peak-valley regulation and frequency control technology," in *Large-Scale Wind Power Grid Integration*, N. Wang, C. Kang, and D. Ren, Eds., 2016, pp. 211–232.

[4] S. Afshari, J. Wolfe, M. S. Nazir, I. A. Hiskens, J. X. Johnson, and J. L. Mathieu, "An Experimental Study of Energy Consumption in Buildings Providing Ancillary Services," in *IEEE Power & Energy Society Innovative Smart Grid Technologies Conference*, 2017.

[5] M. O. Panão, N. Mateus, and G. Carrilho da Graça, "Measured and modeled performance of internal mass as a thermal energy battery for energy flexible residential buildings," *Applied Energy*, vol. 239, 2019.

[6] C. Pajot *et al.*, "An Approach to Study District Thermal Flexibility Using Generative Modeling from Existing Data," *MDPI Energies*, 2019.

[7] J. Ramos, M. Moreno, M. Delgado, S. Dominguez, and L. Cabeza, "Potential of energy flexible buildings: Evaluation of DSM strategies using building thermal mass," *Energy & Buildings*, vol. 203, 2019.

[8] A. Gougeon, B. Camus, A. Blavette, and A.-C. Orgerie, "Impact of wired telecommunication network latency on demand-side management in smart grids," in *IFIP/IEEE Int. Symp. on Integrated Netw. Management (IM)*, 2021, pp. 295–303.

[9] A. Al Zishan, M. M. Haji, and O. Ardakanian, "Adaptive Congestion Control for Electric Vehicle Charging in the Smart Grid," *IEEE Trans. on Smart Grid*, vol. 12, no. 3, pp. 2439–2449, 2021.

[10] W. Shi *et al.*, "Optimal Residential Demand Response in Distribution Networks," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 7, pp. 1441–1450, 2014.

[11] S.-G. Yoon, "Performance analysis of power saving strategies for power line communications," in *IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 2017, pp. 314–319.

[12] K. Samarakoon, J. Ekanayake, and N. Jenkins, "Investigation of Domestic Load Control to Provide Primary Frequency Response Using Smart Meters," *IEEE Trans. on Smart Grid*, vol. 3, no. 1, pp. 282–292, 2012.

[13] D. Baimel, S. Tapuchi, and N. Baimel, "Smart grid communication technologies - overview, research challenges and opportunities," in *Int. Symp. on Power Electronics, Electrical Drives, Automation and Motion*, 2016, pp. 116–120.

[14] R. N. Gore and S. P. Valsan, "Wireless communication technologies for smart grid (WAMS) deployment," in *IEEE International Conference on Industrial Technology (ICIT)*, 2018, pp. 1326–1331.

[15] M. Ghorbanian, S. H. Dolatabadi, M. Masjedi, and P. Siano, "Communication in Smart Grids: A Comprehensive Review on the Existing and Future Communication and Information Infrastructures," *IEEE Systems Journal*, vol. 13, no. 4, pp. 4001–4014, 2019.

[16] P. Wang, J. Y. Huang, Y. Ding, P. Loh, and L. Goel, "Demand Side Load Management of Smart Grids using intelligent trading/Metering/ Billing System," in *IEEE PES General Meeting*, 2010.

[17] J. C. Hastings, D. M. Laverty, and D. J. Morrow, "A Converged Approach to Physical-Layer Communications in Supporting Domestic-Level Automated Demand-Response Systems utilizing ISO/IEC 20922," in *IEEE PES General Meeting*, 2018.

[18] A. Zaballos, A. Vallejo, and J. M. Selga, "Heterogeneous communication architecture for the smart grid," *IEEE Network*, vol. 25, pp. 30–37, 2011.

[19] A. De Domenico, C. Gavriluta, M. Mendil, V. Heiries, R. Caire, and N. Hadjsaid, "Communication network assessment for distributed smart grid applications," in *General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*, 2017.

[20] J. Cordova-Garcia, X. Wang, D. Xie, Y. Zhao, and L. Zuo, "Control of Communications-Dependent Cascading Failures in Power Grids," *IEEE Transactions on Smart Grid*, vol. 10, no. 5, pp. 5021–5031, 2019.

[21] A. Jahić, J. Hastings, D. Morrow, and D. Laverty, "Hardware-in-the-loop demonstration of automated demand response for distribution networks using PMU and MQTT," *IET Smart Grid*, vol. 5, 2021.

[22] IEEE PES AMPS DSAS Test Feeder Working Group, "European Low Voltage Test Feeder," http://sites.ieee.org/pes-testfeeders/resources/, 2015.

[23] O. Ardakanian, C. Rosenberg, and S. Keshav, "Real-Time Distributed Congestion Control for Electrical Vehicle Charging," *ACM SIGMETRICS Performance Evaluation Review*, vol. 40, no. 3, 2012.

[24] J. Vaubourg *et al.*, "Multi-agent Multi-Model Simulation of Smart Grids in the MS4SG Project," in *Advances in Practical Applications of Agents, Multi-Agent Systems, and Sustainability*, 2015, pp. 240–251.

[25] "ns-3, Discrete Event Network Simulator," http://www.nsnam.org.

[26] L. Thurner *et al.*, "Pandapower - An Open-Source Python Tool for Convenient Modeling, Analysis, and Optimization of Electric Power Systems," *IEEE Trans. on Pow. Syst.*, vol. 33, no. 6, 2018.

[27] H. Casanova *et al.*, "Versatile, Scalable, and Accurate Simulation of Distributed Applications and Platforms," *Journal of Parallel and Distributed Computing*, vol. 74, no. 10, pp. 2899–2917, 2014.

[28] A. Fernández-Guillamón, A. Molina-García, K. Das, and M. Altin, "Comparison of different tools for power flow analysis with high wind power integration," in *Int. Conf. on Clean Electrical Power*, 2019.

[29] A. Gougeon *et al.*, "Co-Simulation of Power Systems and Computing Systems using the FMI Standard," in *IFIP/IEEE Int. Symp. on Integrated Netw. Management (IM)*, 2021, pp. 730–731.

[30] P. Schneider *et al.*, "Analytic Considerations and Design Basis for the IEEE Distribution Test Feeder," *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 3181–3188, 2018.

[31] OFGEM, "Insights paper on households with electric and other non-gas heating," EU, 2015.

[32] B.-K. Choi *et al.*, "Analysis of point-to-point packet delay in an operational network," in *IEEE INFOCOM 2004*, 2004, pp. 1797–1807.

[33] S. Sundaresan, W. De Donato, N. Feamster, R. Teixeira, S. Crawford, and A. Pescapé, "Broadband Internet Performance: A View From the Gateway," in *ACM SIGCOMM*, 2011, pp. 134–145.

[34] V. Bajpai, S. J. Eravuchira, and J. Schönwälder, "Dissecting last-mile latency characteristics," *SIGCOMM Comput. Commun. Rev.*, vol. 47, no. 5, p. 25–34, 2017.

[35] M. Kuzlu, M. Pipattanasomporn, and S. Rahman, "Communication network requirements for major smart grid applications in HAN, NAN and WAN," *Computer Networks*, vol. 67, pp. 74–88, 2014.